# 3 Materials

# CHAPTER 3 CONTENTS

# 3 Materials

**Chapter 3** presents guidance on material properties for use in design.

Key inputs from other chapters

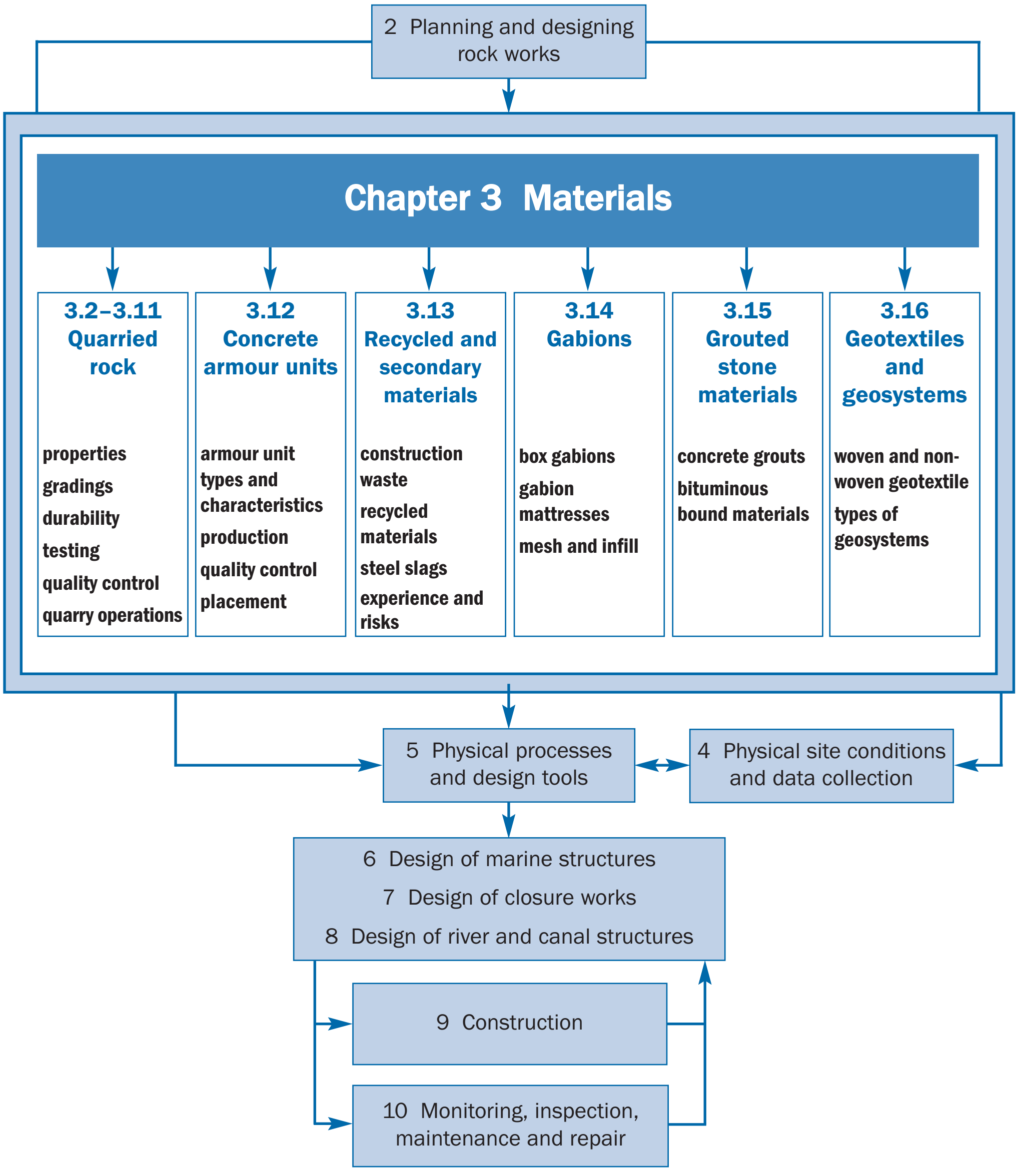
- Chapter 2 ⇨ **project requirements**

Key outputs to other chapters

- **material properties** ⇨ Chapters 5 to 10

**NOTE:** The project process is **iterative.** The reader should **revisit Chapter 2** throughout the project life cycle for a reminder of important issues.

This flow chart shows where to find information in the chapter and how it links to other chapters. Use it in combination with the contents page and the index to navigate the manual.



## 3.1 INTRODUCTION

The main considerations for a rock project are its scale and the availability, quality and handling of materials. Large projects that require a new quarry to be opened will be very different to smaller projects in regions where there are many established sources of rock products. The availability and quality of materials should be established at an early stage, as material production and transportation costs can be an important consideration when selecting a design solution. Also, the prescribed execution methods and available equipment associated with a choice of materials may influence this selection process. In some cases, labour availability may promote the use of local rock that is both selected and placed in a structure by hand.

This manual focuses on materials for structures where armourstone and concrete unit cover layer solutions are typically the most viable. Information is also provided on a range of other materials usually incorporated into such structures.

This introductory section presents the materials issues that should be addressed during the concept stage of the design. It also gives a summary of the functions that the materials have in the design and discusses durability considerations. Subsequent sections then cover the different material types – rock, concrete units, alternative granular materials, gabions, grouted stone composites and geotextiles.

The wide range of stakeholders in rock projects has been highlighted in Chapter 1 (see Table 1.1). The logic diagram in Figure 3.1 is designed to help the reader identify relevant sections of this chapter, identifying links between data to be gathered, materials evaluation and the main design process.

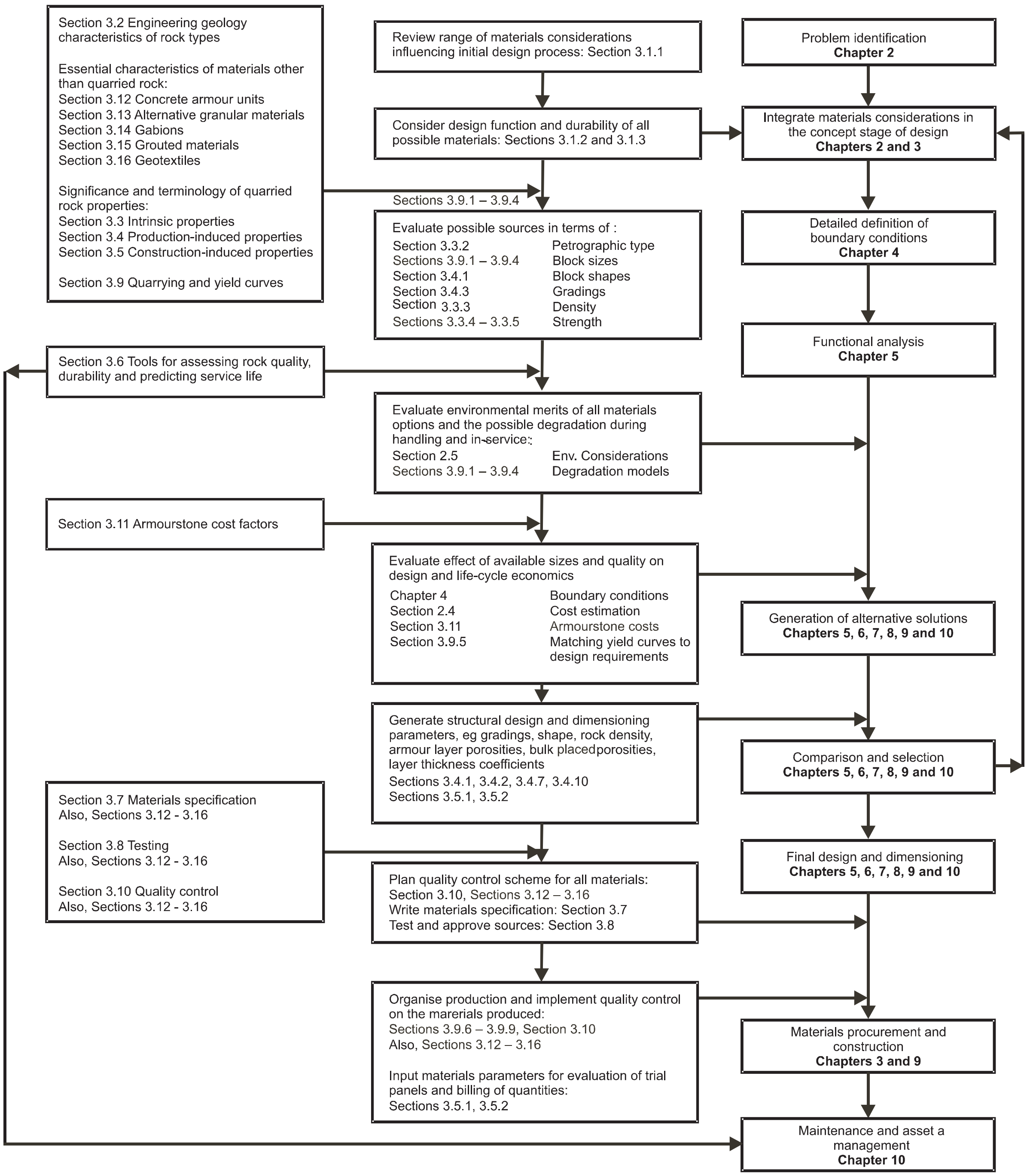



**Figure 3.1** *Flow chart relating sections to the materials evaluation and design process*

## 3.1.1 Materials considerations for concept stage

Materials considerations should be addressed in a logical, iterative and inclusive process (see Figure 3.2) at the concept design stage (see Section 2.2.1) before preliminary design is started. This may mean that one or more potential contractors will go through a preliminary evaluation process in parallel. This should consider available materials sources, specification requirements, site conditions and available transport. After a detailed design is tendered, the contractor works out the best choice of rock source, transport method, construction method, and the total cost. The successful contractor should go through further cycles of iteration and refinement to finalise the plan for handling of materials. Bringing design and construction expertise together, for example in *design and build* and *partnering alliance* contracts, has the advantage of simplifying design optimisation with respect to materials considerations.

The principles informing the early thinking about materials in the design process are summarised in the following sections and then illustrated in Boxes 3.1 to 3.3 using case histories that emphasise different materials aspects.

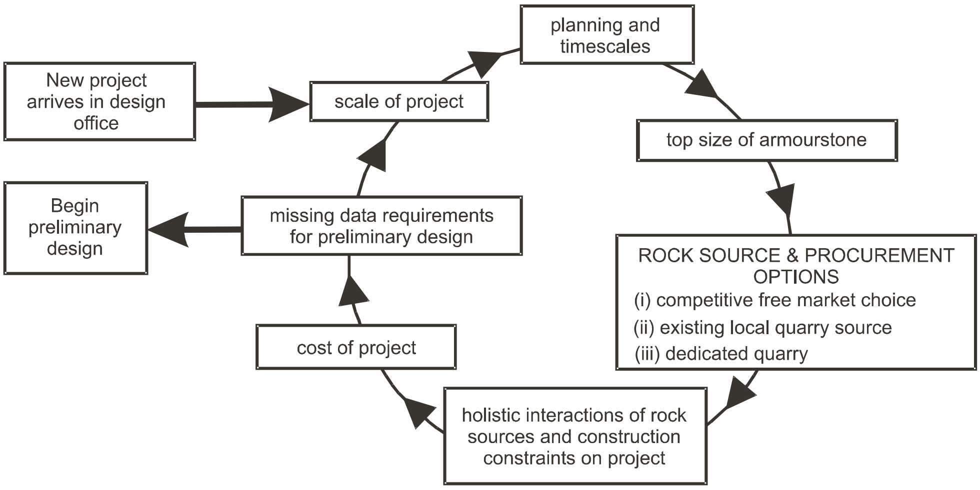



**Figure 3.2** *Flow diagram of materials consideration process to be applied at concept stage*

### *3.1.1.1 Scale of project*

The scale of project is usually related to the total investment cost and/or to the level of technical difficulties but for the purpose of this manual, the scale of the project is defined in terms of rock quantities, ie including armourstone, core and granular materials. For example:

- small local — eg < 50 000 tonnes
- medium regional — eg 50 000 – 500 000 tonnes
- large national/international — eg > 500 000 tonnes.

The scale of a rock project, whether small, medium or large, is normally expressed in terms of total quarried rock tonnages, a function of the spatial scale and water depths, or cost. It may be possible to compare cost directly with data from recently completed similar projects. For greater accuracy, tonnages can often be estimated from initial approximate site data, eg using rules of thumb for packing densities (see Section 3.5) and volumes based on simple cross-sections and metre-run linear distances, for example using other similar designs.

Small and medium-size projects are more dependent on established sources of armourstone such as aggregate quarries. Many repair and upgrade projects will be small. As project scale increases, it becomes increasingly important to locate an acceptable source of material, while minimising its distance from the project site and hence transport cost. For very large projects,

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demanding large volumes of core material, dedicated quarries opened in greenfield sites within a few kilometres from the site are the most attractive option, but they may take a considerable time to set up.

### 3.1.1.2 Planning and timescales

Suppliers and contractors can assist designers to estimate the likely time for delivery of the first consignment of suitable armourstone to site. For small and medium-scale projects, it will be necessary to evaluate stockpile volumes from within existing quarries, and their future supply rates, together with other quarry information. Aggregate-producing quarries differ in their ability to adjust normal practices to achieve greater rates of armourstone production. Production rates from dedicated quarries can more easily be maximised to match ideal construction rates, eg by utilising extra machine power, resources or time. Project planning usually includes an estimation of the time required to obtain planning permissions, complete detailed design, conduct a risk analysis, obtain funding, submit tender, mobilise site and complete construction. The project plan must be compatible with the lead time to achieve a certain rate of materials supply (eg of armour stones or concrete units) and the specific client restrictions for the construction site and transportation time windows.

### 3.1.1.3 Top sizes of armourstone

The mass of individual armour stones required for stability in the armour layer of a structure can be obtained from boundary conditions at the site, as discussed in more detail in Chapter 5. The maximum stone size may be critical at the concept stage. For example, a demand for 10–15 t armourstone may rule out many or all the locally available and established sources within economic transport distances because the quarries only have smaller top sizes available. The top size for a design may be constrained by the construction plant available for placing such large sizes, or the cost of supply. Where large stone sizes are required, it is always advisable to consider alternatives to armourstone; in particular, concrete armour unit solutions may be appropriate. Concrete units offer possibilities for steeper slopes, which in turn require smaller material volumes and land-take, permit the use of shorter-reach construction plant and may provide environmental benefits (see Section 3.12).

The maximum armourstone size that can be produced in a quarry is determined by the geology. Geological and geotechnical expertise are required to locate sources with a desired range of stone mass or to predict the best location of large stone sources within a certain kilometre radius. Tools for such evaluations are outlined in Section 3.9.2.

If a local quarry is an obvious potential source, the heaviest grading that can be produced (ie without unprofitable over-production of finer material) should be considered in relation to the top sizes demanded by conventional (statically stable) structures. Many less conventional rock structure designs – eg with berms, dynamically stable structures, thicker layers and gentler slopes – may enable use of local sources with restricted top sizes for the supply of all materials required for a viable design.

### 3.1.1.4 Rock source and procurement options

All projects have a responsibility to assess the potential use of secondary or recycled granular materials as alternatives to primary sources of armourstone, especially for use as core material. Possible local sources of these materials should be assessed (particularly within a mining, power generating, minerals processing or urbanised region), to minimise transport costs compared with more distant sources.

Quarries are typically **aggregates quarries**, **dedicated armourstone quarries** or **dimension stone quarries** (see Section 3.9). For rock supply, the range of procurement options generally fits one of the following scenarios:

- demand-based competitive market
- existing local quarry
- new quarry dedicated to the project.

**Demand-based competitive market scenario**

Within Europe, demand has stimulated an increasingly recognised market in armourstone such that designs are often demand-based, predicated on producers competing to supply satisfactory materials. Confidence that the required materials will be available has grown in Europe, because material property requirement categories for hydraulics works have been defined by agreement between European designers and producers in the form of a standard specification for armourstone (EN 13383:2002). Details of the available materials should have only a minor impact on the design process provided the armour stone sizes demanded are not exceptionally large for the region. Despite *factory production control* of armourstone in the European market, quarry inspections by the structure owner's representative, prior to source approval, are highly recommended (see Section 3.10.2). For example, in rare cases visual appearance can be the overriding requirement for client approval of projects in amenity areas.

**Local existing quarry scenario**

The considerable environmental and economic advantages of reduced materials transport suggest that every effort should be made to design a satisfactory supply-based solution where a local quarry exists. This should include careful consideration of design solutions that may require higher maintenance, including the public nuisance impact that maintenance works may have. A major part of the materials should be obtained from the local source and where possible any timely availability of local secondary and recycled sources should also be accommodated. Careful analysis of available sizes, quality, durability, transport implications and environmental acceptability should be undertaken. The need for transport of large consignments of core materials over great distances should be avoided. Known local quarries, together with local concrete unit manufacture or imported stones for heavier armour, may provide an optimal mix to meet demands for different sizes of materials.

**Dedicated quarry scenario**

For large projects where the geology near to the site is favourable for good armourstone and a legal/planning framework for granting quarrying permissions exists, new dedicated quarry sources are generally most economical.

### 3.1.1.5 *Holistic considerations*

In general, a project design team should consider the technical engineering, ecological and construction site consequences of using different materials from the different sources, paying particular attention to responsibilities of the various parties.

**Technical innovation**

Possibilities exist for utilising extremes of rock density and rock durability. Section 3.5 presents the advantages of volume filling below water using rock of low density and armouring against wave or current attack with rock of high density. Section 3.6 describes degradation models to inform mitigating strategies for designing with low-durability stones (often associated with low-density rock), eg over-dimensioning, gentler slopes, higher maintenance.

The shape characteristics of certain potential sources of armour stones (blocky armourstone pieces) combined with possible individual placement construction methods may introduce opportunities to design and build stable structures with tighter packing of smaller sizes or fewer layers at lower cost (see Section 5.2.2.2).

In general, smaller sizes of armourstone used for riverbank and dam-face designs impose less severe constraints on material sources. Use of local superficial deposits, such as glacial deposits and river boulders, should be considered in addition to crushed rock quarry sources, especially for river training works. Design innovations can often arise from creative use of materials such as gabions, grouting or hand-pitching to improve the stability of otherwise undersized stones. Even unconventional, high-maintenance options become viable where there is access to readily available labour and cheap supplies of easily transported and handled materials. In beach control and coastal structures, the characteristics of local materials may promote the adoption of less conventional, but viable, low-cost designs (see several examples in Crossman *et al*, 2003, and also discussion in Section 6.3.5).

Large-scale breakwater projects using dedicated quarries will benefit considerably from designs that are tailored to minimise waste and ensure the total utilisation of rock that is blasted. An early understanding of yield curves in dedicated quarries can have a major impact on total project costs. This requires reasoned predictions of the armour stone size distribution (or block size distribution) to be generated upon fragmentation by blasting. Preliminary design should not progress without such quarry yield predictions. Both preliminary and detailed design should be kept informed of progressive results from geotechnical investigations. These will usually involve a rock drilling programme. The predictions enable the total materials costs of conventional, berm (dynamically stable) and Icelandic-style (statically stable) breakwater designs to be compared (see Section 6.1.6). See Box 3.1, Section 3.9.4 and Section 3.9.5 for yield prediction and examples of cost comparison analysis.

**Ecology**

Many projects will disrupt ecology and the design should aim to encourage the most rapid return to a healthy ecology, in part, through appropriate material choices. Disruption to ecologically sensitive foreshores that are required to act as foundations to revetments and seawall rehabilitation projects may be minimised by designs that have a smaller footprint ie steeper structures with larger armour. The additional conservation value of artificial marine habitats such as those provided by rock armoured structures, most notably rock reefs, is influenced by material choice and is receiving increased attention. Recolonisation of fluvial environments may be more rapid with biosystems comprising gabions that incorporate planting during construction. These issues are discussed further in Section 2.5.

**Site constraints**

Limited materials transport options are likely to restrict the range of potential sources. River, closure dam and coastal works may have site constraints that forbid either road or waterborne transport. If the design involves concrete units, extensive areas will be needed for casting yards. A common constraint to minimise nuisance in built-up amenity areas requiring coastal works is a requirement that materials should be delivered by sea and within a certain seasonal window. This can rule out apparently viable land-won local sources. Sea delivery options, eg for imported materials, will often incur additional costs for construction of temporary landing or other transport-related infrastructure to enable transhipment of sea deliveries. Transport issues are discussed further in Section 9.4. Among other issues influencing the choice of materials is the ease of creating staircases for public access to beaches at the foot of old seawalls upgraded by armourstone revetments. Public safety concerns may encourage material options where a smooth rubble pavement finish to a revetment surface is easier for a contractor to achieve. For repairs to degraded structures, armourstone reuse is the first choice, as it is an extremely flexible construction material. Where the new is to blend with the old, visual impact and functional performance are of crucial importance. A mix of concrete units and armour stones in cover layers is a last resort.

**Responsibilities**

If materials are considered too late in the design process, and if contractors are insufficiently involved, the designer should expect alternative designs to be submitted at tender stage, which can delay the project considerably. The contractor will not usually risk proceeding with an alternative design, such as one based on a rock source with properties that vary from the materials specification of the detailed design. An exception would be if the contractor agrees with the terms that the designer and/or owner have made for liability, in the event of unsatisfactory structural performance. To deliver best value to the owner, the designer may need to rewrite the design specification, and even consider redesigning the structure, around the material properties and armourstone gradations that are available from the contractor's designated rock source. Although based on a highly developed understanding of rock sources, construction methods and grading optimisation, economically better designs proposed by contractors are often not adopted because of responsibility issues.

#### 3.1.1.6 Cost of project

Initial estimates of approximate project costs should be developed from available data such as the cost of comparable projects, construction cost information supplied by contractors, projected production costs for the preliminary stone or concrete tonnages, and the potentially overriding cost of transporting material to site. Social acceptability and sustainability of materials use, as well as cost, should influence decision-making.

#### 3.1.1.7 Towards preliminary design

The objective of the next phase, preliminary design, is to:

- generate potentially viable design options
- provide enough detailed data to select and dimension the final design
- specify the materials requirements.

Precise design data are needed, including final design dimensions, materials volumes, construction methods, aggressiveness of the site environment, design life and maintenance requirements. Before the preliminary design can be prepared, guidance on properties of armourstone and how these are related to functional requirements (see Sections 3.3–3.5) should be considered, especially for local and dedicated supply-based design scenarios where the best use should be made of all the available material. Identifying and working with the vast range of possible armourstone quality requires practical methodologies for assessing service life, as presented in Section 3.6. To appreciate the new legislative context of the Eurostandards and EU Directives, guidance on the preparation of the materials specification for rock materials and setting requirement levels is given in Section 3.7. How to sample and test to evaluate material properties is also explained (see Section 3.8). The efficiency of quarrying operations for armourstone production (see Section 3.9) can seriously affect project costs especially for dedicated quarries. Great effort is often needed to understand the rock resource before production. As rock is not an off-the-shelf material, an understanding of quality control and peculiarities associated with different rock sources and quarry procedures is essential. Setting up quality control in the quarry (see Section 3.10) and on site (see Section 9.6) is therefore also explained. Sections 3.12–3.16 provide information on materials other than quarried rock and refer the reader to key references and specifications.

**Box 3.1** *Dedicated quarry (Melkoya, Hammerfest, Norway)*

A liquified natural gas plant development and breakwater construction project on the island of Melkoya required levelling part of the island consisting of foliated gneiss. Where possible, the excavated stone was to be utilised for breakwater materials. The project site and dedicated quarry were therefore part of the same complex. Crest elevation, water depth and dimensioning for a dynamically stable berm breakwater design indicated that for significant wave height, $H_s$ = 7 m, this would be a large project requiring about 700 000 $m^3$ of armourstone exceeding 1.5 t with a top size of 17 t.

Initial investigations in 1998 concluded that the Melkoya rock would need to be supplemented with 150 000 $m^3$ of imported armour stones in the size range of 4–17 t from a good gabbro quarry. The potential cost implications necessitated a further geotechnical investigation. Estimates of armourstone yields on Melkoya were drastically revised after an investigation of the geology below the weathered surface rock, based on detailed diamond-drilled cores, which was completed in October 2001. The typical joint spacing and three-dimensional configuration of *in situ* blocks at significant depths in the planned quarry and the expected size distribution after blasting were calculated using methodologies now beginning to be applied to armourstone quarry investigations but rarely used in conventional stone excavation, aggregate quarries and mining site investigations. The analysis was undertaken with sufficient levels of confidence for the design team to be reassured of predicted yields of 3–5 per cent of stones in the 20–35 t heavy grading class that would be suitable for the most exposed breakwater sections. A statically stable berm breakwater design that closely matched this yield curve prediction for Melkoya was later submitted for tender, with the option of obtaining a small fraction of 10 000 $m^3$ of 20–35 t armour stones from outside the island. The application of technically innovative approaches to quarry site investigation and increased confidence in favourable quarry yields eventually enabled the design phase to move from preliminary to final.

The contractor did not have access to the quarry yield predictions used by the breakwater design team. The contractor had sufficient experience, through work on similar projects, to use the size distribution in breakwater design to make his own requirements for quarry yield and thus was able to contribute to maximising the usage of quarried rock.

The rock excavation, breakwater construction and levelling of the island was carried out in a nine-month period from July 2002 to April 2003 and the maximum weekly production exceeded 100 000 $m^3$. The completed breakwater required 670 000 $m^3$ of armour stones exceeding 1.5 t with a top size of 35 t. All breakwater material was obtained from Melkoya and not a single stone needed to be imported.

**Box 3.2** *Use of local materials as alternative, Le Havre, France*

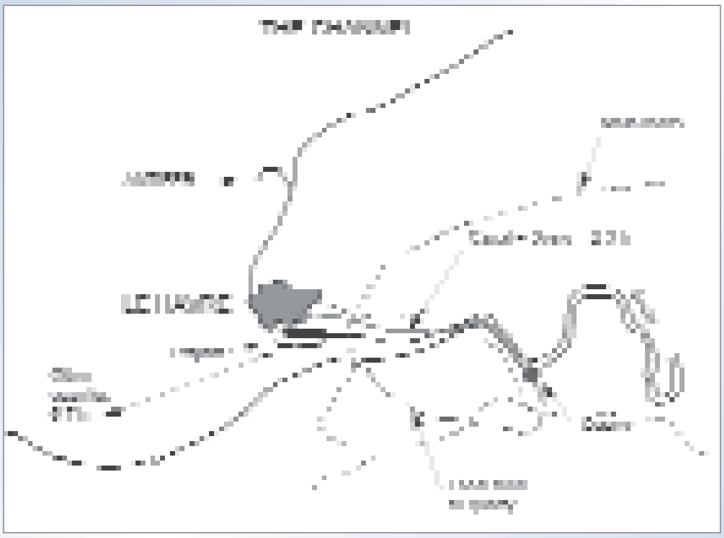
Since 1994 the Port Authority of Le Havre has been undertaking studies and construction to double its container throughput capacity by 2007. The solution adopted was the creation of a 200 ha reclamation in the estuary of the River Seine to be closely linked to the hinterland through a road, railway and canal network. The first breakwater was constructed to form a containment bund for dredged material for the landfill reclamation during the construction phase. A second 5.5 km-long breakwater was then constructed to form the port and provide protection for navigation and terminal operations. The initial concept for the breakwater design was based on three elements.

1 A core of highly variable low-quality stone consisting of flinty chalk (nodular siliceous chalky limestone).
2 Sublayers and filters composed of siliceous chalky limestone armourstone.
3 Cover layer of Antifer cubes.

Alternative designs were proposed and the construction of the final design began in 2001. The materials modifications included the use of the following materials.

1 34 000 units of 1.5 $m^3$ and 3 $m^3$ Accropode to reduce the armour to a single-layer system, gradings of armourstone being modified accordingly.
2 Close to 5 million tonnes of the breakwater core was constructed using material dredged from the channel instead of quarried rock, to maximise the reuse of dredged material and limit transport of core material from distant quarries.
3 110 000 $m^3$ of high-quality armourstone was replaced by the flinty chalk armourstone in specially selected locations of the structure where loads are not aggressive, high quality being retained for the crest where traffic of dumpers during construction is significant.
4 A quarry in the flinty chalk was re-opened locally in a protected environment zone to produce both tout-venant core materials and some armourstone gradings.

Transport times by barge decreased from 7 h for coastal deliveries down to 2.5 h for delivery by canal and river. The cost of this material, delivered to site, was reduced by an estimated one-third.



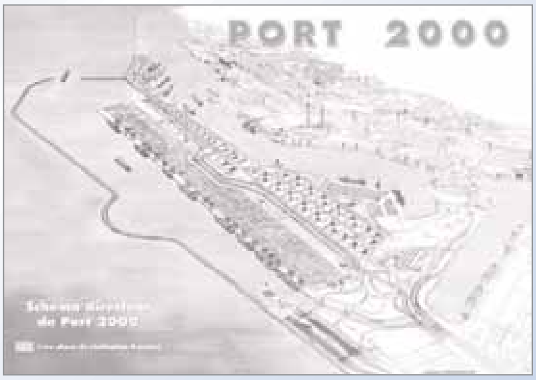



**Figure 3.3**

*General view of the Le Havre port extension project with reference to the rock sources and main access to the local flinty chalk quarry*

The dedicated quarry was an old quarry, closed in the 1930s and re-opened for this contract. Different geological horizons were identified early for use as core material or for armourstone. The old quayside was refurbished and used for barge loading, solving the potential problem of nuisance from local truck traffic. The regional environmental body, Parc de Brotonne, required high-quality rehabilitation of the quarry area as a remediation to the quarry work. Much of the project's success resulted from creative use of materials that were locally available but of variable quality.

**Box 3.3** *Selection from alternative solutions, River Lochy, Scotland*

The River Lochy, Scotland, is subject to substantial flood flows and scour had been developing around the piers of the Lochy Bridge. The scour was likely to have resulted from a combination of the following factors: extreme river flow velocities associated with relatively small-sized bed material; misalignment of the bridge piers; and exposure of the pier foundations, which increased the potential for scour. Several potential solutions were considered for the protection of the piers.

1. Armourstone around the bridge piers.
2. Rock bund downstream of the bridge.
3. Concrete-filled mattress.
4. Gabion mattress.
5. Interlocked concrete blocks.

The advantages and disadvantages of each option were weighed against their cost and applicability. For example, gabion mattresses were ruled out because of potential difficulties in shaping the gabions around the complicated pier structures. The recommended solution, armourstone, was not the lowest cost solution but presented the most advantages:

- rock was available locally (several quarries supplying igneous roadstone and armourstone were present within a radius of about 10 km)
- transport of the material through towns was negligible, which limited disturbance to local residents
- it is a proven technology that withstands high-velocity flows and has the necessary flexibility to adjust to the realignment of the bed.

This solution required a maximum size of 1–3 t armourstone to ensure stability. The volume used was 1550 $m^3$. This illustrates the case of river projects where the quantities of stone required are relatively small and tend to be specified in terms of size and volume rather than tonnage, and where there are numerous alternatives to armourstone that may present advantages.

## 3.1.2 Important design functions and properties of materials

### *3.1.2.1 Functions of materials in the structure*

This section provides an overview of the principles governing the functions of loose stones and other appropriate materials systems. Section 3.1.2.2 explains the link between properties and functions for armourstone in general terms. The details of the properties are given in Sections 3.2–3.6 for quarried rock, Section 3.12 for concrete armour units, Section 3.13 for alternative granular materials, Section 3.14 for gabions, Section 3.15 for grouted stone composites and Section 3.16 for geotextiles.

The main functions of materials used in hydraulic structures are:

- to provide volume filling
- to provide a foundation and a filtering system
- to protect the structure against wave or current action and scouring.

Detailed guidance for designing to provide the required functional performance for different structure types is given in Chapters 6, 7 and 8.

The use of each different material has consequences, not necessarily hydraulic, that are important to designers, as they may bring additional advantages or disadvantages in, for example, visual appearance, durability, permeability to groundwater, ease of construction, flexibility, availability, effectiveness, access, maintenance, public safety, hygiene and cost. Table 3.1 summarises the hydraulic functions that may be provided by the different types of materials:

**Table 3.1** *Hydraulic functions*

| | Type of material | | | |
|---|---|---|---|---|
| Function | Natural armourstone | Concrete armour units | Gabions | Alternative granular materials |
| Volume fill | *** | – | – | ** |
| Filtering | *** | – | * | * |
| Armouring | *** | ** | ** | * |

**Note**

*** usually ideal, ** suitable for this function, * may be used to provide this function; a requirement under specific conditions, – not suitable.

**Volume filling**

This is the principal function of materials used in the core of a hydraulic structure. The materials' structural characteristics should enable them to support internal loads such as self-weight and external loads such as difference in water level or traffic. Their compaction characteristics should preclude significant, unacceptable post-construction settlement. Low fluid velocities and mild exposure of the materials used for volume-filling mean that, depending on the structure design and construction technique, it is usually acceptable to use lower-quality materials and widely differing mean particle sizes when compared with materials serving a filtering or armouring function. The hydraulic characteristics should be in accordance with the overall degree of permeability required by the design of the structure. Material for use in the core does not always require specification to an international standard. It will nonetheless have certain property requirements depending on its intended uses. Examples of different functional uses where property requirements for core materials will differ include:

- permanently submerged impermeable breakwater core
- intermittently submerged permeable reef breakwater core
- reef breakwater foundation for poorly consolidated clayey foreshores (low density for reduced subsidence).

The **core materials** may consist of either primary rockfill such as quarry run, alternative granular materials such as secondary or recycled aggregates, or dredged sand and gravel. In the core of a structure, notably for underwater placement, the placed bulk density (see Section 3.5.1) is the most important indicative material parameter, as it relates closely to shear strength and possible settlement as well as to permeability. It is governed by grading width and particle shape. For further discussion on geotechnical aspects, refer to Section 4.4 and Section 5.4.

**Filtering**

To prevent underlayer and core materials being piped or washed out by hydraulic forces induced by waves, current or water level difference, they should be protected by a filtering system. Filter systems are generally composed of granular materials, geotextile filters or a combination of both (known as geosystems). In some structures, such as breakwaters, an additional hydraulic requirement is sometimes expected and the filter system is also required to contribute to the energy dissipation by turbulent flow through the void spaces.

The mechanical and durability characteristics of the filter material (including geotextiles, if applied) should be compatible with the armour layer. For example, the use of filter layers with limited durability may not be compatible with concrete armour units for which there is a strong requirement for no settlement and unit deformation.

The most important design considerations in this context are the grading curves, stone shape characteristics and density of rock relative to site water. Layer packing is also important in relation to the porosity and, together with particle shape and grading, will control interlock between particles and hence the shear strength of particles within the pack and between layers.

**Armouring**

In most severe environmental conditions, the main structure is to be protected against:

- hydraulic forces, such as wave action or current forces due to tide or stream
- weathering agents such as cyclic stresses from freeze-thaw, salt crystal growth, thermal or wet-dry cycles that will tend to exploit any of the stone's inherent weaknesses
- additional forces such as ice load or ship collision or the action of shingle abrasion.

In some structures wave attack may cause movement of armour stones. As the severity of the wave action increases, this motion will vary from rocking through to rolling or sliding for the worst wave conditions. For such structures, breakage and attrition leading to general wear and rounding is potentially much more rapid. There will also be implications for the design specification, as the stones' mass will decrease with time. Consequently, high-durability characteristics will be required as well as stringent geometric constraints on the production of stone size, mass, shape and grading.

Some aesthetic functions may be required for the most visible part of the structure. For architectural reasons, specific placement methods may be expected and their influence on stability and hydraulic properties should, if relevant, be verified. Where structures are accessible by the public, amenity value, safety and hygiene are functions that have to be considered at both the design and construction stage. The armour layer may be a habitat for some species that colonise the voids in the armour or its surface. If relevant, this *habitat* function, which includes the organism's capability to stay adhered to the armourstone, should be considered when studying the grading and rock type to use, see Section 2.5.

#### 3.1.2.2 Material properties

The European standard EN 13383 Parts 1 and 2:2002 defines *armourstone* as:

***coarse aggregate used in hydraulic structures and other civil engineering works.***

Armourstone therefore has a loose granular form and includes all alternative (manufactured and recycled) armourstone as well as primary quarried rock. Along with other European aggregates standards, the new armourstone standard treats primary, secondary and recycled materials equally: provided a material meets the required standard for the application, its origin is immaterial. This may lead to more countries redefining their descriptions of armourstone in line with those of the EN standards:

- **natural armourstone:** armourstone from mineral sources that has only been subjected to mechanical processing
- **manufactured armourstone:** armourstone resulting from an industrial process involving thermal or other modification, excluding armour units
- **recycled armourstone**: armourstone resulting from the processing of inorganic material previously used in construction
- **concrete armour units:** prefabricated concrete units for armouring.

In relating properties to functions, it is useful to distinguish the following three types of property that relate to different phases in the life cycle of armourstone.

*Intrinsic properties* (see Section 3.3) relate to the properties of the rock source, its geological history or the industrial process involving thermal or other modification. They account for engineering geology considerations such as mineral fabric characteristics, discontinuity sets, weathering grade and the tectonic context of the quarry.

*Production-induced properties* (see Section 3.4) relate to the armourstone as an individual piece or as a granular material composed of individual pieces. They are affected by the intrinsic properties and controlled by the production technique such as blast design, selection, handling and sorting techniques or devices.

*Construction-induced properties* (see Section 3.5), such as layer thickness or layer porosity, are controlled by the construction of the armourstone as a granular material and are heavily influenced by the placement technique, the shape and the conditions of execution, for example above or below water.

Some of these properties are also susceptible to change with time as a function of loadings from the physical, chemical and biological environment. These are considered further in terms of durability in Sections 3.1.3 and 3.6.

A conceptual understanding of properties and functions of any material used in construction (such as gabion stone, recycled materials, concrete units, grouted stone, and the many and varied applications of aggregates and armourstone) is given by the scheme outlined in Figure 3.4, illustrated here for armourstone.

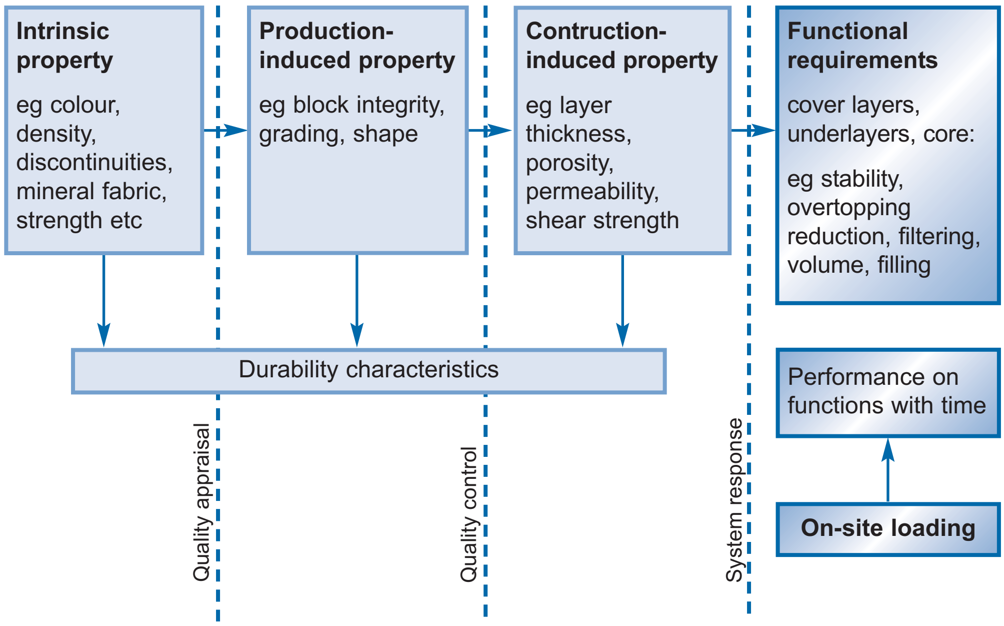



**Figure 3.4** *Conceptual scheme for material properties and functions, illustrated for armourstone*

## 3.1.3 Durability considerations

The **durability** of a material component or system is defined as its ability to continue performing adequately in a specific working environment. Durability may be quantified by the rate of loss of performance in engineering time.

Durability is therefore a balance between the intrinsic resistance of the material and the aggressiveness of the forces acting in service. Poor-quality materials may stand up well in mild environments where degradation forces are virtually non-existent, for example in the permanently submerged core of a relatively impermeable breakwater.

The designer should assess the probability that material degradation will cause a rapid change in, and loss of, structural and functional performance. This is one of the most difficult judgements to be made. As guidance on this topic is often in demand, tools, though tentative, are provided in Section 3.6 for quarried rock. Faced with an assessment that a source will degrade rapidly, the designer has various options.

#### 3.1.3.1 *Mitigation strategies for low-durability scenarios of armourstone*

The greater the movement of armour and material components that is expected in service in a chosen design, the greater is the need for highly durable materials. Similarly, to reduce the rate of degradation, low-durability material should be prevented from moving.

The decision to use lower-quality material for **armouring** and/or **filtering** may be justified in the following circumstances:

- satisfactory performance records for the same armourstone in similar uses are available
- aggressiveness of the site conditions is extremely mild
- a high frequency of maintenance and repairs are acceptable because they can be carried out quite cheaply and with little disturbance
- armouring has been over-dimensioned to reduce mobility in storms
- slopes have been flattened and greater material volumes used to reduce mobility in storms
- armour layer has been placed with higher interlock to reduce mobility in storms
- there is no alternative, because more durable materials or concrete units are too costly and a relatively short design life is therefore acceptable.

Some innovative low-cost options referred to in Crossman *et al* (2003) highlight the use of materials of marginal quality in addition to less conventional design and construction practice (see also Section 6.3.5). The innovation of grouting to achieve the necessary stability in the cover layer is described in Section 3.15. It should be noted that reduction in binding performance of the cementitious or bituminous grout is more rapid for sites affected by severe climate.

**NOTE:** In choosing between armourstone or concrete armour units, armourstone may be more appropriate if a very long life is required. Many sources of igneous and metamorphic rock and some compact crystalline limestones have low water absorption and good integrity and will be considerably stronger and more durable than unreinforced concrete.

#### 3.1.3.2 *Durability considerations for material other than armourstone*

**Armouring**

For armouring, the main factors that cause breakdown of gabions and geotextiles are abrasive agents, movements inducing localised rupture and ultraviolet breakdown of polymers and plastic shielding wire. Corrosion prevention can be costly. Geosystems and geobags are only rarely used for armouring but in such cases strength and durability of the geotextile/geomembrane is critical as it is essential to prevent degradation from ultraviolet exposure and puncture damage. For materials other than rock, such as concrete units and gabions, suggestions and detailed references to durability assessment are included within Sections 3.12–3.16.

**Volume-filling and filtering**

For most projects where quarried rock is used for volume-filling, it should be emphasised that degradation rates are insignificant in permanently submerged environments with low water flows. There is one important exception: inland waters may become significantly more acidic than sea waters, so dissolution of carbonate in softer limestone may result in settlement of the core. The site water's acidity should be considered and, especially in freshwater applications, rock used for volume-filling should be free of soluble constituents such as sodium chloride and gypsum, which may be removed in solution in quantities that could affect the environment.

Use of alternative granular materials is particularly encouraged when employed as a coastal reclamation fill material. For recycled or secondary materials, it is important to ensure that their leaching characteristics, such as quantity and type of substance released, are compatible with the environment of use. Risk of degradation, settlement and leaching can be most effectively mitigated using a *volume stability and water solubility* testing regime together with geotextile and/or clay liner systems to provide barriers to flow routes. Any secondary minerals that may grow and thus alter the characteristics of the core should be identified and appropriate treatments employed. The guiding principle is that volume filling and filtering materials should be physically and chemically stable when in use and be prevented from interacting harmfully with their environment. Risk assessment methodologies for secondary and recycled materials are given in Section 3.13.

### 3.1.4 Standards for armourstone

A major development in Europe over the past decade has been to consider armourstone as a standard construction material, which has led to the introduction of a dedicated European standard for armourstone, EN 13383. This standard, along with a number of aggregates standards, was introduced to comply with the requirements of the European Commission mandate M125, Aggregates, given under the Construction Products Directive (89/106/EEC). EN 13383 supersedes conflicting recommendations for armourstone in national standards. Amendments to remove these conflicting recommendations have been introduced. EN 13383 is divided into two parts:

**Part 1:** Specification – gives the requirements for armourstone to fulfil "essential requirements" as expressed in Directive 89/106/EEC

**Part 2:** Test methods – gives dedicated methods to test armourstone when standard aggregate or rock mechanics methods are not suitable.

EN 13383-1 specifies a range of categories for properties to enable users to select the appropriate limiting values for the wide range of armourstone produced in Europe (see Section 3.7, which discusses armourstone specification). In most instances, provision is also made for producers to identify a declared value for properties when the value of the property is outside the indicated categories.

Owing to the special functions and large sizes of armourstone materials, some special test methods and sampling methods, which differ from those associated with aggregates, have been specified in EN 13383-2:2002. The remaining test methods required draw on new European test method standards for aggregates that supersede the methods previously used in European countries. A tabular summary of all sampling and testing requirements for a particular property is given in EN 13383-2 Annex G as an aid for armourstone producers and testing authorities. This summary is considered necessary because of the particularly wide range of test types, test portions and sample reduction procedures needed to accommodate armourstone tests both on individual test pieces of rock as well as on a sample selection of stones.

When considering the reasons for testing, it is useful to make the distinction between:

- the mandatory tests performed by the producer for obtaining CE marking (see Section 3.7.1)
- other tests required by the designer or the contractor for a specific project or to control the deliveries.

For CE marking, the type of compliance that the tests are intended for (see EN 13383-1:2002, Clause 8) are as follows:

- Initial Type Testing (ITT) – tests are performed as one-off characterisations, either of new sources or of existing sources where there is a major change in the rock mass being quarried or the methods being used
- Factory Production Control (FPC) – the producer periodically performs tests to ensure the production process continues to generate materials of expected properties.

There is another context for ITT that has no direct part in the specification and compliance process. This is where the test information for a test property outside the EN 13383 system is not known through any previous testing, but obtaining and declaring the result is considered of value to the producer and/or purchaser. In this context, for heavy gradings, block shape characterisation and integrity testing by the Full-Scale Splitting Test (FSST) method are to be encouraged because of their potential to assist the designer (see Section 3.8, which discusses testing).

Examples of tests commonly applied for FPC would be particle density, while for the case of coarse standard gradings, mass distribution checks are particularly important. Tests carried out for ITT may include all tests carried out for FPC.

The system has produced clear benefits by defining geometric properties, such as standard armourstone gradings that allow the producer to prepare materials in advance and inform the designer of the availability of gradings. Caution is advised when using the standard, as the requirements it sets out cannot ensure all aspects of durability or a given service life. For certain scenarios, different requirements may be required to ensure satisfactory performance, based on site-specific requirements. For example, full-scale armourstone integrity tests are not included in EN 13383, which restricts its laboratory-testing programme to relatively small homogeneous pieces and these cannot represent the long-term behaviour of full-scale heterogeneous stones weighing several tonnes.

In many parts of Europe, there are abundant sources of armourstone of excellent quality. Once the required gradings are determined, insufficient attention may be given to rock quality and often high quality requirements from the standard specification are simply given. This may exclude local armourstone of perfectly acceptable quality that is cheaper to supply. Worldwide, projects typically use quarried rock that is locally available but gives only good, marginal or even poor quality indications from test results. Outside Europe, therefore, standards such as EN 13383 should be applied with care and may need to be adapted as appropriate. In North America, where the range of climatic conditions is extreme and excellent quarried rock is often scarce, ASTM D4992-94 (2001) *Standard practice for the evaluation of rock to be used for erosion control* suggests rock be examined at source. It indicates that the laboratory tests to be used will depend on the rock type. It does not attempt to say which tests are required but mentions those available and lists the rock properties that are of special concern. In many cases, evaluation by a qualified geologist, for example using a systems approach (Lienhart, 2003), may be invaluable in preparing a specification. Extensive evaluation of rock source suitability may be necessary, particularly if rock of less than excellent quality is to be used (see Section 3.6). This will depend on project scale, complexity and risk.

## 3.2 QUARRIED ROCK – OVERVIEW OF PROPERTIES AND FUNCTIONS

### 3.2.1 Introduction to quarried rock

Large quantities of quarried rock are often needed for marine projects, for example an estimated 9.3 million tonnes per year were used over five years to build the new Hong Kong Airport. A single large breakwater in Iceland required 1 847 000 t of quarried rock, of which 80 per cent was core material and 20 per cent armourstone. In contrast, a bridge pier scour protection scheme in Scotland used 4 200 t of armourstone, and river training works may use just a few hundred tonnes of armourstone or gabions. Whatever the scale of the project, a good understanding of quarried rock, its production and processing will often prove as vital to the economic success of a project as a good understanding of hydraulic design. This is largely because armourstone is not an off-the-shelf building material, and each combination of rock and site conditions is unique.

Unfortunately, an expert assessment of the expected service life rarely accompanies a portfolio of standard test certificates or "fit-for-purpose" trade marks. Potential rock sources therefore need to be evaluated and matched with their intended function at the site.

Sections 3.2 to 3.11 on quarried rock aim to explain the key properties of rock materials and to:

- introduce the main rock types and quarry evaluation process (see Sections 3.2.2, 3.2.3)
- explain the main properties, functions and terminology needed for projects (see Section 3.2 to 3.5)
- provide a systematic approach for service life prediction (see Section 3.6)
- help the designer to prepare a suitable specification for rock materials (see Section 3.7)
- summarise test methods for armourstone grading and armourstone quality (see Section 3.8)
- provide guidance on quarry operations for production, selection and transport of armour stones (see Section 3.9)
- outline realistic quality control procedures (see Section 3.10)
- highlight cost implications (see Section 3.11).

There are limits to the guidance that can be given here. Further reading of engineering geology textbooks such as Blyth and De Freitas (1984), Waltham (2001) and Goodman (1993) is recommended for those seeking a greater understanding of geological factors. In recent years, useful special publications on use of stone and aggregate materials relating to hydraulic structures include Smith (1999) and Smith *et al* (2001). For collections of papers specifically on armourstone, including case history experience, see Magoon and Baird (1991), McElroy and Lienhart (1993), Thorne *et al* (1995) and Latham (1998a). For seminal papers on armourstone, see Lienhart and Stransky (1981) and Fookes and Poole (1981).

### 3.2.2 Introduction to engineering geology

**Rock types**

Geologists divide rocks into the following groups depending on their mode of formation:

- *igneous rock* – formed by the crystallisation and solidification of a molten silicate magma
- *sedimentary rock* – formed by sedimentation and subsequent lithification of mineral grains, either under water or more rarely on an ancient land surface

- *metamorphic rock* – formed by the effect of heat and pressure on igneous, metamorphic or sedimentary rocks for geological periods of time, resulting in new minerals and textures developing within the pre-existing rock.

These groups may be split into 20 rock types. Each rock type has similar characteristics and the engineering properties and use of these rock types can be presented in a general summary form as shown in Table 3.2. Typically, rock materials are obtained by conventional quarrying operations as discussed in Section 3.9. There are extensive areas where rock outcrops are not present on the Earth's surface and deposits of glacial till, river or marine sediments may be used.

**Table 3.2** *Generalised evaluation of the use of unweathered rock in hydraulic structures*

| Rock | | Use | | | Property | | |
|---|---|---|---|---|---|---|---|
| Group | Type | Armour | Filter | Core | Density ($t/m^3$) | Maximum size | Shape |
| Igneous | Granite | * | * | * | 2.5–2.8 | HG | Equant |
| | Diorite | * | * | * | 2.6–3.1 | HG | Equant |
| | Gabbro | * | * | * | 2.8–3.2 | HG | Equant |
| | Rhyolite | * | * | * | 2.3–2.8 | LG | Irregular to equant |
| | Andesite | * | * | * | 2.4–3.1 | LG | Equant |
| | Basalt | * | * | * | 2.5–3.1 | HG | Equant |
| | Syenite | * | * | * | 2.6–2.9 | HG | Tabular to equant |
| Sedimentary | Quartzite | * | * | * | 2.6–2.8 | HG | Tabular to equant |
| | Sandstone | ! | * | * | 2.3–2.8 | LG | Tabular |
| | Siltstone | ! | ! | * | 2.3–2.8 | LG | Tabular |
| | Shale | ! | ! | * | 2.3–2.7 | LG | Tabular |
| | Limestone | * | * | * | 2.3–2.7 | HG | Tabular to equant |
| | Chalk | ! | ! | * | 1.5–2.3 | LG | Equant |
| Metamorphic | Slate | × | × | * | 2.7–2.8 | LG | Tabular |
| | Phyllite | × | × | * | 2.3–2.7 | LG | Elongated |
| | Schist | ! | ! | * | 2.7–3.2 | LG | Elongated to tabular |
| | Gneiss | * | * | * | 2.6–2.8 | HG | Equant |
| | Marble | * | * | * | 2.7–2.8 | HG | Equant |
| | Serpentinite | * | * | * | 2.5–2.6 | LG | Irregular |
| | Eclogite | * | * | × | 3.3–3.6 | HG | Irregular |

**Notes**

* suitable for use; ! specific attention to ensure suitability; × not suitable
CG: coarse grading; LG: light grading; HG: heavy grading (see Section 3.4.3).



1 2 3 4 5 6 7 8 9 10

**Discontinuities of the rock mass**

Quarrying takes place in an *in situ* rock mass, consisting of intact rock and discontinuities cutting through it. Both are important for production and use of armourstone. The characteristics of a rock mass at outcrop scale are usually dominated by the naturally occurring discontinuities (see Figure 3.5). In many respects, large armourstone pieces may have similar characteristics to the rock mass; smaller aggregates, however, do not. Natural discontinuities have geological or geomorphological origin, whereas artificial discontinuities are generally induced by extraction techniques, such as blasting. Engineering geologists use a special terminology (eg Blyth and De Freitas, 1984) to cover a variety of discontinuities, the most common types being bedding planes that separate different successive beds of rock in the ground, joints, schistosity planes and stylolites.

Discontinuities are generally characterised by their origin, orientation, persistence, frequency, surface geometry and infill material. Significant decrease of mechanical characteristics can occur at discontinuities. Evaluation of the discontinuity pattern of the rock mass will provide the following essential information:

- the block sizes in the rock mass prior to production, also called *"In situ Block Size Distribution"* (IBSD). The IBSD is close to the largest size of the recoverable blocks to be expected. In addition, it controls the excavated mass distribution and may be taken into account in the blast design (see Section 3.9.3)
- the likelihood and distribution of weathering in both the rock mass and the armourstone produced (see Section 3.6)
- the expected block shape of light and heavy armourstone pieces, Figure 3.5 (see Section 3.4.1)
- the likelihood of armourstone integrity problems for light or heavy gradings (see Section 3.3.4).

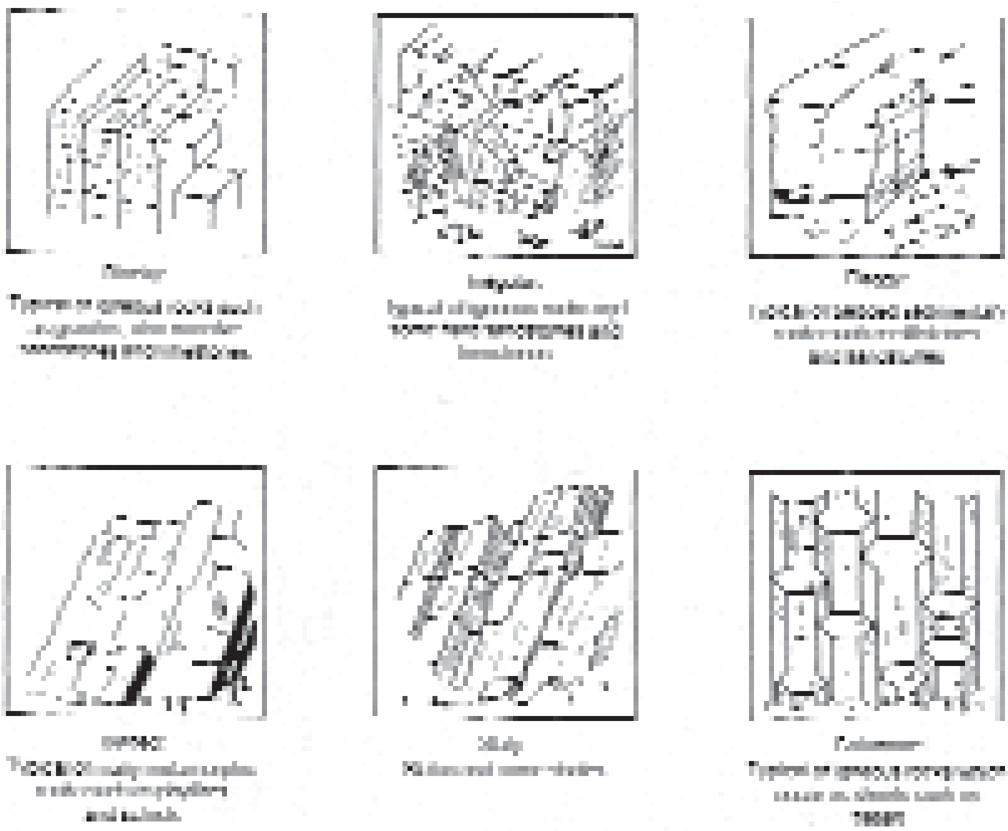


**Figure 3.5** *Idealised sketches of common discontinuity patterns in natural outcrop forms (showing about 5–10 m)*

The discontinuity pattern may be analysed from:

- **rock faces**, when accessible. Photogrammetric and laser-based hardware and software systems for direct appraisal and discrimination of discontinuities are just becoming available at the time of writing. The type of technology is illustrated in Slob *et al* (2002). Direct analysis of scanlines at the face provides characteristic values or statistics of the distribution of orientation, spacing and frequency. Details of scanline methods are given in Priest (1993) and explained in Section 3.9.2
- **drill cores** or **borehole logs** can provide typical spacing information in the borehole direction and the Rock Quality Designation (RQD) index (see Zhang and Einstein, 2000, for details). In addition, sonic velocity analysis using emitters and receivers down the boreholes can provide information on estimates of the expected mass distribution and shapes of blocks.

Application of these analysis methods to *in situ* block size distribution assessment is discussed in Section 3.9.2. When service record information exists, sometimes it is possible to ascertain whether discontinuities seen within blocks will be detrimental in projects. Discontinuity types and patterns in the rock mass of the quarry and in the stockpiled armour stones can be studied, together with a survey of the performance of the same discontinuity types both during construction and in service. Marcus (1995) used such an approach to provide qualitative guidance on the type of discontinuity likely to break, which he adapted to quality control (see Section 3.10). This approach can also be used as guidance when selecting zones for armourstone production that will best avoid problematic discontinuities.

**Weathering grade of the rock**

Rock weathering is brought about by the exposure of the rock over long periods of geological time to the climatic conditions at the Earth's surface and involves mechanical disintegration and chemical decomposition acting together. The effects are most marked in humid, hot climates, but it must be remembered that climatic conditions in the geological past as well as present conditions may influence the weathered state of a given rock mass. The influence of climate on the weathering profiles of rock is illustrated in Box 3.4 for typical quarries in three different climates: north-western European, tropical hot-wet and hot dry regions.

**Box 3.4** *Influence of climate on weathering of rock in quarries*

Proper recognition should be given to the weathering profiles existing within the rock face being excavated (Fookes, 1980). In general, the igneous and metamorphic rocks, which were formed in conditions of high temperature and pressure not found at the earth's surface, show the greatest tendency for well-developed weathering profiles, with the breakdown of their darker iron and magnesium bearing minerals in particular, to form secondary minerals which can be clearly seen under the microscope. The sedimentary rocks break down less easily because they were formed at conditions of temperature and pressure existing at the Earth's surface, which are probably similar to the climatic regime they experience at the present ground surface.

Figure 3.6 shows three quarries in an extremely simplified form. The right-hand one (no 1) portrays an igneous rock quarry in north-western Europe. Immediately prior to the current geological processes operating on the Earth's surface, the Pleistocene ice advances have planed off much of the existing residual soil and weakened weathered rock to leave fairly fresh rock, generally containing only faintly to slightly weathering grades of material. Often this rock is shattered near the surface by freeze-thaw cycles and it may be covered with glacial or post-glacial debris (Fookes, 1980).

The centre quarry (no 2) shows the same rock in a tropical hot and wet climate. Here, physical planing by ice during the Ice Ages did not occur, and therefore a thick development of residual soil still exists, which is sometimes lateritic. The soil passes down into highly weathered rock, which in turn passes down into less weathered and finally into the fresh rock. In such a quarry the various grades of weathering can easily be seen and recognised.

The left-hand quarry (no 3) portrays a limestone quarry in a hot desert climate. The rock is usually fairly porous and weakened some metres below the existing ground surface by leaching, but has a thick hardened surface duricrust composed of calcrete (the specific type of duricrust formed by the upward leaching of a limestone bedrock).

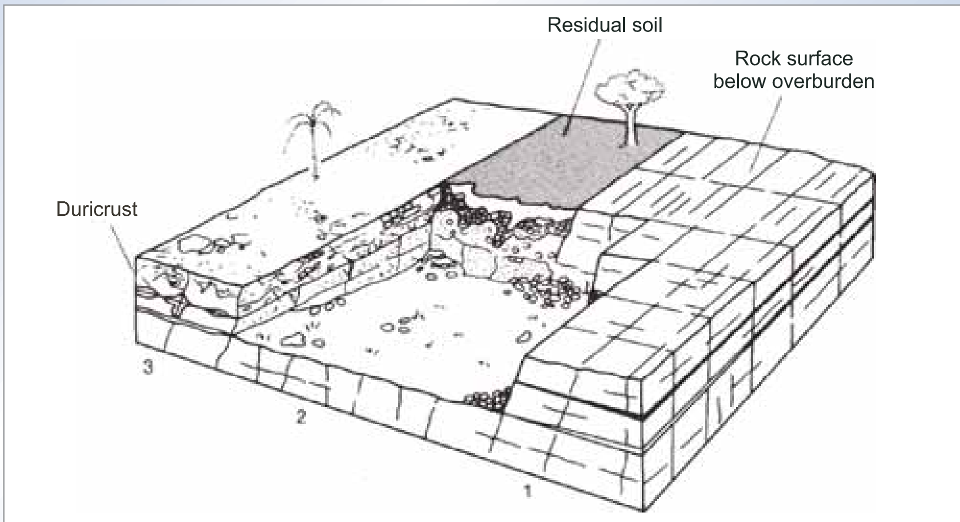



**Figure 3.6** *Three idealised quarries showing different types of weathering*

Rock degradation processes may have taken place very slowly over geological timescales, due to physical, chemical and biological weathering or hydrothermal alteration processes. Depending on the degree to which this degradation has occurred, the general properties expected for a fresh specimen as given in Table 3.2 may not apply. For example, weathering over many thousands of years may have developed an abundance of microcracks in the mineral fabric of an igneous rock, and originally strong interlocking minerals may have been altered or completely replaced by weaker ones such as clays.

The severity of geological weathering disintegration is indicated by the **weathering grade** which may be assessed subjectively and assigned to the rock mass or the intact rock at the quarry, as follows:

- Grade 1A – no sign of rock material weathering
- Grade 1B – discoloration on major joint surfaces, sound mineral constituents
- Grade 2 – discoloration on all joint surfaces, discoloration and some weakening of mineral fabric

1
2
3
4
5
6
7
8
9
10

- Grade 3 – less than half the rock is decomposed and/or disintegrated to a soil
- Grade 6 – the rock is reduced to an unstructured soil.

Numerous weathering grade assessment schemes exist. For rock engineering site investigation work, BS 5930:1999 is widely recommended. Classifications and test procedures designed for different rock types (Cassar and Vella, 2003; Lee and De Freitas, 1989) are particularly useful.

Weathering of rock may occur in geological time (usually many tens of thousands of years) and in service in engineering time (typically 50–100 years for coastal structures). For example, a stone may not lack overall strength and quality at the time of excavation. However, if the rock mass shows signs of weathering Grade 2 or above, the armourstone is likely to break down more rapidly by splitting, spalling and abrasion when exposed to the rigours of the site. This weakening should be suspected and laboratory tests, even if they include tests for resistance to weathering, should be interpreted with caution, ideally with the aid of thin-section petrographic analysis to identify secondary deleterious minerals and microcracking in the rock fabric.

**NOTE:** If rock strength or density results for a rock type are unusually poor, the results may still satisfy specification requirements. Such results may be indicative of geological weathering of Grade 2 or higher, including the possibility of chemical weathering of the intact material. Additional field evaluation and petrographic examination is recommended to improve predictions of performance and to identify higher quality regions to concentrate armourstone production within the quarry. In many European, temperate and hot wet climates, weathering grade decreases with depth in the quarry so that quality and block size increases. If improvement with depth fails, design concept changes and alternative sources should be considered; see also quality control in Section 3.10. However, in hot and dry desert climates, the best rock is found in the hardened duricrust layer near the surface; see Box 3.4.

### 3.2.3 Quarry evaluation principles

Field and laboratory examination of an existing quarry or new dedicated (greenfield) site being considered as a materials source has essentially two distinct purposes:

- **stone sizes and armourstone quantities;** to establish that the required tonnages of the necessary sizes can be produced and delivered at the desired time at the desired rate (see Section 3.9 especially Section 3.9.5 on matching yield curves and demand, Section 3.10 on quality control, and Section 9.2 on site preparation)
- **armourstone quality;** to provide data to make a prediction of the service life of the armourstone (see Section 3.6).

The initial visit should establish first if the armour sizes and proportions are possible, estimate quality visually and take test samples. It might then consider reserves, distances and transport systems to the site, load-out facilities and stockpiling facilities, and finally issues of confidence in the experience and quality control systems of the quarry. Methods for prediction and evaluation of quarry yields are developed further in Section 3.9.2.

In adopting a systematic approach to the evaluation of armourstone quality, (Lienhart, 1998, 2003), and in addition to field evaluation **at the project site** of aggressiveness (frequency of extreme loadings, mobility of armour, attrition agents) and site climate (in-service weathering intensity, cyclic stressing), the field evaluation **in the quarry** should address the following:

- **geological setting** – spatial variation of best rock units, intensity of faulting and jointing
- **rock type** – intact rock strength and resistance to in-service weathering and attrition

- **regional *in situ* stress regime** – faulting and folding suggests quarried blocks will tend to split
- **weathering grade** – geologically weathered rock decomposes faster in service
- **groundwater conditions** – water flowing or seeping from the quarry walls suggests weathered seams
- **discontinuities** – *in situ* block sizes, stone shapes and integrity
- **production methods** – non-blasting methods generate fewer internal cracks than aggregates blasts
- **set-aside** – stones cured by storing for several months before selection will rarely split
- **shape as seen in stockpiles** – mean blockiness and aspect ratio
- **armourstone integrity as seen in stockpiles** – proportion of stones with visible flaws after known set-aside period
- **sampling** – to obtain representative material for laboratory tests
- **block integrity testing** – full-scale destructive testing.

Rock samples are tested in a laboratory and results interpreted for the site conditions. This will allow an informed prediction of the service life of armourstone to be made (see Section 3.6), based on knowledge of rock mechanics and weathering properties of the various rock types during engineering service conditions. The expected pattern and rate of degradation of the stones should then be considered in design, in addition to damage caused by storms. With an estimate of quarry yields, a more inclusive local scenario-based design can provide better whole-life costing outcomes and the materials specification can be written accordingly. The effort will be in proportion to the project scale and risk. In general, sources that yield large blocks will have satisfactory physical and weathering resistance properties, but this is not always the case. Furthermore, sources are inherently variable, so rock quality testing is necessary.

The systems approach to quality evaluation can also work within the framework of EU or other statutory or policy constraints, provided the potential stone sources are known prior to design. A design based on selected armourstone category test requirements (eg for physical, mechanical and resistance to weathering properties) without investment in evaluating the quarry and making a service life prediction, is possible but may not be optimal. In the EU, evaluation of armourstone from suppliers is simplified by the provision of certified test results and production control documentation. This will help the quality of armourstone sources to be assessed as nominally “excellent”, “good” or “marginal”, on the basis of hand-sized specimens and aggregate-sized test material. Producers with significant supplies of armour-sized gradings for sale may also declare certain test results, so designers can consider “marginal” and even “poor” property materials in appropriate circumstances. In many cases, supplementary full-scale integrity testing of armour stones (Dupray *et al* (2003), see Section 3.8.5) will greatly increase confidence in assessing the relative suitability of several nearby sources.

In practice, the evaluation of the two aspects, namely size and quality, is often carried out simultaneously and can interact with the design process and decision-making in many ways, as illustrated in Figure 3.7. Note that Step 3 is not applicable if there are no stocks of armourstone available at the quarry. In this case, trial blasting may be required. Alternatively, if blasts are performed for other applications such as aggregate production, sorting may allow selection of suitable material to provide the information.

| Input: preliminary design (top size and required quantities) |
|---|

↓

| 1 Initial site visit – design-related issues | | | |
|---|---|---|---|
| Properties to assess: | | See section | In case of poor results |
| Top size | By visual inspection | 3.9.2 | A,C |
| Quarry yield | First estimate, for greenfield quarries | 3.9.2 | B |
| Available quantity | First estimate, for existing quarries | 3.9.1 | A,B,C |
| Durability | First estimate | 3.6 | A,D |
| Shape | First estimate | 3.4.1 | B,E |

↓

| 2 Initial site visit – other issues | | | |
|---|---|---|---|
| Issues to assess: | | See section | In case of poor results |
| Reserves | Including existing stockpiles | 3.10 | A,C |
| Location | In relation to construction site and transport facilities | 3.10 | A,C |
| Expected performance of material | From experience/past projects | 3.6, 3.10 | A,C |
| Environmental issues | Especially for greenfield quarries | 3.9, 2.5 | A,C |
| Stocking facilities | | 3.10 | A,C |
| Site facilities | | 3.10 | A,C |
| QA system in place | | 3.10 | A,C,E |

↓

| 3 *In situ* tests and measurements | | | |
|---|---|---|---|
| Properties to test: | | See section | In case of poor results |
| Grading | | 3.4.3, 3.8 | E |
| Integrity | | 3.3.4, 3.8 | A,B,C,D,E |
| Petrography | Weathering | 3.3.2 | A,D |
| | Quality | 3.3.3, 3.6 | A,C,D |
| Discontinuities | Top size | 3.9.2 | B,C |
| | Quarry yield | 3.9.3 | A,B,C |
| | Shape | 3.4.1 | B,E |

↓

| 4a Sampling of the material (3.8.1) | | | |
|---|---|---|---|
| **4b Detailed investigations: laboratory tests (3.8)** | | | |
| Properties to test | | See section | In case of poor results |
| Detailed petrography | | 3.3.2, 3.8.2 | Accel. weath. test. |
| Physical properties | Water absorption, porosity | 3.8.2 | Accel. weath. test. |
| Accelerated weathering test | Only when required | 3.8.6 | A,B,D |
| Mechanical properties | (of the mineral fabric) | 3.8.5 | A,B,D |
| **4c Detailed investigations: trial blasting (3.9)** | | | |
| Properties to test: | | See section | In case of poor results |
| Top size | | 3.9.4 | B,C |
| Quarry yield | | 3.9.4 | A,B,C |
| Shape | | 3.4.1 | B,E |
| Integrity | | 3.3.4, 3.8 | E |

**Notes**

Letters A to E identify proposed actions to be taken in case of poor results during the quarry evaluation process:

A consider using another rock source

B consider revising the design

C consider using alternative material (eg concrete units etc)

D consider accepting higher maintenance

E consider adapting the quarry production/quality control system.

Trial blasts can be unreliable because different methods are often used in production blasts. The armourstone may therefore be unrepresentative of the ultimately quarried rock mass due to near-surface weathering in the trial blast rocks.

**Figure 3.7** *General scheme for quarry evaluation*

## 3.2.4 Properties and functions – general

This section identifies where to find information on properties and functions of quarried rock previously introduced in Section 3.1.2. Properties of armourstone can be geometrical, physical (such as density), mechanical (such as strength), chemical and environmental (such as leaching potential). **Durability and service life** are considered as a system outcome rather than a property and are treated together with rock quality in Section 3.6.

Different properties may need consideration at different phases in the life cycle of the armourstone, such as at the quarry prior to extraction, or after many years in service. To reflect this, the following terms previously defined in Section 3.1.2 are used to structure the main sections that follow, namely:

- intrinsic properties
- production-induced properties
- construction-induced properties.

Table 3.3 lists and classifies the properties of natural armourstone, indicating the sections of this chapter where the reader can find further information. Throughout the chapter extensive reference is made to EN 13383:2002, the European standard for armourstone.

**Table 3.3** *Properties of quarried rock described in Chapter 3*

| Property | Intrinsic | Production -induced | Construction - induced | Category of property | Discussion |
|---|---|---|---|---|---|
| Aesthetics | ** | – | * | Physical and environmental | 3.3.1 |
| Petrography | ** | – | – | Physical, chemical and environmental | 3.3.2 |
| Rock density | ** | – | – | Physical | 3.3.3 |
| Rock porosity | ** | – | – | Physical | 3.3.3 |
| Rock water absorption | ** | – | – | Physical | 3.3.3 |
| Rock resistance to attrition and wear | ** | – | – | Mechanical | 3.3.5, 3.6.5 |
| Rock resistance to weathering agents | ** | – | – | Physical and mechanical | 3.6, 3.8.6 |
| Rock fabric strength | ** | * | – | Mechanical | 3.3.4 |
| Size of armourstone piece | ** | ** | – | Geometrical | 3.4.2 |
| Integrity of armourstone piece | ** | * | – | Physical and mechanical | 3.3.4 |
| Shape of armourstone piece | ** | ** | – | Geometrical | 3.4.1 |
| Armourstone mass or size distribution | * | ** | – | Geometrical | 3.4.3 |
| Armourstone layer (or volumetric) porosity | – | * | ** | Geometrical and environmental | 3.5.1 |
| Armourstone layer thickness | – | * | ** | Geometrical | 3.5.1 |
| Armourstone integrity | * | ** | * | Geometrical | 3.3.4, 3.8.5 |

**Note**

** very relevant; * relevant; – not relevant

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# 3.3 QUARRIED ROCK – INTRINSIC PROPERTIES

## 3.3.1 Aesthetic properties of armourstone

The aesthetic requirements of armour in amenity areas can make the correct choice of rock colour a vital consideration. Often, to help integrate the new structure with the landscape, the public preference will be for a rock with an appearance similar to that in local cliff and hill outcrops.

When specifying armourstone (see Section 3.7), selection of particular colours should be avoided. Instead, the client should indicate which of the realistic possibilities offered from suppliers' sources are acceptable, with their associated ranges of shades or colour. Colour can only be important for the visible part of armour layers. Biological colonisation (seaweed, barnacles etc) may rapidly alter the shade as well as the overall appearance of the intertidal zone.

Shape, grain size and roughness also have a significant influence on the aesthetic perception of the armourstone material. Weathering phenomena, such as attrition, produce smooth, rounded rocks and will thus modify the general appearance of the structure.

Finally, the placing method may have a significant visual impact and can affect the acceptability of the structure on aesthetic grounds. In certain sensitive environments, architectural placement may help the structure to fit to its environment. On riverbanks and coastal revetments, a certain placement technique may give significant porosity and preferred hydraulic properties, whereas public preference might well support a placement that looks like a regular tight pavement.

## 3.3.2 Petrographic properties

The mineral composition and mineral texture of rock specimens can be the subject of petrographic examination by hand specimen and thin section to classify the rock source and to determine its suitability for construction materials. The extent to which microcracks have formed and secondary minerals such as clays have replaced former harder minerals, for example as a result of weathering, is an intrinsic property of the rock source that should be evaluated by petrographic examination. Concerns can be addressed with specialised durability and accelerated weathering tests (Section 3.8.6).

## 3.3.3 Mass density, porosity and water absorption

### *3.3.3.1 Phase relations*

Figure 3.8 (left) shows an image of a real rock sample of sandstone in a dry situation. The grey and white part of the image is mineral with a volume $V_M$. The black part of the image corresponds to voids (volume $V_P$), which are empty here, but which may be filled totally or partially by water depending on the value of degree of saturation, $S_r$. Figure 3.8 (centre and right) presents schematically the different components of the rock ie minerals and pores partially filled with water. Their respective masses and volumes are $M_M$, $V_M$ and $M_P$, $V_P$. The pores are filled by water ($M_W$ and $V_W$) and/or air ($M_A = 0$ and $V_A$) to a certain extent, known as the degree of saturation, $S_r$ (-).

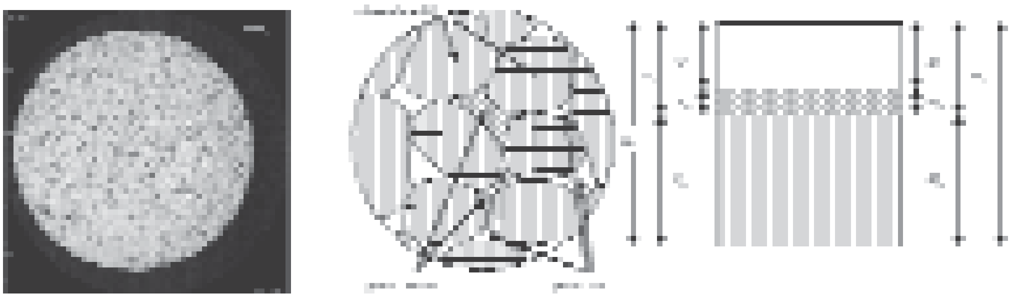


**Figure 3.8** *Micro Computerised Tomography scan, schematic thin section and representation of components of a porous rock specimen and their respective volumes and masses (courtesy Ghent University)*

### *3.3.3.2 Density definitions*

Rock density definitions differ according to the approach considered, ie rock characterisation, design of hydraulic works. The following list is an *aide-mémoire* of the different densities that may be referenced. **NOTE: the apparent mass density is to be used for design of hydraulic works.**

The **real mass density**, $\rho_{real}$ or $\rho_{min}$ (kg/m³ or t/m³), of the rock is the mass density of the **mineral** components of the rock as defined in EN 1936:1999. It is controlled by the petrography of the rock and is not used for design.

The **apparent mass density**, $\rho_{app}$ (kg/m³ or t/m³), is the mass density, being the ratio of mass to its volume displayed by a sample of rock that may have water in its pores. It is mainly controlled by the real density and the voids in the rock fabric but it also varies with the degree of saturation of the rock. When the rock is in a totally dry state (oven dry), the degree of saturation is zero. In this case, the apparent mass density is then known as $\rho_{rock}$. In test results provided by a material laboratory, the mass density is $\rho_{rock}$. Test methods are described in Section 3.8.2. **NOTE:** $\rho_{rock}$ is not the density to be considered in the design but rather $\rho_{app}$, often called $\rho_r$.

The **relative buoyant density**, $\Delta$ (–), is defined as:

$$\Delta = \rho_{app}/\rho_w - 1 \qquad (3.1)$$

where $\rho_w$ is the density of water (kg/m³). $\Delta$ is used in many hydraulic stability formulae and related subjects (see Chapter 5).

The **porosity** of the rock, $p$ (–), is the ratio of the pore volume to the total volume, $p = V_P/V_T$, and should not be confused with the porosity of a bulk granular material.

The **water absorption**, $WA$ (–), is the ratio of the maximum mass of water that can be absorbed by the rock to the mass of the dry rock material. Equation 3.2 gives the relationship between the water absorption and the porosity. Note the influence of water density, $\rho_w$ , which can vary from 1000 kg/m³ to above 1040 kg/m³ for highly saline seas.

$$WA = (\rho_w/\rho_{rock}) \cdot p/(1 - p) \qquad (3.2)$$

The **degree of saturation**, $S_r$ (–), is the ratio of the water volume in the material to the volume of the pores, $S_r = V_W/V_P$. Equation 3.3 gives the relationship between the apparent mass density of the rock and its water content through this $S_r$ value. Further discussion on the effect of the rate of saturation on the apparent mass density is included in Box 3.5 and Figure 3.9.

$$\rho_{app} = \rho_{rock} \cdot (1 - p) + \rho_w \cdot \ p \cdot S_r \tag{3.3}$$

**NOTE:** The apparent mass density is to be used for design of hydraulic works.

### 3.3.3.3 *Degree of saturation in stability calculations*

The value of mass density $\rho_{app}$ that is used when applying armourstone stability formulae, eg Hudson and Van der Meer (see Section 5.2.2.2), has traditionally been assumed to be the *saturated surface dry* mass density (ie $\rho_{rock}$) as it was considered the most applicable density term for armourstone in the intertidal zone under wave action. When fully saturated, the value of $\rho_{app}$ is therefore the value determined by testing in a saturated surface dry condition (ie degree of saturation, $S_r$ = 100 per cent). More recently, it has been recognised that different degrees of saturation are appropriate for stones in different zones of the structure. A correction to the density is now recommended for stability calculations to reflect the lower stability of blocks in the intertidal zone when they are not fully saturated. An assumed saturation of 25 per cent is recommended for armourstone that is not in permanent contact with water and for armourstone permanently below water, a saturation of 50 per cent is suggested (Laan, 1999); see also Table 3.17.

**Box 3.5** *Effect of water saturation on apparent mass density*

For material with limited water absorption, the water content has a limited influence on the apparent density. However, for rock displaying a larger water absorption or porosity, the additional mass density attributable to the mass of water existing in the pores may be accounted for. Figure 3.9 gives the additional mass density due to the amount of water absorbed in accordance with Equation 3.3.

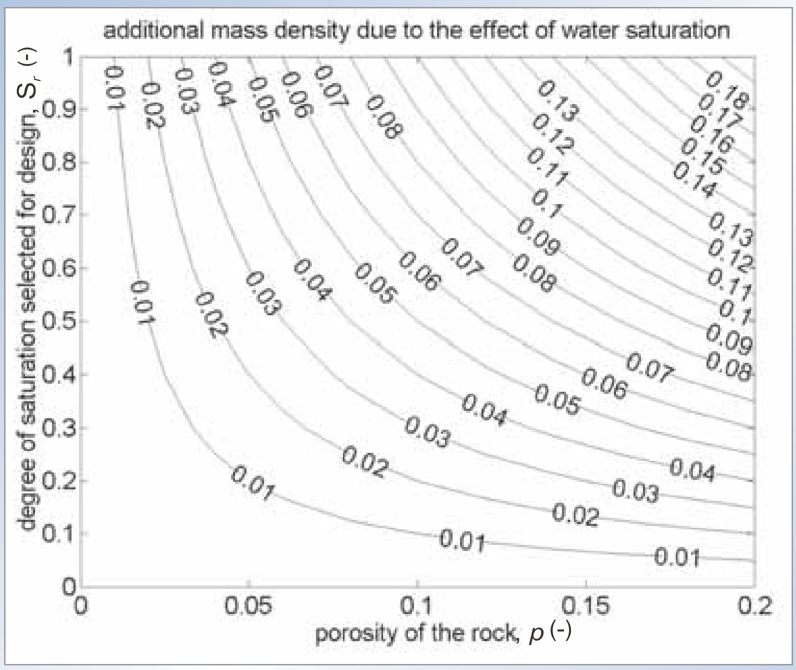



**Figure 3.9** *Effect of degree of saturation $S_r$ (-), on the apparent mass density of porous rock $\rho_{app}$. Contours indicate the correction value (in t/m³) to be added to the dry mass density $\rho_{rock}$*

For example, a rock with dry mass density of 2.4 t/m³ and a porosity of 10 per cent ($p$ = 0.1) has a correction value of 0.05 t/m³ for degree of saturation, $S_r$ = 50 per cent and 0.10 t/m³ for a fully saturated situation. In other words, the apparent mass density is 2.45 t/m³ or 2.50 t/m³ for 50 per cent or 100 per cent saturation respectively.

#### 3.3.3.4 *Density variation in a quarry*

The rock mass density will generally correlate with the darkness of the rock's minerals and decrease with porosity and degree of weathering. Density variation is a good indicator of quality variation and should be tested where variation is suspected. In general, the variability of mass density of one type of rock in a quarry is limited and the 90 per cent exceedance value is not more than 100 kg/m³ less than the average density. Higher variability may be due to genuine rock type variability in the source or the result of weathered zones.

#### 3.3.3.5 *Mass density as a durability indicator*

Low-density material tends to have limited durability, generally because of the high porosity (see Section 3.6). In 2006, the European armourstone standard EN 13383 specifies a mass density greater than 2.30 t/m³ to ensure minimum durability. Local material with a lower density is therefore not supposed to be used within Europe. In areas deprived of good-quality rock, the use of low-quality rock should be studied, paying specific attention to durability assessment using accelerated weathering tests.

#### 3.3.3.6 *Mass density as a design parameter*

Design implications of variation in mass density due to varying rock sources can be very significant (see point 1 below), whereas that resulting from different degrees of saturation is important only in porous rock (see point 2 below).

1. **Varying rock source**. The designer or contractor may often select a default apparent mass density value such as 2.7 t/m³ or the known density of a given source to prepare a design, specify the grading of armourstone and determine the dimensions of the various layers. In the case of consideration of alternative rock sources with a different rock mass density it is necessary to respecify and redesign the various components of the rock structure. For the same hydraulic stability, the designer is interested in the consequent reduction or increase of the median mass, $M_{50}$, the total mass of the armour, the number of armour stones and the layer thickness, as these are influenced by a change in density. These density effects and the consequent effects on stability can be taken into account by using the graphs of correction factors given in Section 3.5.2.
2. **Effect of water saturation on porous rocks**. The designer may also want to take into account the degree of water saturation and then account for the increase of apparent mass density and stability due to the amount of water in the rock pores. This variation in density between dry and fully saturated density is usually negligible and only becomes significant for porous rocks, see Box 3.5.

### 3.3.4 Resistance to breakage and armourstone integrity

Potential breakage of armourstone is of particular concern when many rough handling events can be expected after purchase and when the rock is intended for dynamically stable structures, eg berm breakwaters. Over-dimensioning the specified $M_{50}$ and anticipating breakages where broken and sub-size pieces can be removed during construction is sometimes used to compensate for poor resistance to breakage, but this is a potentially high-risk approach. This risk can be mitigated by assessing likely changes in mass distribution using an appropriate degradation model (see Section 3.6.6) and suitable assessment techniques or test methods to measure resistance to breakage (see Section 3.8.5).

Armourstone resistance to breakage and armourstone integrity are generally distinguished (Latham and Gauss, 1995; Dupray *et al*, 2003) since the former governs **minor breakage** while the latter determines **major breakage**. During quarrying, construction and in service, armourstone pieces may display these two types of breakage, as described below.

**Major breakage** refers to breakage of individual armour stones along pre-existing defects, as shown in Figure 3.10 for armourstone with different geological origins. Any defects are controlled by the geology of the rock source and the production technique. For example, sedimentary rocks may contain bedding planes, stylolites, calcite veins or shaly partings, while igneous rocks may contain mineral veins, contacts between distinct petrographic units or cooling cracks. In addition, macro-flaws may be induced by blasting or fragmentation of the rock mass during extraction. If these defects propagate, a proportion of stones will be transformed into large fragments. If major breakage takes place on a significant number of stones, this may significantly affect the mass distribution of the armourstone and consequently the value of design parameters such as $M_{50}$ or $D_{n50}$ (see Section 3.6.6). Resistance to major breakage is known as **integrity**.

**Minor breakage** refers to breakages of asperities. This often occurs when stone edges or corners are knocked off during routine handling, by the traffic of heavy plant during construction, or during initial settlement of the structure (see Figure 3.11). This phenomenon takes place along new fractures created through the mineral fabric of the stone. It is often associated with bruising and crushing, and generally creates fragments of limited size (up to a few tens of kilogrammes) depending on the armourstone grading. This phenomenon has a limited impact on the mass distribution and the $M_{50}$ value (see Section 3.6.6), but can contribute to edge rounding. Many strength tests exist for measuring the resistance of mineral fabric to breakage and are discussed in Section 3.8.5 but they do not correlate with armourstone integrity tests (Perrier *et al*, 2004).

In simple terms, **armourstone integrity** is the ability of armourstone pieces to withstand excessive breakage during their life cycle. It should not be confused with resistance to breakage through the mineral fabric, ie resistance to minor breakage that might be tested on small laboratory specimens or aggregates. From a survey of feedback from 200 professionals, including designers, contractors, quarry companies, port and waterways authorities, armourstone integrity was identified as an **essential property** (Dupray, 2002). Two aspects of integrity should be distinguished.

1. The integrity of armourstone as an individual piece is its ability not to display excessive breakage. The threshold for excessive breakage is discussed in Section 3.8.5.
2. The integrity of armourstone as a granular material is the ability of a consignment not to display excessive changes of mass distribution and especially of its characteristic masses.

Integrity is a property of heavy armourstone, among others such as shape characteristics, that may be evaluated by initial type tests, ie one-off tests giving information about an armourstone source to promote design optimisation. Such initial type testing is distinct from routine testing of the quality of consignments in association with factory production control.

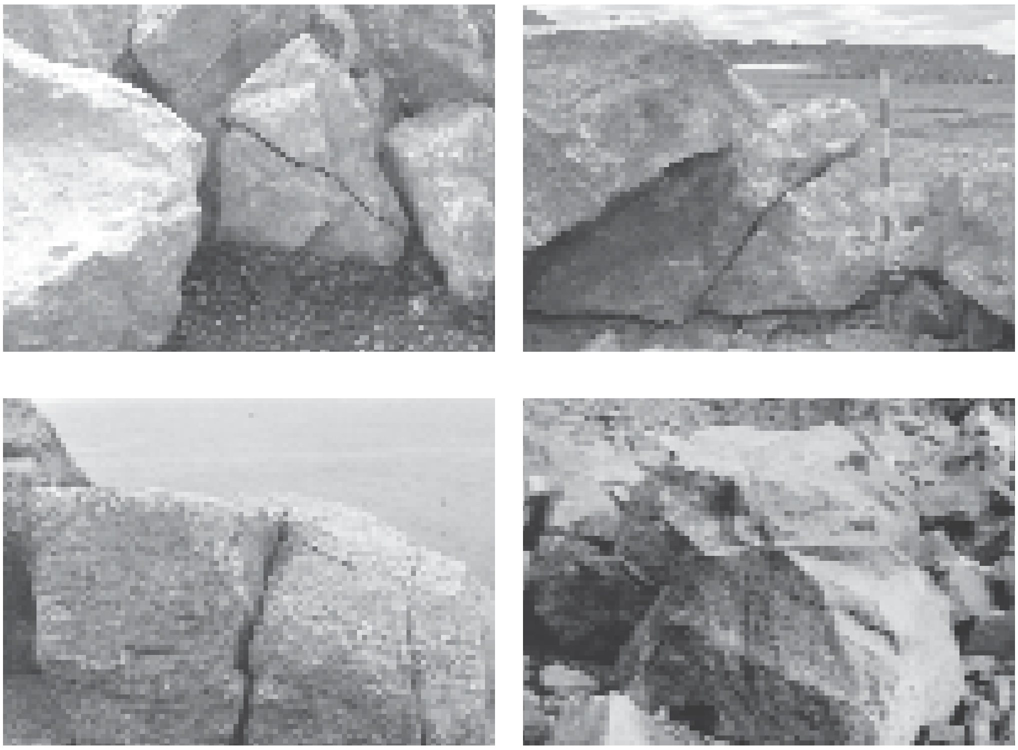


**Figure 3.10** *Examples of major breakage taking place in sedimentary and igneous rock (courtesy S Dupray and G Laan)*

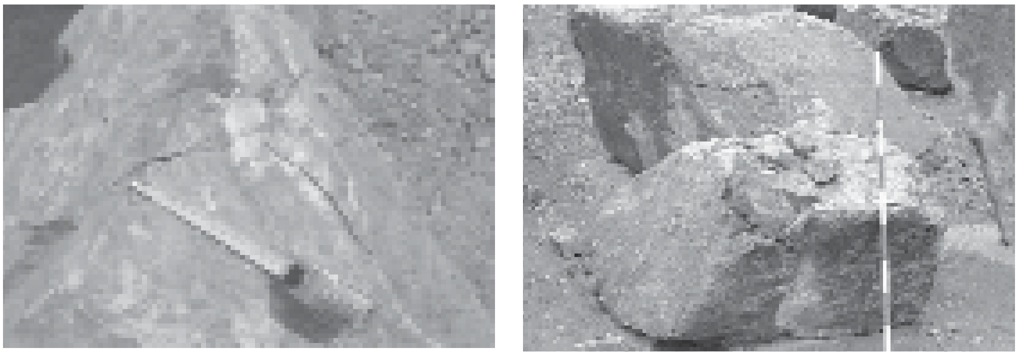


**Figure 3.11** *Examples of minor breakage taking place in sedimentary and igneous rock (courtesy S Dupray)*

Methods to assess and measure integrity are given in Section 3.8.5. A new approach to predict degradation induced by breakages is given in Section 3.6.6. Common measures for resistance to breakage are:

The **breakage rate**, $B_n$ (-), defined as the number of stones that display major breakage expressed as the fraction of the number of stones in the consignment. An objective method to determine $B_n$ is given in Section 3.8.5.

The **relative decrease of characteristic percentage passing mass** $I_{Mx}$, defined by Equation 3.4:

$$I_{Mx} = \frac{M_{x,i} - M_{x,f}}{M_{x,i}} \tag{3.4}$$

where $x$ is the percentage passing value, $i$ is the value of $M_x$ before degradation and $f$ is the value of $M_x$ after degradation. For example the relative decrease of $M_{50}$ induced by degradation events is $I_{M50}$, defined as $(M_{50,i} - M_{50,f})/M_{50,i}$.

Other indicators based on the bounded area between mass distribution curves before and after degradation are introduced in Section 3.8.5.

### 3.3.5 Armourstone resistance to wear

Materials handled in bulk (typically core and underlayer materials of less than 300 kg) and/or loaded many times will undergo considerable mutual shearing, resulting in abrasive degradation with greater proportional mass losses for finer materials. Resistance to abrasion in service is most important for sites where shingle or sand in suspension can attack the armour (Figure 3.12). Also, for structures using dynamic design concepts, the increased risk of rocking, sliding and rolling of stone will require that materials used should be sufficiently abrasion-resistant. Certain applications in river engineering need careful consideration of resistance to wear, for example where high suspended loads act in torrents or at the base of high-velocity fall channels or scour focus points. Suggested requirement levels and test methods are given in Sections 3.7.1 and 3.8.5.

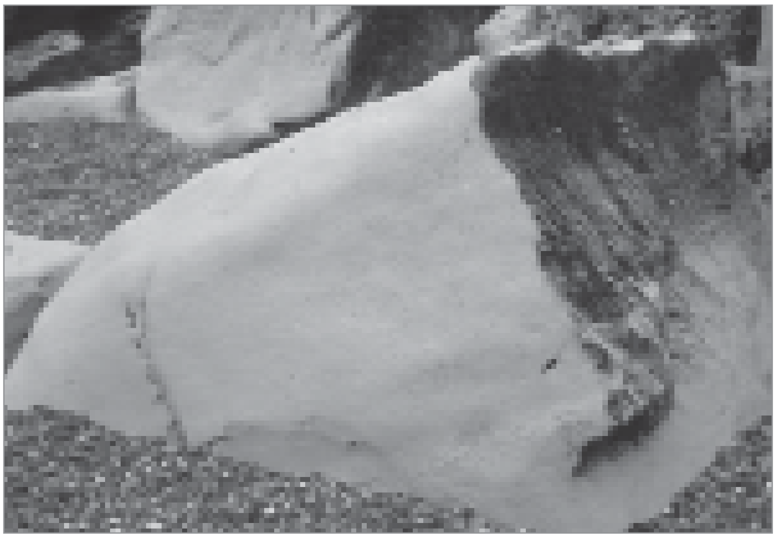


**Figure 3.12** *Rapid erosion and mass loss of oolitic limestone armour stones by shingle wear (courtesy J-P Latham)*

## 3.4 QUARRIED ROCK – PRODUCTION-INDUCED PROPERTIES

This section deals with the properties of shape, size and mass of individual armour stones and the systems used for the assessment and representation of their statistical variability in the bulk granular material. These properties are affected by the producer's methods of extraction and selection. They govern the bulk material properties that can be expected in the structure. As the client usually bears the cost of production and selection of both acceptable and reject materials, shape and grading specification should not be set tighter than is functionally necessary.

The production of armourstone typically involves both loosening of joint and bedding-plane bounded blocks and blast-induced fracturing. Shapes, sizes and the occurrence of flawed blocks are controlled by the interplay between these processes. Although shape is mostly governed by intrinsic properties for large stones, it is convenient to consider shape in this section.

### 3.4.1 Shape

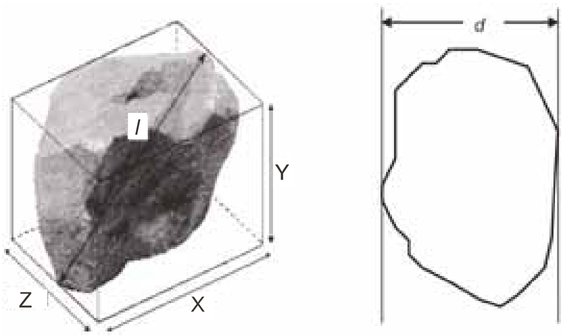
Shape is particularly important for armouring material that is individually placed above water, as it can significantly affect the armour layer stability.

For any size range of particles in a bulk granular material, the dominant factors governing porosity are size and shape distribution. Shape therefore has an indirect effect on shear strength, permeability and filtering properties of core and underlayer materials. Bulk materials that are flaky may crush more easily, for example if subjected to traffic.

For individually placed armourstone, shape will affect ease of construction, layer thickness, packing density and hydraulic stability. For typical angular armourstone sources, two uncorrelated armourstone shape descriptors are required to quantify these effects (Newberry, 2003; Stewart *et al*, 2003). One is for form and the other relates to compactness. Both are practical and sufficiently reproducible.

### 3.4.1.1 Length-to-thickness ratio (LT)

Length-to-thickness ratio, $LT$ (-), is defined as the maximum length, $l$ (m), divided by the minimum distance, $d$ (m), between parallel lines through which the particle would just pass; see Figure 3.13. This form description is the industry standard now embodied in EN 13383 for both armourstone and aggregates. $LT$ is sometimes termed *aspect ratio*.




**Note**

For a cube $X/Z = 1$, $LT = 1.73$.
In EN 13383, the symbol E is used to denote thickness $d$.

**Figure 3.13** *Illustration of armour stone shape measurement systems*

### 3.4.1.2 Blockiness (BLc)

Blockiness, $BLc$ (%), is defined as the volume of a stone divided by the volume of the enclosing XYZ orthogonal box with a minimum volume (see Figure 3.14). Blockiness is defined in Equation 3.5:

$$BLc = \left( \frac{M}{\rho_{app}} \cdot \frac{1}{X \cdot Y \cdot Z} \right) \cdot 100 \qquad (3.5)$$

Blockiness is a shape descriptor, sometimes termed the “volume reduction factor” or “shape factor”. It relates to compactness, or “rectanguloidness” and correlates well with the packing behaviour of individually placed stones. This is because higher blockiness promotes stone positioning with more sub-parallel face alignments, giving higher density, greater numbers of contact points and thus greater interlock.

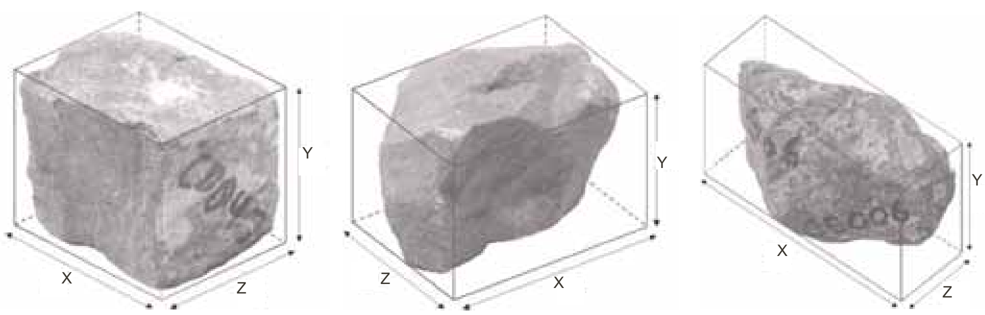



**Figure 3.14** *Examples of different blockiness values (from left to right, BLc = 80%, 60% and 40%)*

Note that to obtain this shape descriptor, the stone mass, $M$, and density, $\rho_r$, need to be known. $BLc$ is determined by measuring the maximum $X$, intermediate $Y$, and minimum rectangular dimensions $Z$ of the smallest hypothetical box that would enclose the block, and by weighing. To help find the $X$, $Y$, and $Z$ dimensions, $Z$ is set parallel to $d$ and $X$ and $Y$ are then defined by the axes of the perpendicular plane with projected minimum area.

Advantages of using blockiness, $BLc$, with $LT$ include:

- accurate prediction of porosity and packing
- better stability and hydraulic performance prediction
- ability to match armourstone behaviour in a hydraulic model with that in prototype.

To characterise the shape of an armourstone piece, the dimensions $X$, $Y$, $Z$, $l$ and $d$ are required. It is often most convenient to obtain these data when a representative sample is undergoing weighing during a mass distribution check. For blockier shapes, $l$ differs significantly from $X$ and $d$ tends to coincide with $Z$ (see Figures 3.13 and 3.14).

### 3.4.1.3 Cubicity

The **form index** used in France, sometimes termed **cubicity**, is given by $(L+G)/(2E)$, where $L$, $G$ and $E$ are the longest, intermediate and shortest orthogonal dimensions starting by defining $L$ and then taking the orthogonals $G$ and $E$. These dimensions differ from $X$, $Y$ and $Z$. For highly irregular shapes, cubicity can be more objectively measured than blockiness. For blocky pieces, $X$, $Y$ and $Z$ are more relevant to characterise the shape since $X$ is the longest side of the enclosing box and $L$ would be close to the longest dimension of the box, ie its diagonal. For characterising the likely behaviour of armourstone, it is therefore not certain whether cubicity discriminates unwanted pieces any better than length-to-thickness ratio, $LT$. In some special cases, however, cubicity departs from unity more than $LT$, eg for certain disc-like shapes, and has been suggested as an additional constraint parameter to help avoid platy stones.

### 3.4.1.4 Roundness

Armourstone may be sourced from naturally abraded boulders and glacial deposits or from *core stones* in weathered igneous rock. In such cases, the roundness may have a major influence on bulk properties in the structure. Armourstone pieces may also become rounded while in service. If the mineral fabric strength is poor, materials may become significantly rounded during handling by the crushing of edges and corners. To quantify roundness, visual comparison charts such as for Powers Roundness (Powers, 1953) are often the most practical. The **Fourier asperity roughness**, $P_R$ (-), was introduced for quantifying wear and rounding (Latham and Poole, 1988) and later used to compare the hydraulic stability of different armourstone shapes (eg see Bradbury *et al*, 1991). The latter study is informative for assessing reduction of stability with increased roundness as estimated using $P_R$. Typical $P_R$ values are very round: $P_R$ < 0.009; semi-round: $P_R$ = 0.009–0.011; angular: $P_R$ > 0.011 (see Figure 3.15). For angular individually placed stones, however, these values are of minor importance as the shape is primarily determined by the blockiness, $BLc$, together with length-to-thickness ratio, $LT$. More detail is given in Sections 3.7.1 and 3.8.3.

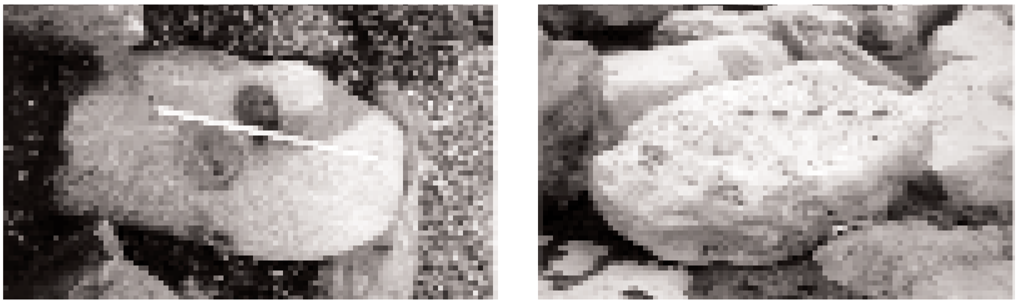


**Figure 3.15** *Visual comparison of stone shapes showing roundness quantified using the Fourier asperity roughness. Left: Rounding of gneiss; very round. Right oolitic limestone by shingle attack, 1 m scale bar; semi-round (courtesy J-P Latham)*

### 3.4.1.5 Proportion of crushed or broken surfaces

In some European countries rounded glacial boulders, cobbles and core stones from basalt and dolerite quarries have been used for hydraulic structures. In order to ensure adequate mechanical interlock for these materials, the percentage of crushed or broken surfaces is also specified where appropriate.

### 3.4.1.6 Shape for specification purposes

Shape is an example of a property that may be used in two distinct ways. It may be specified in order to establish the stone consignment's fitness for purpose. If quantified in more detail, it can provide information useful for design. Integrity is a similar property in this respect.

For specification, it is desirable to limit the proportion of pieces with a length-to-thickness ratio, $LT$, of greater than 3:1 to a level that is reasonable for the intended use. Because smaller stones tend to have larger $LT$, in Europe (see Section 3.7.1) the following levels are suggested:

- heavy armourstone in cover layers — typically < 5 per cent
- light armourstone in cover layers (< 40 kg) — typically < 20 per cent.

Restricting the proportion of pieces with $LT > 3$, ie the flaky or elongated pieces, should ensure reasonable interlock. It will also limit the damage from breaking eg induced by construction plant trafficking over granular surfaces.

It has also been suggested that removal of all stones with cubicity values greater than 3 will target the removal of flaky pieces more effectively than applying an $LT$ limit at 3. In practice, it remains unclear whether further criteria based on cubicity would have this desired effect.

### 3.4.1.7 Shape for design and dimensioning purposes

In Section 5.2.2.2 possible stability increases corresponding to lower armour layer porosities achieved by tighter non-random placement methods are tentatively presented. These lower porosities can only be achieved with certain armour shape characteristics. In Section 3.5.1 conversion charts for armour layer porosity of individually placed layers as a function of two shape parameters ($LT$ and $BLc$) and placement method are given to aid stability and dimensioning calculations.

For CE marking $LT_A$ is required (ie a specified maximum percentage of stones with $LT > 3$) to ensure shape control (see Section 3.7.1). However, average values for $LT$ and $BLc$ should not be specified as a requirement for factory production control as, by doing so, there is a risk of significantly decreasing the production rate, increasing the price of armourstone or even excluding rock sources that have the potential to provide the most economic project outcome. A producer should nevertheless be encouraged to declare the average and standard deviation values of *LT* and *BLc* as part of initial type testing, as it provides the client, contractor and designer with valuable information. Average values of both *LT* and *BLc* for a proposed armourstone source are required for an accurate prediction of construction-induced properties of cover layers individually placed above water (see Section 3.5.1). Both shape parameters are uncorrelated, so one cannot be deduced from the other. The variability of shapes in a consignment of armourstone can be considerable – see Figure 3.16, where it is clear that *LT* has no relationship with *BLc*. Note the parameter independence and wide spread about the mean. Other rock types and gradings may show different forms of scatter plot, eg dimension stone product. Examples of shapes of limestone and granite stones are illustrated in Figure 3.17. When armourstone is placed in bulk rather than individually, *BLc* appears to have no significant influence on bulk density, while *LT* has a considerable influence.

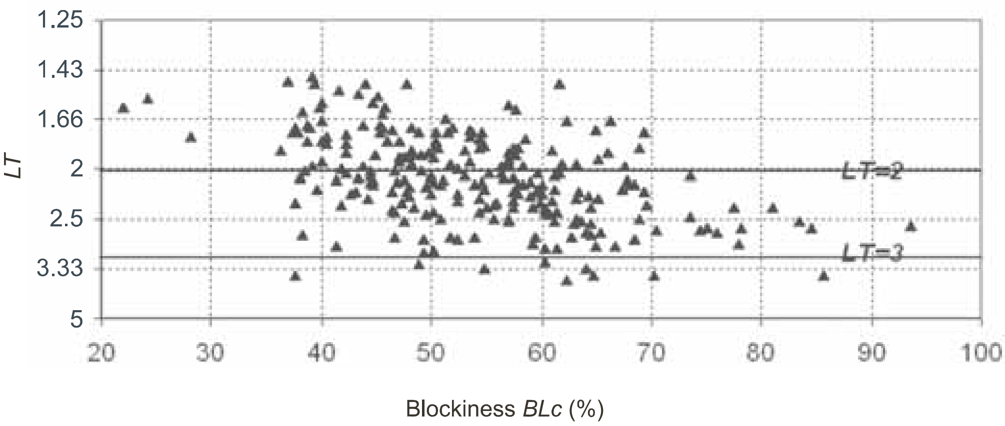



**Figure 3.16** *Distribution of shapes measured in a consignment of 1–3 t limestone blocks (BLc is given as a percentage)*

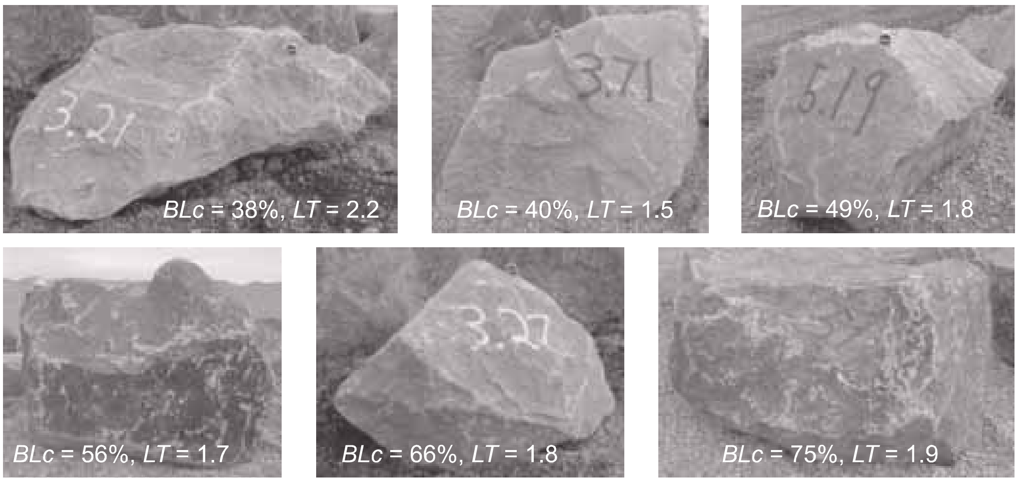



**Figure 3.17** *Comparison of shape parameters of heavy armourstone, where increase in blockiness does not always correspond with increase or decrease in value of LT (mass shown in tonnes) (courtesy S Newberry)*

### 3.4.1.8 *Factors controlling armourstone shape during quarry production*

An indication of the typical *LT* or *BLc* of a rock source is given by the pattern of dissecting discontinuities in the outcrop (see Figure 3.5). Factors that influence the blockiness and other shape characteristics of a proposed grading of armourstone also depend on the grading size in question and its relationship to the discontinuity spacing, as illustrated in Figure 3.18.

The extent of blockiness reduction by fracturing depends on the thickness between bedding planes. For example, a limestone sequence with mean bedding spacing of 2 m, (≈20 t *in situ* blocks) is shown schematically on the left of Figure 3.18. After blasting, a typical grading based on the largest stones, eg 10–15 t, will consist of many highly blocky stones still bounded by their original orthogonal joint and bedding surfaces. The smaller blast-pile gradings (eg 0.3–1 t) are almost certainly derived from blocks bounded by new irregular blast-induced fractures (ie low blockiness), as the natural *in situ* rock mass does not have these small orthogonal blocks. In contrast, a smaller *in situ* mean spacing of 0.6 m (see example b in Figure 3.18) means it is reasonable to expect relatively blocky pieces in the 0.3–1 t range bounded by natural bedding and joint surfaces to be liberated by the blast.

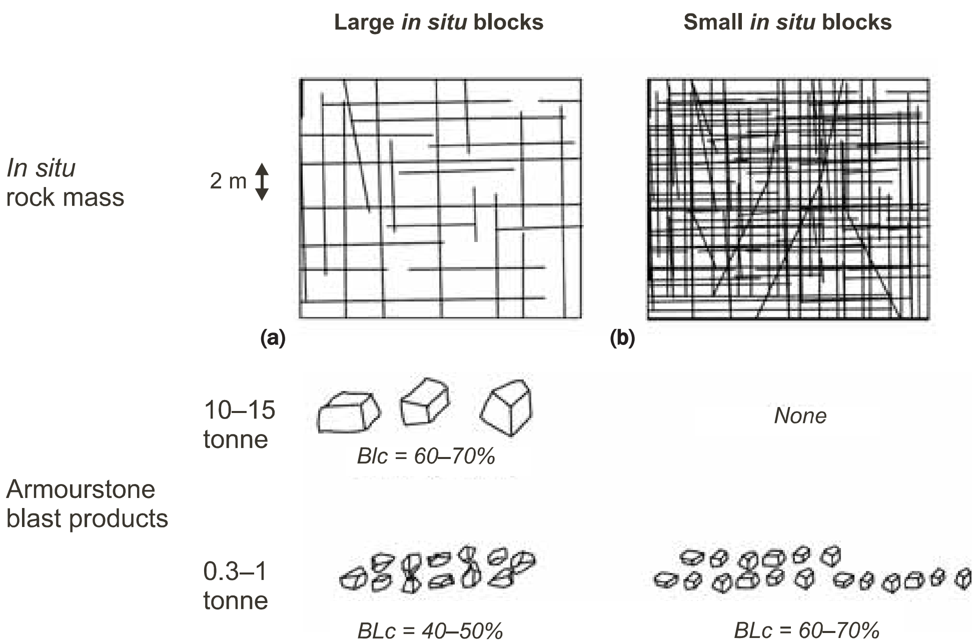



**Figure 3.18** *Schematic illustration of the influence of discontinuity spacing and grading on the blockiness of armourstone in orthogonally jointed rock masses. Any spacing is possible; the 2 m spacing is an illustrative example (see text)*

Armourstone shape is generally influenced by rock type and production as follows:

- bedded sedimentary sequences can produce very blocky armour stones (see Figure 3.49)
- discontinuity patterns and spacings vary in all rock types, igneous patterns are often less orthogonal
- columnar joints are common in basalts and dolerites: high blockiness often occurs when columnar joint spacing is matched to grading dimensions, elongate columns are rarely preserved after blasting
- sub-horizontal sheeting joints in granite may provide a dominant discontinuity set causing the rock mass to break up similar to bedded sedimentary rocks, promoting blocky armourstone
- metamorphic rocks exhibiting natural banding (ie foliation produced by mineral alignment or mineral segregation), such as gneiss, often yield rocks with a higher aspect ratio if the foliation is well developed and clearly visible.

Armourstone may also be obtained from *dimension stone* quarries. These quarries typically produce blocks cut out (or pneumatically split using a row of closely spaced holes) and these have a very orthogonal blocky shape. The materials that have not been selected for further cutting and polishing are a good source for armourstone. Natural blocks that are bounded by several angled joints are also of no use and, if very large, are further broken up, eg by a breaker, to help manoeuvre them into the waste piles. In most cases, these by-products of the dimension stone industry make excellent armourstone, and a large proportion of the stones in any such consignment will retain the blocky characteristics resulting from the original cutting and splitting processes.

### 3.4.2 Dimensions of pieces of armourstone

The simplest measurement of an armourstone piece is its mass, $M$ (kg), which can be determined by weighing. The dimension of the equivalent cube, $D_n$ (m), known as nominal diameter is used in design. The diameter of the equivalent sphere, $D_s$ (m), is now rarely used for armourstone. For a rock of density, $\rho_{app}$ (kg/m³), relationships between $M$, $D_s$ and $D_n$ are:

$$D_n = (M/\rho_{app})^{1/3} \quad \text{or} \quad M = \rho_{app}\, D_n^3 \tag{3.6}$$

$$D_s = (6/\pi)^{1/3}\,(M/\rho_{app})^{1/3} \quad \text{or} \quad M = (\pi/6)\,\rho_{app}\, D_s^3 \cong 0.52\,\rho_{app}\, D_s^3 \tag{3.7}$$

$$D_n = (\pi/6)^{1/3}\, D_s \cong 0.81\, D_s \tag{3.8}$$

These relationships are also valid for relating characteristic sizes of armourstone, ie they are valid for any percentage of passing, such as the median value:

$$D_{n50} = (M_{50}/\rho_{app})^{1/3} \quad \text{or} \quad M_{50} = \rho_{app}\, D_{n50}^3 \tag{3.9}$$

$D$ (without a subscript $n$ or $s$) refers to the square opening sieve size (m). An adjustable square gauge may be used to provide an objective measure of the sieve size of any armourstone piece of acceptable size. The sieve size $D$ and the nominal diameter $D_n$ are proportional for a given shape of armourstone. Laan (1981) experimentally determined a recommended conversion constant based on a study of several different rock types and gradings of armourstone.

$$D_n = 0.84\, D \tag{3.10}$$

The median sieve size $D_{50}$, the median nominal diameter $D_{n50}$ and the median mass $M_{50}$ are related using the conversion factor $F_s$ (-):

$$F_s = M_{50}/(\rho_{app}\, D_{50}^3) = (0.84)^3 \cong 0.60 \tag{3.11}$$

The assumption of $F_s \cong 0.60$ is considered best practice and compares well with values in the field, which vary from 0.34 to 0.72. For model-scale armourstone materials used in hydraulics laboratories the value of $F_s$ ranges from 0.66 to 0.70. For different kinds of screening or selection techniques the value of $F_s$ varies from 0.35 to 0.70.

### 3.4.3 Size and mass distribution of armourstone gradings

A new European standard EN 13383 has been devised for armourstone. It includes a system for gradings applicable to materials used for armouring and filtering. The system is not applicable to the typically very wide size ranges found in core materials used for volume filling. The guidance here on gradings takes the user through the following:

- grading widths

- standard grading system of EN 13383 for armourstone
- Rosin-Rammler curves
- graphical illustration of grading curves
- fragments and effective mean mass, $M_{em}$
- requirements and compliance of EN 13383 Standard gradings
- additional useful information on EN 13383 Standard gradings
- the relationship between $M_{50}$ and $M_{em}$
- non-standard gradings
- core materials.

#### 3.4.3.1 *Grading width and common terminology*

A sample of natural quarry blocks will display a range of block masses or sieve sizes. The percentage of total mass lighter or smaller than a given mass or size is often presented as cumulative curves for assessment of mass and size distributions. The block mass is expressed by $M_y$, where $y$ per cent of the total (or cumulative) sample mass is lighter than $M$. For example, $M_{50}$ is the mass of the theoretical block for which half of the mass of the sample is lighter.

The overall steepness of the curve is an indication of the uniformity in mass, generally termed the grading width or gradation. A quantitative indication of the uniformity is the ratio $M_{85}/M_{15}$ or its cube root, which reduces to $D_{n85}/D_{n15}$ or $D_{85}/D_{15}$. Table 3.4 gives the description of the various grading widths, expressed in above mass and size ratios.

**Table 3.4** *Armourstone grading width related to the uniformity*

| Grading width | $D_{85}/D_{15}$ | $M_{85}/M_{15}$ |
|---|---|---|
| Narrow or *single-sized* gradation | Less than 1.5 | 1.7–2.7 |
| Wide gradation | 1.5–2.5 | 2.7–16 |
| Very wide or *quarry run* gradation | 2.5–5.0 | 16–125+ |

For wide gradings, the phrase *well graded* merely implies that there are no significant *gaps* in material sizes over the total width of the grading. *Gap-graded* material may occur naturally, or can result when two quite different single-sized products have been blended.

The gradings required by designers and controlled by producers generally become wider as they become lighter. In most cases, **armourstone** is narrow graded. **Rip-rap** or **riprap** is the term usually applied to armourstone with a combination of the following characteristics: wide gradation, generally bulk placed, often placed as a cover layer and frequently used in estuarial and riverbank applications. Rip-rap has had entire proceedings of an international workshop devoted to it; see Thorne *et al* (1995).

Determination of the gradation of the granular material is important for the following reasons:

- the packing and the volumetric layer (or void) porosity of bulk-placed materials is highly dependent on the overall slope of the grading curve (see Section 3.4.4.3, Box 3.6)
- behaviour such as filtering and piping, especially across transitions between different granular materials, is governed by rules based on gradation (see Section 5.4)
- wider gradings will tend to segregate during bulk handling and stockpiling. Limiting the grading width can control this.

### 3.4.3.2 EN 13383 system for standardisation of gradings

EN 13383 divides armourstone products into:

- **Heavy gradings ("HM")** for larger sizes appropriate for armour layers – normally handled individually
- **Light gradings ("LM")** appropriate for armour layers, underlayers and filter layers – produced in bulk, usually by crusher opening and grid bar separation
- **Coarse gradings ("CP")** often used for filter layers – of such a size that all pieces can be processed by production screens with square openings (ie typically less than 200 mm).

The system for defining heavy gradings requirements is based on setting limit values with an associated percentage passing by mass (see Figure 3.19). A set of nominal limits corresponds to the target size of the armourstone. A set of extreme limits corresponds to tolerances. The standard grading requirements and associated passing values are summarised in Table 3.5.

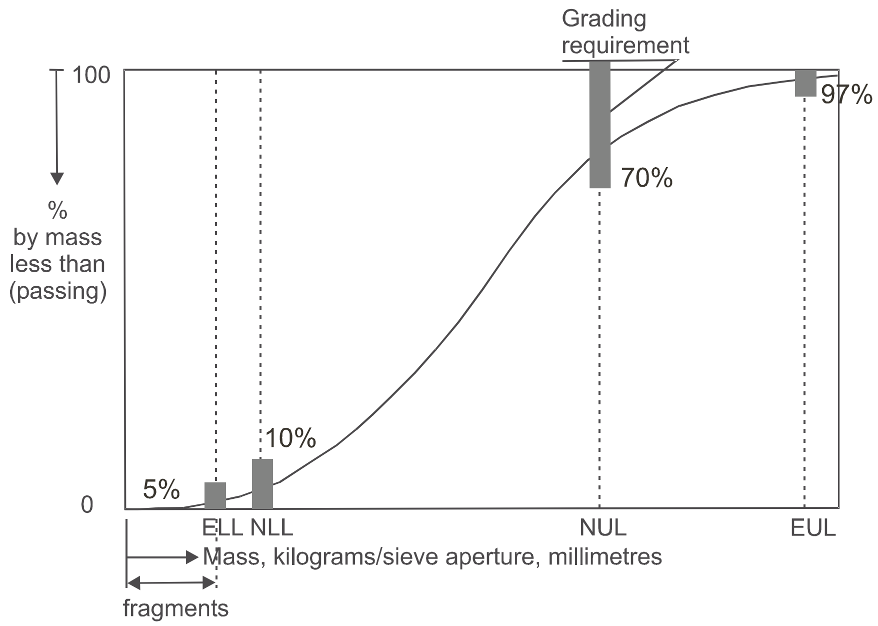



**Figure 3.19** *System for limits of EU standard gradings – percentages of passing as given are for heavy grading*

For **heavy gradings**, the associated limits are:

- ELL (Extreme Lower Limit) – the mass below which no more than 5 per cent passing by mass is permitted
- NLL (Nominal Lower Limit) – the mass below which no more than 10 per cent passing by mass is permitted
- NUL (Nominal Upper Limit) – the mass below which no less than 70 per cent passing by mass is permitted
- EUL (Extreme Upper Limit) – the mass below which no less than 97 per cent passing by mass is permitted.

In Table 3.5 limits for $M_{em}$ are also given, defined as *effective mean mass*, ie the average mass of a sample of stones without *fragments* (those below the ELL-value of the grading, see Section 3.4.3.5).

**Table 3.5** *Heavy, light and coarse European EN 13383 standard grading requirements*

| | Class designation | ELL | NLL | NUL | EUL | $M_{em}$ | |
|---|---|---|---|---|---|---|---|
| Heavy | Passing requirements kg | < 5% kg | < 10% kg | > 70% kg | > 97% kg | lower limit kg | upper limit kg |
| | 10 000–15 000 | 6500 | 10 000 | 15 000 | 22 500 | 12 000 | 13 000 |
| | 6000–10 000 | 4000 | 6000 | 10 000 | 15 000 | 7500 | 8500 |
| | 3000–6000 | 2000 | 3000 | 6000 | 9000 | 4200 | 4800 |
| | 1000–3000 | 700 | 1000 | 3000 | 4500 | 1700 | 2100 |
| | 300–1000 | 200 | 300 | 1000 | 1500 | 540 | 690 |

| | Class designation | ELL | NLL | NUL | EUL | $M_{em}$ | |
|---|---|---|---|---|---|---|---|
| Light | Passing requirements kg | < 2% kg | < 10% kg | > 70% kg | > 97% kg | lower limit kg | upper limit kg |
| | 60–300 | 30 | 60 | 300 | 450 | 130 | 190 |
| | 10–60 | 2 | 10 | 60 | 120 | 20 | 35 |
| | 40–200 | 15 | 40 | 200 | 300 | 80 | 120 |
| | 5–40 | 1.5 | 5 | 40 | 80 | 10 | 20 |
| | 15–300 * | 3 | 15 | 300 | 450 | 45 | 135 |

| | Class designation | ELL | NLL | NUL | EUL | $M_{em}$ |
|---|---|---|---|---|---|---|
| Coarse | Passing requirements mm | < 5% mm | < 15% mm | > 90% mm | > 98% mm | < 50% mm |
| | 45/125 | 22.4 | 45 | 125 | 180 | 63 |
| | 63/180 | 31.5 | 63 | 180 | 250 | 90 |
| | 90/250 | 45 | 90 | 250 | 360 | 125 |
| | 45/180 ** | 22.4 | 45 | 180 | 250 | 63 |
| | 90/180 *** | 45 | 90 *** | 180 *** | 250 | NA |

**Notes**

* = wide light grading, ** = wide coarse grading, *** = gabion grading, NLL = 20% and NUL = 80%.
See Table 3.6 in Section 3.4.3.7 for additional information on standard gradings.

For example, to fulfill the mass distribution requirements for an EN standard heavy grading designated "3–6 tonnes" (or 3000–6000 kg), up to 10 per cent (by mass) may be below the nominal lower limit NLL of 3 t, and up to 30 per cent may be above the nominal upper limit NUL of 6 t. These undersize and oversize tolerances make the grading more practical to produce. The grading is allowed a further margin for borderline stones at the extremes using extreme lower (ELL) and extreme upper (EUL) limits. So for the 3–6 t example, ELL restricts the percentage below 2 t to 5 per cent and EUL limits blocks above 9 t to less than 3 per cent, see also Figure 3.21. Similar definitions with slightly different percentage requirements are introduced for light and coarse gradings.

The introduction of a system of standard gradings within EN 13383 has brought several advantages. For the producer, these mostly concern the economics of production, selection, stockpiling and quality control. The system enables engineers and producers to refer to a batch or consignment of stones by its designated bottom NLL and top sizes NUL (using masses or sieve sizes) with a meaning that is consistent to all. Standard gradings are considered essential for coarse and light gradings as these are selected by mechanical means. If non-standard gradings are specified, selection by mechanical means requires changing bar openings, new screen decks or completely new barrels. With only a few grading classes recognised within Europe, producers can pre-select armour stones and stockpile the materials as standard graded products, knowing that designers will specify standard gradings wherever possible.

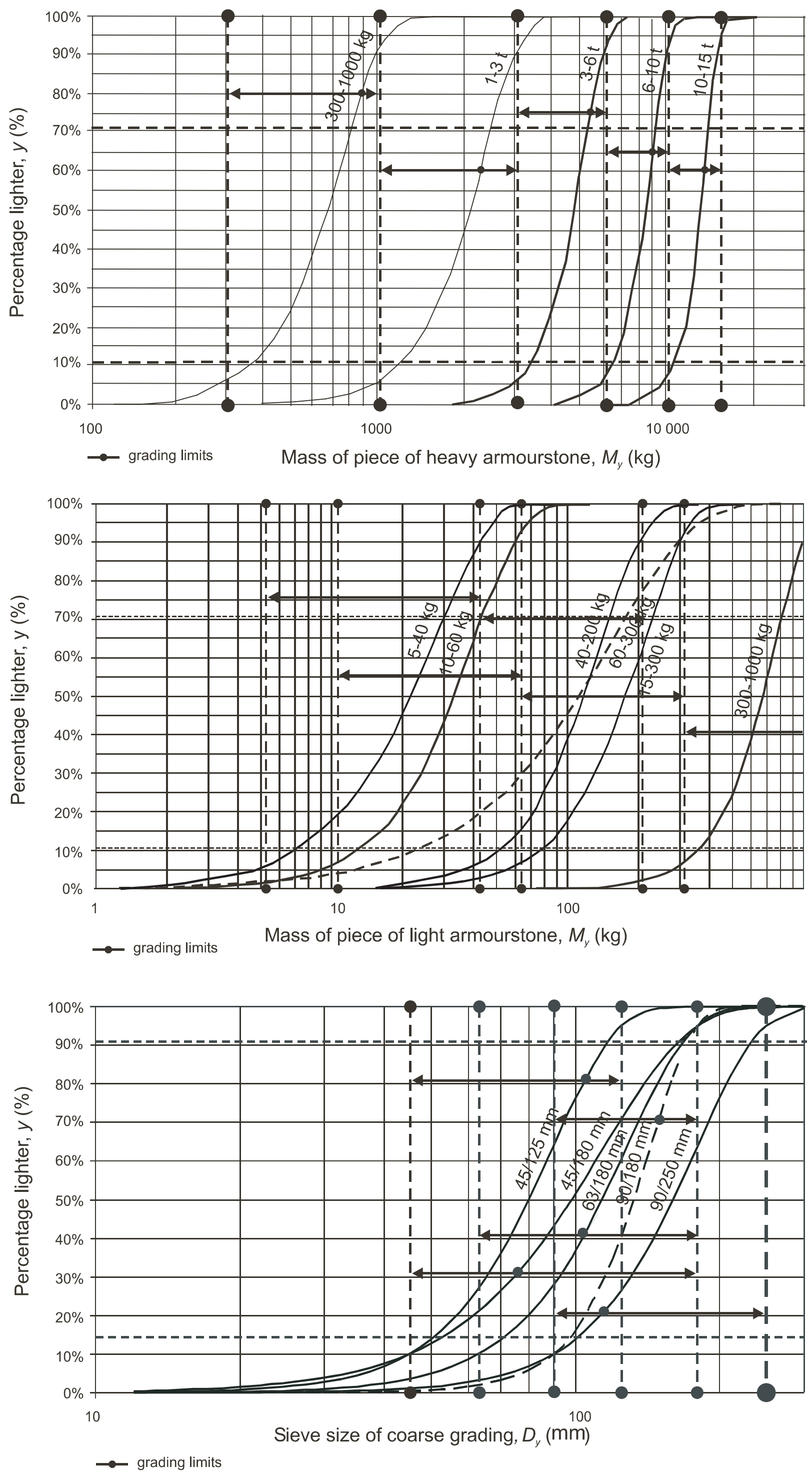



**Figure 3.20** *Illustration of all EN 13383 standard grading curves using idealised Rosin-Rammler curves designed to conform optimally to all EN 13383 grading requirements*

As heavy gradings are selected by eye, it is not difficult to define and produce them in a non-standard way. Instead of having to select either 1–3 t or 3–6 t, a 2–4 t grading could be chosen if it was considered that the 1–3 t grading would be too light and specifying the safer 3–6 t range would involve an excessive layer thickness (although there would be fewer blocks to place). For temporary dedicated quarries supplying single projects, where maximised utilisation of the blasted rock is the guiding principle, standard gradings are less essential. The following practical constraints apply to the production of gradings and the specifier should always consider the cost implication, particularly for dedicated quarries:

- a producer cannot produce *overlap gradings* of say, 1–3 t, 2–5 t and 3–6 t by any efficient means, as the mass distributions overlap excessively (see also Section 3.9)
- a producer cannot afford to supply *gap gradings*, such as 10–60 kg together with 300–1000 kg, if there is no demand for the 60–300 kg material that will also be created (see also Section 3.9).

### 3.4.3.3 *Rosin-Rammler curves for mass and size distributions and idealised gradings*

This section on Rosin-Rammler curves is included:

- to help interpolate between limits of standard gradings and generate complete graphical curves (see examples given in Figure 3.20)
- to explain theoretical gradings of core materials (see Section 3.4.4)
- to predict *in situ* block size distributions (see Section 3.9.2) and quarry yields (see Section 3.9.4)
- to help match demands for materials with predicted quarry yields (see Section 3.9.5).

**Derivation of an idealised grading curve**

If the $M_{50}$ is given together with a measure of the grading width, eg NUL/NLL as given by a standard grading designation, or by $M_{85}/M_{15}$, theory enables a unique idealised curve to be drawn for each standard grading. To be able to derive, plot and see the grading curve of the expected product when specifying or purchasing a standard grading, in addition to knowing the requirement limits, is a useful tool for designers, contractors and producers.

**Theory**

The basic form of the typical curve shape is the Rosin-Rammler (Ros-Ram) equation given by:

$$y = 1 - \exp\left\{\ln\left(\frac{1}{2}\right)\left(\frac{M_y}{M_{50}}\right)^{n_{RRM}}\right\} \cong 1 - \exp\left\{-0.693\left(\frac{M_y}{M_{50}}\right)^{n_{RRM}}\right\} \qquad (3.12)$$

or its inverse:

$$M_y = M_{50}\left\{\frac{\ln(1-y)}{\ln\left(\frac{1}{2}\right)}\right\}^{1/n_{RRM}} \cong M_{50}\left\{\frac{-\ln(1-y)}{0.693}\right\}^{1/n_{RRM}} \qquad (3.13)$$

where $y$ is the fraction passing value; $M_y$, is the mass corresponding to that value using a percentage subscript to express that fraction, and $n_{RRM}$ the uniformity index, being a measure for the steepness of the grading curve (see Equation 3.15).

As well as providing idealised standard gradings, the Ros-Ram curve shape can be fitted to give a useful representation of most sets of grading data measured during production and processing in the quarry, including core materials. To produce a good fit to real data, numerical regression or other methods are used to select $M_{50}$ and the uniformity index $n_{RRM}$. The Ros-Ram equation is the most universally applicable of several possible two-constant models for cumulative mass or size distribution. It is always possible to find real data for which Ros-Ram is not a good fit.

The Ros-Ram form can be used for distributions of size (using $D$ to replace $M$ in Equation 3.12). Two uniformity coefficients, $n_{RRD}$ and $n_{RRM}$, are therefore often used, where $n_{RRD}$ =

$3n_{RRM}$. This relationship between uniformity indices of mass and size is valid for nominal diameter, equivalent sphere diameter and can also be considered valid for sieve sizes. If a graded material is represented by Equation 3.12 using masses, it may also be represented by its equivalent Ros-Ram equation using nominal sizes. Masses may be converted into sizes in term of nominal diameter $D_n$ or sieve diameter $D$, which should not be confused. Conversion of masses to sizes is achieved by dividing by density to give volume, the cube root of which gives the nominal diameter $D_n$. To plot particle size obtained as $D_n$ in terms of sieve diameter $D$, divide by 0.84.

**Relating theory to NUL/NLL**

Given any two fixed points on the Rosin-Rammler curve, $M_{50}$ and $n_{RRM}$ can be determined. For example, if the nominal lower limit mass of a grading is NLL and the fraction passing at that value is $y_{NLL}$, and similarly the nominal upper limit mass is NUL and the fraction passing at that value is $y_{NUL}$, then by solving the following two equations:

$$M_{50} \cong NLL\left(\frac{\ln(1-y_{NLL})}{-0.693}\right)^{-1/n_{RRM}} \qquad M_{50} \cong NLL\left(\frac{\ln(1-y_{NUL})}{-0.693}\right)^{-1/n_{RRM}} \tag{3.14}$$

to give

$$n_{RRM} = \log\left(\frac{\ln(1-y_{NUL})}{\ln(1-y_{NLL})}\right) \Big/ \log(NUL/NLL) \tag{3.15}$$

the full curve described by Equation 3.12 is given.

**How the idealised standard grading curves are obtained**

The position and steepness of each idealised standard grading curve is set up not only to comply with the limit requirements, but also to lie in the middle of the range of compliant specifications for that grading. Standard EN gradings (eg 1000–3000 kg) impose requirements such that $y$ lies between 0 and 10 per cent passing at NLL (1000 kg) and between 70 and 100 per cent at NUL (3000 kg). To define each idealised grading curve uniquely and keep the system simple, each standard heavy and light grading has been constrained using Equation 3.15 at the same two percentage passing points on the curve for each pair of NLL and NUL values designated in the EN 13383 standards. The values chosen are $y_{NLL}$ = 6 per cent and $y_{NUL}$ = 90 per cent respectively. Theoretically, these values give designers maximum reassurance that the $M_{50}$ plotted lies near 0.5 (NLL+NUL). The more obvious first choice of 5 per cent and 85 per cent would lead the wider idealised standard grading curves to miss 0.5 (NLL+NUL) by an unacceptable degree. The values chosen minimise these differences to within 10 per cent of the target for the full suite of standard heavy and light gradings. The only exception is the special wide grading of 15–300 kg, where $M_{50}$ is 26 per cent lower than the average of the nominal limits. For a more typical example such as the 1000–3000 kg grading, the idealised curve gives $M_{50}$ = 2.08 t, ie within 4 per cent of 0.5(NLL+NUL). For further details see Latham *et al* (2006).

**Plotting grading curves using Rosin-Rammler**

Substitute a series of mass values $M_y$ into Equation 3.12. This will return the series of fraction passing $y$ values needed to complete the plot. Before doing so, first set the $n_{RRM}$ and $M_{50}$ values needed in Equation 3.12. To plot any heavy or light standard grading designated with NUL and NLL, calculate the uniformity index $n_{RRM}$ using Equation 3.15 with $y_{NLL}$ = 0.06, $y_{NUL}$ = 0.90. To obtain $M_{50}$, substitute $n_{RRM}$ using either the NLL or NUL form of Equation 3.14. The resulting idealised grading curves are presented in Figure 3.20. These summarise the expectations of a purchaser of standard gradings.

### 3.4.3.4 Graphical illustration of EN 13383 standard grading curves

To see the difference between different standard gradings as graphs plotted in this manual, theory based on the Rosin-Rammler equation has been used. Idealised curves (Figure 3.20) defined by each standard grading pair of NUL and NLL, (see Table 3.5), show the degree of overlap (to allow for undersize and for oversize in the grading) and the changes in grading steepness for the families of heavy, light and coarse standard gradings. The figures show, at a glance, the approximate values that might be anticipated anywhere along the grading curve, for any standard grading that has been specified. The idealised approximation becomes less reliable at the more extreme ends of the grading curve.

**NOTE:** For the optimal curve idealisation, $y_{NLL}$ and $y_{NUL}$ are set at 6 per cent and 90 per cent respectively for light and heavy gradings, and at 10 per cent and 95 per cent for coarse gradings.

### 3.4.3.5 Fragments and effective mean mass, $M_{em}$

In the European grading system, *fragments* is a technical term for stones below the ELL. Some fragments from crushed corners etc always exist however small their percentage of the total mass. By excluding fragments from the total mass of a sample of stones, it is possible to obtain a meaningful average mass simply by bulk weighing and counting all the stones. This is termed the effective mean mass, $M_{em}$, of the sample and it provides a rapid method of grading control. In the EU standard, it is referred to as "**the average mass of the sample heavier than a fragment**". For cover layer applications, the range of $M_{em}$ will normally be specified. Producers are required to keep $M_{em}$ within this specified range rather than applying controls on $M_{50}$ directly. The minimum and maximum allowable $M_{em}$ (ie lower limit and upper limit of effective mean mass) are given the symbols $M_{emll}$ and $M_{emul}$. Guidance on conversion between $M_{em}$ and $M_{50}$ is given in Table 3.6 and Section 3.4.3.8.

### 3.4.3.6 Requirements and compliance of EN 13383 standard gradings

The exact requirements that define the range of masses users can expect from a heavy or light standard grading or a coarse standard grading defined by sieve size, are set out in Table 3.6. Note NLL and NUL, for **coarse gradings** are set at 15 per cent and 90 per cent passing while the ELL and EUL are set at 5 per cent and 98 per cent passing. The exceptionally narrow 90/180 mm grading is intended for gabions. The 45/180 mm grading is relatively wider than the others. In addition to the limit requirements for coarse gradings, there is a need to constrain the median size further. A minimum value is therefore imposed on $D_{50}$.

Examples of non-compliance are illustrated in Figure 3.21, which shows test results producing failing and passing curves according to the combination of limit requirements and $M_{em}$ requirements of EN 13383, together with the idealised Ros-Ram grading curve for 3–6 t.

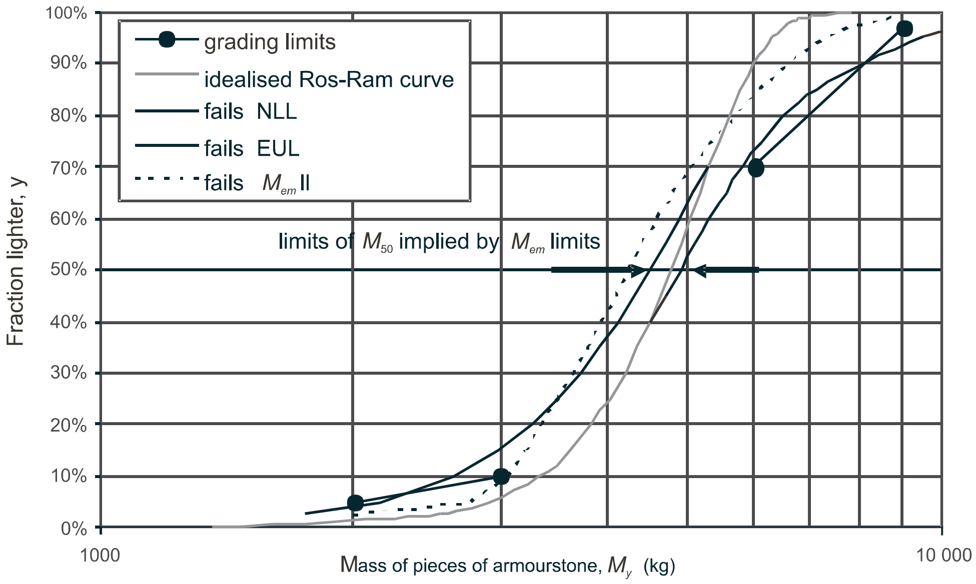



**Figure 3.21** *Illustration of compliance and non-compliance with the grading system requirements for a 3–6 t standard grading*

### 3.4.3.7 Additional information on EN 13383 standard gradings

Designers require information on the range of $M_{50}$, especially the minimum $M_{50}$ that they may reasonably expect when specifying a given NLL-NUL designated heavy or light grading. To provide this information it is necessary to understand the relationship between $M_{em}$ and $M_{50}$ as explained in Section 3.4.3.8 and the additional information given in Table 3.6, column (b).

The designer is concerned with the minimum and maximum $M_{50}$ that can be expected given compliance with the $M_{emll}$ and $M_{emul}$ limits. These are given in columns (c) and (d) of Table 3.6.

**Example**: the designer should be prudent in specifying a standard 1–3 t grading when his design requires a minimum $M_{50}$ value of 2.3 t; an actual $M_{50}$ value of 1.87 t can be expected (see column (c) of Table 3.6) while still complying with the requirements of the standard grading. Alternatively, he may select a non-standard grading of eg 2–4 t, see Section 3.4.3.9.

Table 3.6 also presents similar information on the five standard coarse gradings. When a standard coarse grading is specified, the designer may choose to determine stability on the basis of a $D_{n50}$ value calculated from $D_{50}$ ($D_{n50} = 0.84D_{50}$) specified in Table 3.6, column (b). This is a conservative approach since in most cases the delivered material will have a greater $D_{50}$.

**NOTE:** The coarse gradings may be grouped as three gradings of similar width or three gradings with differing width.

Grading width indicators and Ros-Ram uniformity coefficients can also be compared for all gradings in Table 3.6.

**Table 3.6** *Additional information on standard gradings*

| | a | b | c | d | e | f |
|---|---|---|---|---|---|---|
| | kg | $M_{50}/M_{em}$ (Equation 3.18) | $M_{50min}$ = $M_{emll}$ × (b) kg | $M_{50max}$ = $M_{emul}$ × (b) kg | Ideal $n_{RRM}$ | Ideal $n_{RRD}$ |
| Light and heavy | 10 000–15 000 | 1.002 | 12000 | 13000 | 8.92 | 26.76 |
| | 6000–10 000 | 1.024 | 7680 | 8710 | 7.08 | 21.24 |
| | 3000–6000 | 1.054 | 4430 | 5060 | 5.22 | 15.65 |
| | 1000–3000 | 1.099 | 1870 | 2310 | 3.29 | 9.88 |
| | 300–1000 | 1.163 | 628 | 802 | 3.00 | 9.01 |
| | 60–300 | 1.243 | 162 | 236 | 2.25 | 6.74 |
| | 10–60 | 1.352 | 27 | 47 | 2.02 | 6.06 |
| | 40–200 | 1.269 | 101 | 152 | 2.25 | 6.74 |
| | 5–40 | 1.386 | 14 | 28 | 1.74 | 5.22 |
| | 15–300*) | 1.570 | 70 | 211 | 1.21 | 3.62 |

| | a | b | c | d |
|---|---|---|---|---|
| | mm | $D_{50}$ = 0.5 (*NLL* + *NUL*) mm | Ideal $n_{RRM}$ | Ideal $n_{RRD}$ |
| Coarse | 45/125 | 85 | 1.09 | 3.28 |
| | 63/180 | 122 | 1.06 | 3.19 |
| | 90/250 | 170 | 1.09 | 3.28 |
| | 45/180** | 113 | 0.80 | 2.41 |
| | 90/180*** | 135 | 1.61 | 4.83 |

**Notes**

* the 15–300 kg grading is exceptionally wide and values of $M_{50max}$ and $M_{50min}$ are presented that use Equation 3.16 rather than Equation 3.18; ** wide coarse grading; *** gabion grading.

### 3.4.3.8 Relationship between $M_{em}$ and $M_{50}$, and grading widths including practical experience

**Approximate relationship for any grading width**

The values of $M_{50}$ and $M_{em}$ were measured on numerous projects across a range of standard heavy and light gradings identical to those in EN 13383. Since $M_{85}/M_{15}$ can be estimated with reasonable confidence, Equation 3.16 shown in Figure 3.22 based on field project data can be used to estimate $M_{50}/M_{em}$ for any grading. Alternatively, using a direct theoretical relationship between $M_{85}/M_{15}$ and *NUL*/*NLL* for idealised curves, the relationship can also be summarised using Equation 3.17, which enables immediate estimates of $M_{50}/M_{em}$ from contract specification.

$$M_{50}/M_{em} = 0.860\,(M_{85}/M_{15})^{0.296} \tag{3.16}$$

$$M_{50}/M_{em} = 0.860\,(NUL/NLL)^{0.201} \tag{3.17}$$

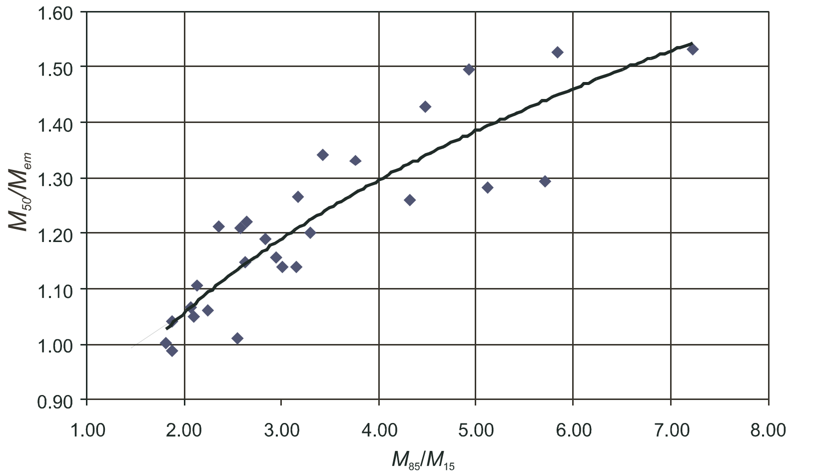



**Figure 3.22** *$M_{50}/M_{em}$ as a function of the grading width, $M_{85}/M_{15}$, measured from field project data (see Equation 3.16) (on the basis of invesigations carried out by J A van Meulen)*

**Recommended relationship for standard gradings**

Standard light and heavy gradings of EN 13383 were designed to become systematically wider with decreasing $M_{50}$. This fact has been harnessed to develop a prediction Equation 3.18 **applicable only to standard gradings**. It combines empirical data with theoretically derived results.

$$M_{50}/M_{em} = 1.61\ M_{50}^{-0.05} \tag{3.18}$$

It is important to note that a better prediction of $M_{50}/M_{em}$ is to be expected using Equation 3.16 than Equation 3.18 for those cases where gradings are uncharacteristically wide or narrow for the given $M_{50}$ such as may occur for certain non-standard gradings.

### 3.4.3.9 *Non-standard gradings*

The cost-effectiveness of using standard gradings versus non-standard gradings should always be evaluated. Standard gradings should be used whenever possible unless the armourstone is being supplied by a dedicated quarry. The restriction on standard sieve dimensions and screens that are manufactured means that credible non-standard coarse gradings are few, although alternative grading requirements to the 90/180 mm could be devised, eg for gabions.

**NOTE:** Reference is made in the following sections to Category A gradings when requirements on $M_{em}$ apply and Category B gradings when there is no control on $M_{em}$. Category A gradings are normally to be used for cover layers, as these gradings have a control on the average mass. Category B gradings are not intended for use in cover layers (see Section 3.7.1 for further information).

**Mass or size distribution similar to standard gradings – simple approach**

A simple approach consists of determining non-standard gradings using the average characteristics of all the standard gradings. This approach is applicable to **Category B** heavy, light and coarse standard gradings by only calculating extreme limits from user-defined nominal limits as follows:

- set NUL and NLL to the desired values where the design $M_{50}$ or $D_{n50}$ will be close to the mean of NUL and NLL, ie $M_{50} \cong 0.5$ (NUL+NLL). Note the gradation should be kept reasonable and that the ratio NUL/NLL should not be taken too small as this may lead to difficulties for production. The precise ratios should be adjusted by careful consideration of standard gradings of similar width

- set ELL = 0.7 NLL and EUL = 1.5 NUL. It is assumed that no further constraints will be required for the effective mean mass or for maximum $D_{n50}$ in such a non-standard grading specification and that if the grading is to be specified or declared with reference to EN 13383, it would be of Category B status unless a more detailed approach is adopted
- assign the class limits ELL, NLL, NUL, EUL for the gradings family concerned (coarse, light and heavy) to definitions based on 5, 10, 70 and 97 per cent respectively.

If an equivalent non-standard grading of **Category A** is to be declared or specified with reference to EN 13383, the average mass (excluding fragments) should be bounded between:

- a lower limit $M_{emll}$ = 0.8 (NLL + NUL)/2
- an upper limit $M_{emul}$ = (NLL + NUL)/2

**Mass distribution similar to standard gradings for Category A specification – detailed approach for light and heavy gradings**

The simple approach can be improved upon considerably as there is a number of relationships that will generally hold for all the standard mass gradings (except 15–300 kg) and any new non-standard ones with similar grading widths. The width of a standard grading can be characterised by NUL/NLL, $M_{85}/M_{15}$ or $n_{RRM}$. Any non-standard grading likely to be practical to produce in the quarry and have a similar potential application to the existing standard gradings can have their **specification limit masses**, $Y$ (kg), derived relative to $M_{50}$ (kg) using coefficients presented in Table 3.7. They are related by the power law:

$$Y = AM_{50}^{B} \qquad (3.19)$$

where A and B are coefficients (see Table 3.7).

These requirement values will need to be further adjusted and rounded at the discretion of the specifier, to generate credible limit masses for quality control.

**Table 3.7** *Coefficients suggested for non-standard grading requirements for the specification or declaration of gradings with similar properties to standard gradings*

| All mass values in kg | | Specification | | | | | | Additional information | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ELL < 5%/ <2%* | NLL <10% | NUL >70% | EUL >97% | $M_{emll}$ min $M_{em}$ | $M_{emul}$ max $M_{em}$ | $M_{15}$ | $M_{85}$ | $M_{50}$ min | $M_{50}$ max |
| factor *A* | | 0.027 | 0.156 | 2.520 | 5.160 | 0.449 | 1.060 | 0.160 | 3.340 | 0.663 | 1.515 |
| factor *B* | | 1.32 | 1.160 | 0.920 | 0.880 | 1.080 | 0.990 | 1.171 | 0.918 | 1.041 | 0.959 |
| eg for a standard grading | | | | | | | | | | | |
| $M_{50}$ =35 kg | calculated | 2.9 | 9.6 | 66.4 | 117.9 | 20.9 | 35.8 | 10.3 | 87.2 | 26.9 | 45.9 |
| | rounded | 3 | 10 | 65 | 120 | 20 | 35 | 10 | 90 | 27 | 45 |
| eg for a non-standard grading similar to a standard grading | | | | | | | | | | | |
| $M_{50}$ = 3000 kg | calculated | 1050 | 1685 | 3984 | 5923 | 2556 | 2935 | 1893 | 5180 | 2768 | 3279 |
| | rounded | 1000 | 1700 | 4000 | 6000 | 2500 | 3000 | 1900 | 5200 | 2750 | 3250 |

**Note**

* for a light grading (NLL <300 kg) the mass indicated is limited to 2%, otherwise the limit is <5%.

**Size distribution similar to standard gradings for Category A specification – detailed approach for coarse gradings**

The first three coarse gradings shown in Table 3.5 have ratios characterised by the following:

$ELL/D_{50} = 0.28$ $NLL/D_{50} = 0.56$ $D_{50min}/D_{50} = 0.79$ $NUL/D_{50} = 1.57$ $EUL/D_{50} = 2.24$

For any user-defined $D_{50}$, all appropriate limits can be obtained and rounded to available screen sizes.

**Mass distribution not similar to standard gradings for Category B – graphical method**

If a given design $M_{50}$ requires specification of a non-standard grading wider (easier to produce) or narrower (more difficult to produce) than the equivalent nearest standard grading, the suggested limit requirements in Table 3.7 should be disregarded in favour of limits governed directly by the grading width chosen. Once the user has set the desired NUL and NLL masses, the following graphical method, which assumes a log-linear form to the grading curve, can be used:

- using a log scale for mass and a linear scale for percentage passing, plot the NUL mass point at 70 per cent passing and the NLL mass point at 10 per cent passing
- join the two points with a straight line and interpolate to find the $M_{50}$ value
- linearly extrapolate to read off mass values at 2 per cent (if light gradings) or 5 per cent (if heavy gradings) to obtain ELL. Similarly, read off mass values at 97 per cent to obtain EUL.

**Designating a non-standard grading**

The EN 13383 gives specifications for a number of standard gradings with both Category A and Category B status, but a producer may wish to declare other gradings for sale. Provided the grading on offer can be tested for conformance using EN 13383 test methods, this is perfectly acceptable within EN 13383 rules, but it must be declared using a labelling system compatible with terms used for EN 13383 gradings: "$HM_A$ declared *NLL-NUL*; extreme limits: *ELL-EUL*; effective mean mass: $M_{emll}$-$M_{emul}$. For example: a 2–4 t grading would be declared by inserting the correct figures in place of the italics, eg using guidance from Table 3.7:

"$HM_A$ declared 2000–4000; extreme limits: 1050–5900; effective mean mass: 2500–3000".

A designer wishing to specify limits different to the standard limits in Table 3.5 (Tables 1 to 5 of EN 13383-1:2002) would designate their requirements in a similar way. Note that the prefix letters $HM_A$, $HM_B$, $LM_A$, $LM_B$ and *CP* are used to distinguish heavy mass, light mass and coarse size gradings respectively, where the subscript A refers to Category A, which imposes the $M_{em}$ restriction, while for Category B it is omitted.

## 3.4.4 Core materials

Core materials are generally used for volume-filling. As such, they do not have requirements for a characteristic size such as $M_{50}$. The top size is generally indicated and bottom sizes may be controlled. The geotechnical properties required for core materials, typically shear strength, placed porosity and permeability are identified in Section 5.4. These geotechnical properties are greatly influenced by the width of the grading and most notably, the content of fines. The fine material content is closely related to the tail of the quarry yield curve and the fines removal technique. An approach for the prediction of porosity suitable for core materials is given in Section 3.4.4.3.

### 3.4.4.1 Core materials terminology

Certain terms in general use indicate the degree to which the grading of natural quarry product in the blast is modified by processing. Core materials with no fines control are termed "**quarry run**", "**tout venant**" (as used in England) or "**brut d'abbatage**" (as used in France). They include all granular material found in the quarry blast-pile that can be picked up in a typical loading shovel. Essentially, stones too large for easy digging and loading are left behind.

**"Crusher run"** includes everything passing through the primary crusher. The top size is restricted by crusher aperture settings.

**"All-in"** includes everything passing through a spacing of a grizzly or a screen aperture. All these materials have an unknown proportion of material below a nominal reference mass indicating fines, say below 1 kg. For use in the core of structures, the possible occurrence of significant proportions of fine material, especially if they contain clays, is of concern as this may be washed away during construction and/or reduce shear strength, leaving the structure more prone to geotechnical instability.

**"Processed core materials"** have been processed for fines removal. The use of grizzlies and other fines-removal methods may introduce profound changes in the grading curve shape and the uniformity parameter describing the gradation width. These materials, while still retaining very wide gradations, may be more costly to produce. The removal or inclusion of fine material, such as that below 1 kg, affects the packing density of material dumped as core. The limit value, such as 1 kg, is typically a notional value. Usually all that is required is demonstration that effective procedures are in place for removal of fine particles. It should be noted that permeability of the core can be greatly enhanced by removal of fines.

### 3.4.4.2 Core materials in a design context

In many cases where material is to be used for volume-filling, the decision whether to specify no fines removed (quarry run) or alternative core materials with fines removed, is difficult as there is a lack of guidance on the subject. The optimal specification requires an understanding of the performance of the differing types of core materials, key parameters often being the porosity or the risk of damage to the structure through piping or internal erosion. For example, in a harbour breakwater, especially where wave transmission is to be limited, the decision to set the fines cut-off at, say, 10 kg, 1 kg or at no cut-off may need consideration of:

- core porosity and, indirectly, permeability
- percentage utilisation of quarry yield if materials are coming from a dedicated quarry
- instability because of clay minerals in the fines
- shear strength and liquefaction potential.

The effectiveness of quarry procedures for limiting smaller particles also deserves consideration (see Section 3.9.5).

1 2 3 4 5 6 7 8 9 10

By considering the uniformity coefficient $n_{RRD}$ of the materials in question and their particle shape, geotechnically significant estimates of the porosity and total mass of material can be given. The procedure for porosity estimation using Tsirel's equation (1997) is described in Section 3.4.4.3. An example is then given in Box 3.6 of how a quarry yield grading curve may be modified, eg by a particular fines removal process in the quarry, from one Rosin-Rammler curve to another steeper one; the consequent changes in bulk porosity can be evaluated using an equation developed by Tsirel (1997). Removal of fines significantly increases porosity and permeability, so where it is desired to reduce wave transmission (as is the case for most breakwaters) it should only be necessary to remove fines if geotechnical design factors make it necessary.

Porosity prediction of core materials is also extremely important for the calculation of material tonnage requirements from the quarry.

### 3.4.4.3 *Calculating the porosity of bulk-placed materials*

The formulae and guidance given in this section can be applied to all bulk-placed granular materials including cover layers, underlayers, filters and core. It provides a prediction of average porosity for different gradings and different characteristic shapes.

The porosity of bulk-placed materials, $n_v$ (-), may be predicted using Equation 3.20 (angles in degrees) adapted from Tsirel (1997) and Equation 3.21:

$$e = \frac{1}{90}\left(e_o\right)\arctan\left(0.645 n_{RRD}\right) \tag{3.20}$$

$$n_v = \frac{e}{1+e} \tag{3.21}$$

where $e$ is the void ratio given by the volume of voids divided by the volume of solids (-) and $e_o$ is the void ratio associated with single-size particles of different shapes (-), as given in Table 3.8.

For any standard or non-standard grading, it is possible to obtain $n_{RRD}$ (see Tables 3.6 and 3.7 and Section 3.4.3.3) and then to estimate $e_o$ (from Table 3.8). Once $e$ has been obtained, the bulk-placed (void) porosity, $n_v$, can be calculated, using Equation 3.21.

**Table 3.8** *Coefficients for porosity prediction using Equation 3.20*

| Shape of fragments | Cube-like | Elongated | Flat | Typical mechanically crushed | Smooth sand and pebbles | Steel balls |
|---|---|---|---|---|---|---|
| Single-size void ratio, $e_o$ | 0.88–0.92 | 0.93–0.96 | 1.00–1.03 | 0.92–0.96 | 0.65–0.80 | 0.52–0.61 |

**Caution**. Equation 3.20 was derived from rock fragments packing experiments in many quarries. It has not been widely applied in hydraulic engineering but is likely to be an improvement on previously available rules of thumb that give wide ranges of possibilities for porosity. The equation suggests there is no absolute size influence on bulk-placed porosity. In practice, the typical $D_{50}$ for the material and the manner of dumping may also affect porosity. This is because smaller materials more easily retain angularity and are of larger aspect ratio. An empirical relationship to quantify this effect for $M_{50}$ (kg) is:

$$LT = 2.31\, M_{50}^{\,-0.02} \tag{3.22}$$

where $LT$ is the length-to-thickness ratio (see Section 3.4.1.1).

Note also that smaller materials with low abrasion resistance will become more rounded during bulk handling. There is evidence to suggest that the above equation of Tsirel, which was calibrated primarily for dumped materials, and Figure 3.23 may tend to overestimate the porosity for dumped standard armourstone gradings if the uniformity coefficient, $n_{RRD}$, is greater than about 5 and where relatively thin layers are considered. Furthermore, Tsirel's empirical relationship was not calibrated for the case of dumping or tipping through a water column.

Various published predictions of porosity of bulk-placed materials are given in Latham *et al* (2002a). Predictions based on Equations 3.20 and 3.21 and Table 3.8 are given in Figure 3.23, where equivalent values of average *LT* (= *l*/*d*, see Section 3.4.1.1) and descriptive shape terms corresponding to Tsirel's shape classes are suggested.

Example calculations on the change in porosity due to fines removal and oversize cut-off are given in Box 3.6.

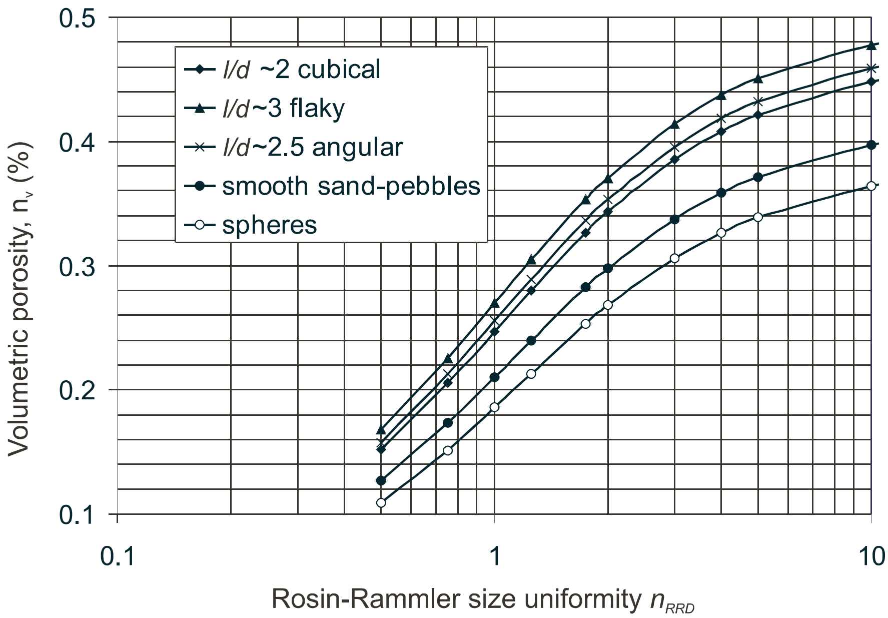



**Figure 3.23** *Bulk-placed (void) porosity, $n_v$ as a function of shape and uniformity in sizes*

**Box 3.6** *Example calculation of changes in bulk porosity resulting from fines cut-off and oversize removal using the Tsirel and Rosin-Rammler equations*

The effect on porosity of removing fines below 100 mm (mass ~ 1.5 kg) and oversize stones greater than 1 m (mass ~ 1.5 t) may be calculated as follows (see also Figure 3.24):

Characterise the Ros-Ram distribution of the quarry blast pile as, eg, $D_{50}$ = 300 mm, $n_{RRD}$ = 0.9. For very efficient quarry processing, set NLL of 100 mm with $y_{NLL}$ at 0.03 (or 0.06 for less efficiency) and NUL of 1000 mm with $y_{NUL}$ at 0.97 (or 0.90 for less efficiency) to represent the fines cut-off and oversize removal efficiency and recalculate uniformity $n_{RRD}$ and $D_{50}$ using (the Rosin-Rammler) Equations 3.14 and 3.15 (see Section 3.4.3.3). The processed core materials then have $D_{50}$ = 455 mm, $n_{RRD}$ = 2.06. Assuming the quarry run has angular shape, the bulk porosity of the quarry run is about 0.24 (using Equations 3.20 and 3.21) and that of the processed core material about 0.36. There is a significant impact on permeability in the core and volume of blasted rock left behind in the quarry. Limited documented experience from contractors suggests quarry run dumped in the sea may have porosity of around 36 per cent and with fines removal, about 40 per cent, which suggests the Ros-Ram plus Tsirel equation approach to porosity prediction illustrated above should be used with caution when applied to materials dumped through water.

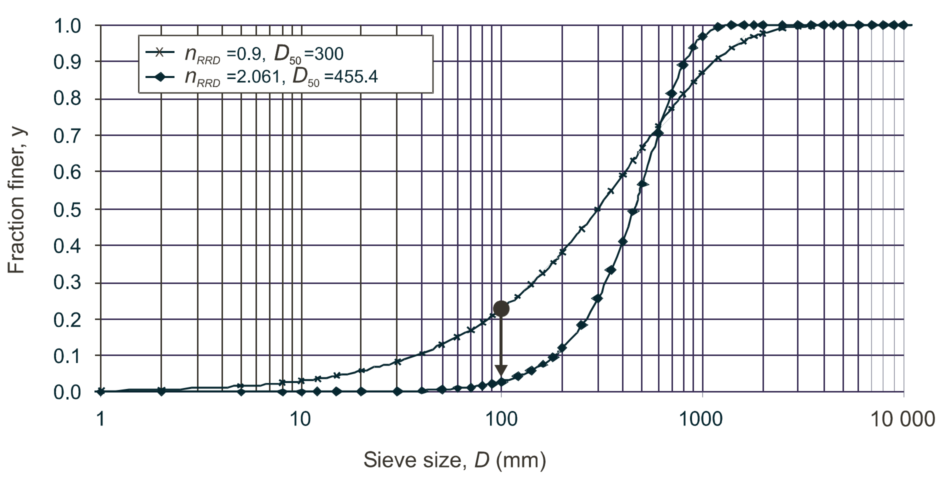



**Figure 3.24** *Illustration of change in size distribution resulting from fines removal below 1 kg and limiting of oversize blocks*

## 3.5 QUARRIED ROCK – CONSTRUCTION-INDUCED PROPERTIES

Thicknesses of cover layers, filter layers and underlayers including rip-rap that are bulk-placed or dumped and raked to profile, are set by design criteria. The designer sets the thickness to be a given proportion of a certain characteristic size of the grading in question, typically as a function of $D_{n50}$ . Guidance on mass-to-volume conversions in such thin layers is rarely given because of unpredictable boundary effects, but for bulk-filling operations porosity is described in the context of core materials in Section 3.4.4.

For layers designed to be built as single or double layers using individually placed pieces, eg from heavy gradings, guidance for layer thicknesses and porosities is given in Section 3.5.1.

In addition to particle geometry, a key property affecting thicknesses, packing and volume-filling relationships is the rock density itself. As rock density also affects hydraulic stability, the consequences to the designer of using material with different density is addressed in Section 3.5.2.

### 3.5.1 Layer thickness and porosity of individually placed armourstone

Geometric information on armourstone as a granular material both for bulk-filling and in layered systems is essential for estimating quantities for design and for billing purposes as well as for predicting hydraulic properties. Details are given in Gauss and Latham (1995), Latham *et al* (2002b) and Stewart *et al* (2003). To enable prediction of volume-filling properties, the type of placements assigned to granular materials in the works, are classified as:

- random placement
- standard placement
- dense placement
- specific placement.

These terms are described in detail in Section 9.8.1. All bulk-placed materials are designated random placement, whereas any type may be appropriate for stones placed individually into armour layers. In principle, for armour layers, there are two distinct calculations adopted to obtain bulk volumes (ie rock volume, $V_r$ (m³), plus void volume) in a panel. $V_{b,d}$ (m³) is the design bulk volume assumed before construction and $V_{b,s}$ (m³) the surveyed bulk volume after construction. $V_b$ (m³) is the bulk volume referring to either method. By following guidance in Boxes 3.7 and 3.8 their differences should be minimised. The Equations 3.23–3.28 (see also Figure 3.25) define the geometry and related properties of armour layers.

Designed bulk volume (m³): $$V_{b,d} = A\, t_d \tag{3.23}$$

Surveyed bulk volume (m³): $$V_{b,s} = A_{cs}\, L \tag{3.24}$$

Theoretical orthogonal thickness (m): $$t_d = n\, k_t\, D_{n50} \tag{3.25}$$

Volume of rock (m³): $$V_r = V_b\, (1\text{-}n_v) \tag{3.26}$$

Total number of stones in panel (-): $$N_a = n\, A\, k_t\, (1\text{-}n_v)/D_{n50}^2 \tag{3.27}$$

Bulk (or placed packing) density (t/m³): $$\rho_b = (1\text{-}n_v)\, \rho_{app} \tag{3.28}$$

where:

| | | |
|---|---|---|
| $A$ | = | total surface area (m²) of the armour layer panel parallel to the local slope |
| $A_{cs}$ | = | cross-sectional area (m²) |
| $L$ | = | panel chainage length (m) |
| $n$ | = | number of layers (-) |
| $n_v$ | = | (volumetric) layer porosity (-) |
| $k_t$ | = | layer thickness coefficient (-) |
| $\rho_{app}$ | = | apparent density of the armourstone (t/m³) (see Section 3.3.3). |

**NOTE:** The volume of rock, $V_r$, should not be confused with the volume of armourstone, which is $V_b$. The only practical possible use of $V_r$ is as an input to determine the mass of rock, $\rho_{app}$ $M_r = \rho_{app} \times V_r$ which is also the total mass of armourstone.

The placed packing density or **bulk density**, $\rho_b$ (t/m³), can be predicted from Equation 3.28 or, if the mass of armour placed into a panel is known, it may be determined directly from the surveyed bulk volume. When dealing with wider gradings, a better prediction for the number of blocks, $N_a$ (-), will result if $D_{n50}$ in Equation 3.27 is replaced by the nominal size calculated from the average mass, $M_{em}$ .

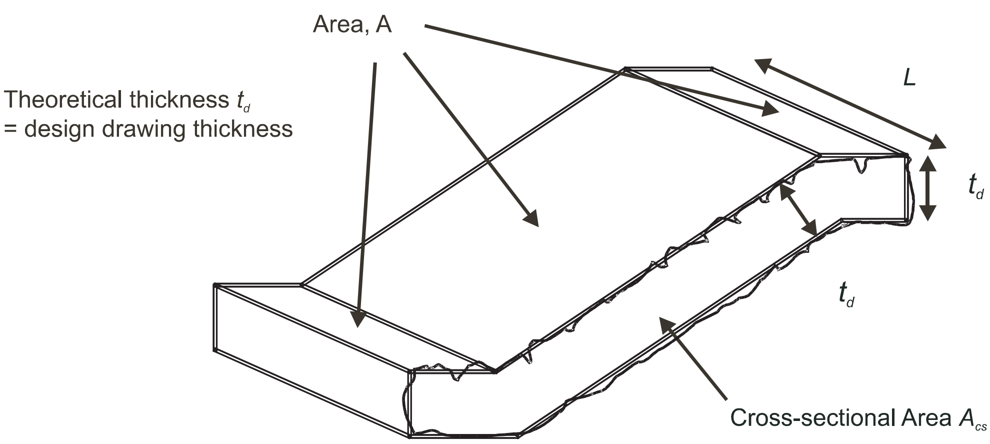



**Figure 3.25** *Armour layer geometry*

The terms *void ratio* and *porosity* are well established for granular materials. However, in Equation 3.26 $n_v$ is termed the *void porosity* of the armour layer, or simply *volumetric armour layer porosity* to avoid confusion with the term *porosity* as applied to a specimen of intact rock (see Section 3.3.3). Furthermore, when using the terms *armour layer porosity* or *void porosity*, the user must be aware that the values depend on the method of surveying the bounding volume.

**NOTE:** The armour layer porosity is calculated as an average property for the whole panel being surveyed. This contrasts with suggested relationships presented by Bosma *et al* (2003), who describe the layer porosity as a spatially varying property. The relationships they propose are more applicable to dumped armourstone. These also have the potential to define local changes in the average proportion of void space in armour layers near transitions, for example where armour abuts concrete seawalls or between successive underlayers.

#### 3.5.1.1 Importance of layer thickness coefficient $k_t$ and porosity $n_v$

Designers and contractors must assume a layer thickness, $t_d$ (m), to prepare drawings and estimate the bulk volume $V_{b,d}$ (m³), eg for preparing materials procurement tonnage details. For individually placed armourstone in single or double layers, this is obtained from Equation 3.25 (with $n = 2$ for a double layer), which in turn requires appropriate values for the layer thickness coefficient, $k_t$ (-), and the median nominal stone size, $D_{n50}$ (m). Equation 3.26 converts the bulk volume, $V_b$ (m³), to rock volume, $V_r$ (m³), using an appropriate value for the armour layer porosity, $n_v$.

In addition to preparing rock volume requirements, estimation of armour layer porosity assists in the prediction of armour layer stability (see Section 5.2.2.2).

Both $k_t$ and $n_v$ can vary considerably. Recent research strongly suggests that more accurate predictions are achieved when blockiness has been used together with length-to-thickness ratio to characterise armour shape. An important finding is that porosity and layer thickness coefficients are lower than suggested in previous guideline documents such as CEM (USACE, 2003). General guidance for standard and dense placement is provided in Table 3.9, illustrating a more blocky armour and a less blocky or irregular armour, defined by the shape descriptor blockiness, *BLc*, for an assumed most typical mean value of the length-to-thickness ratio, $LT = 2$ (see Section 3.4.1.1). Stones with higher mean *LT* values tend to form more porous and thinner layers. Stones with lower mean *LT* values tend to form less porous thicker layers. For double layers with random placement, values for porosity and layer thickness coefficient suggested for standard placement may be assumed, although porosity values will typically range from 0 to 2 per cent higher than for standard placement. The porosity of bulk-placed materials can be predicted using methods that specifically account for the width of grading and aspects of shape; see Section 3.4.4.3.

**Table 3.9** *General guidance for layer thickness coefficient and porosity for various armour layers, placement methods (Section 9.6), and survey methods (Section 9.9)*

| Layer and placement type | Parameter | Reference (spherical foot staff) survey method | | Highest point survey method | |
|---|---|---|---|---|---|
| | | Blocky rock eg mean *BLc* = 0.65 | Irregular rock eg mean *BLc* = 0.50 | Blocky rock eg mean *BLc* = 0.65 | Irregular rock eg mean *BLc* =0.50 |
| Single dense | $k_t$ , $k_{thp}$ | 0.84 | 0.77 | 0.89 | 0.82 |
| Single dense | $n_v$ , $n_{vhp}$ (%) | 32 | 35 | 36 | 40 |
| Double standard | $k_t$ , $k_{thp}$ | 0.91 | 0.87 | 0.96 | 0.92 |
| Double standard | $n_v$ , $n_{vhp}$ (%) | 32 | 35 | 36 | 40 |
| Double dense | $k_t$ , $k_{thp}$ | 0.91 | 0.87 | 0.96 | 0.92 |
| Double dense | $n_v$ , $n_{vhp}$ (%) | 31 | 32 | 35 | 36 |

**Notes**

*BLc* = Blockiness (see Section 3.4.1.2).
Guide values based upon assumption of mean length to thickness ratio *LT* = 2.0, and deduced from research study of Stewart *et al*, 2003.
The subscript "hp" refers to highest point survey method (see Section 9.9).

Guidance presented in Box 3.7 for the standard, controlled method of individual placement of armourstone further illustrates the blockiness concept. Photographs of measured model armour layers (Figure 3.26) and full-scale armour layers (see Stewart *et al*, 2003) show the sensitivity of packing to block shape. These test panels emphasise the importance of matching model armour shape and placement methods used in laboratories to those at full scale, whenever potentially tighter placement procedures are in operation. Full-scale test data that illustrate the wide range of possible values for $k_t$ and $n_v$ (and $\rho_b$), are presented in Table 3.10 (see also Box 9.3).

**Figure 3.26** *Models illustrating shape effects with standard placement on 1:2 slope. Top: $BLc_{mean}$ = 75%, $LT_{mean}$ = 2.4, $n_v$ = 34%, $k_t$ = 0.87. Bottom: $BLc_{mean}$ = 46%, $LT_{mean}$ = 2.0, $n_v$ = 39%, $k_t$ = 0.85*

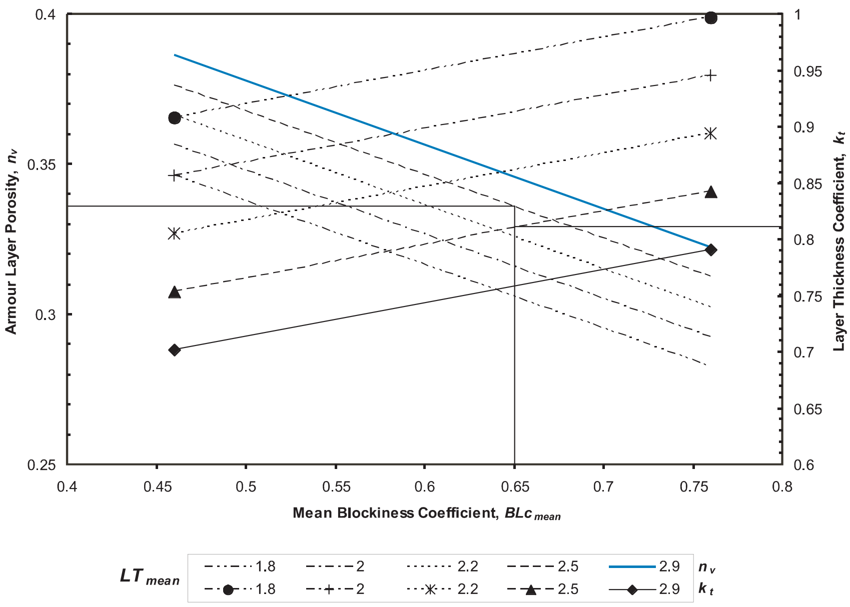
**Table 3.10** *Examples of as-constructed layer thickness and bulk (or placed packing) density properties obtained from full-scale structures surveyed using the $0.5D_{n50}$ spherical probe method*

| Layer and placement type | Parameter | Test location and armourstone grading (t) | | | | |
|---|---|---|---|---|---|---|
| | | Shoreham | Bardon Hill | Immingham | Torr Works | Reculver |
| | | 8–12 | 3–6 | 0.5 | 3–6 | 1–3 |
| Single | $k_t$ (-) | 0.71 | 0.80 | 1.03 | 0.82 | - |
| | $\rho_b$ (t/m³) | 1.90 | 1.84 | 1.63 | 1.79 | – |
| | $n_v$ (%) | 30.0 | 34.3 | 40.0 | 34.8 | – |
| Double standard | $k_t$ (-) | 0.77 | 0.88 | 0.92 | 0.91 | 0.94 |
| | $\rho_b$ (t/m³) | 1.89 | 1.89 | 1.65 | 1.85 | 1.77 |
| | $n_v$ (%) | 30.1 | 32.8 | 39.2 | 32.9 | 34.4 |
| Double dense | $k_t$ (-) | 0.76 | 0.86 | – | 0.92 | – |
| | $\rho_b$ (t/m³) | 1.96 | 1.93 | – | 1.86 | – |
| | $n_v$ (%) | 27.6 | 30.9 | – | 32.5 | – |

Figure 3.27 provides guidance for estimating the layer thickness coefficient $k_t$ (-), and armour layer porosity, $n_v$ (%), for armour stones placed above water, where placement can be controlled. It is based on the **reference survey method**, which uses a spherical-bottomed probe of $0.5D_{n50}$ for surveying. While such a survey method cannot be employed in practice in all situations, guidance based on a reference method is required. This guidance can then be put into practice for more commonly adopted survey methods such as the highest-point method as presented in Section 9.9.8.1, where surveying technique corrections to $k_t$ and $n_v$ are explained.

The empirically derived prediction chart in Figure 3.27 for double layers is applicable to 1:2 slopes using controlled placement termed *standard placement*, as discussed in Section 9.8.1.1. In Figure 3.27 an example with $BLc_{mean}$ = 0.65 and $LT_{mean}$ = 2.5 gives $k_t$ = 0.81 and $n_v$ = 0.335.

More general guidance can be found using the equations given in Box 3.7. Comparison of predicted and measured armour layer porosity is given in Box 3.8.




**Note**

Curves are given to predict armour layer porosity, $n_v$, and layer thickness, $k_t$, for a range of values of $d/l_{mean}$ – this is the inverse of the the length-to-thickness ratio, $LT$ (see Section 3.4.1.1); the blockiness coefficient, $BLc$, on the horizontal axis is defined in Section 3.4.1.2.

**Figure 3.27** *Prediction chart for $n_v$ and $k_t$ of individually placed armourstone in double layers, standard placement*

**Box 3.7** *Guidance on layer porosity (packing) and layer thickness for armourstone individually placed above water*

The guidance in this box is based upon extensive study of armour packing (Newberry, 2003; Stewart *et al*, 2003), which examined the dependency of layer (void) porosity, $n_v$, and layer thickness coefficient, $k_t$, on method of placement, stone shape and definition of the surface. Nineteen full-scale test panels were compared with models, and it was found that scale effects on armour layer geometry were negligible, provided shapes were matched. Ninety-one model revetments were built (see Figure 3.26) to investigate the effect on $n_v$ and $k_t$ of *LT*, *BLc*, standard and dense placement methods, slope angles, single and double layers – all for very narrow size ranges associated with standard heavy armourstone gradings. Border and survey effects were compensated for by using reference methods at laboratory and field scale.

Multivariate linear regression analysis was used to develop the following predictive equations:

$$n_v = A + B\ BLc_{mean} + C/LT_{mean} \quad (3.29)$$

$$k_t = A + B\ BLc_{mean} + C/LT_{mean} \quad (3.30)$$

Mean values of *BLc* and *LT* were used as the governing variables for assessing $n_v$ and $k_t$ values.

Small improvements in the prediction given in the chart in Figure 3.27 can be made when the standard deviations and range of block masses are also included in the regression equations. Substitution of the regression coefficients from Table 3.11 into Equations 3.29 and 3.30 will provide guidance on single- and double-layer geometric parameters for 1:2 slopes when **placed with standard placement**. Steeper slopes generate marginally tighter layers.

To calculate variation of armour layer porosity for **dense placement**, the value calculated as $\Delta n_v$ using Equation 3.31 is to be added to $n_v$ obtained from Equation 3.29, resulting in a slight reduction.

$$\Delta n_v = A + B\ BLc_{mean} + C/LT_{mean} \quad (3.31)$$

**Table 3.11** *Coefficients for determining porosity, $n_v$, and layer thickness coefficient, $k_t$, for a 1:2 slope, using Equations 3.29–3.31*

| Layer type | Parameter | *A* | *B* | *C* |
|---|---|---|---|---|
| Single | $n_v$ | 0.59 | -0.24 | -0.22 |
| Single | $k_t$ | 0.01 | 0.48 | 1.04 |
| Double | $n_v$ | 0.55 | -0.21 | -0.20 |
| Double | $k_t$ | 0.21 | 0.30 | 1.03 |
| Double | $\Delta n_v$ | -0.11 | 0.10 | 0.08 |

Layer thickness can be derived from Equation 3.25 and placed packing (or bulk) density from Equation 3.28 (see Section 3.5.1). Values of void porosity and layer thickness calculated using the methods given in Equations 3.29–3.31 may be used as input.

**Box 3.8** *Predicted versus measured layer porosity*

The 90 per cent confidence limits for $n_v$ are ±2.4 per cent porosity and ±3.7 per cent porosity for double and single layers respectively, and for $k_t$ they are 0.01 and 0.11 for double and single layers respectively; see Stewart *et al* (2003) for further discussion. The quality of fit is shown in Figure 3.28. Both standard and dense placements (see definitions in Section 9.8.1.1) refer to individually placed blocks. Dense placement usually reduces the porosity by about 2–4 per cent compared with standard placement. Materials that are bulk-placed vary considerably in their width of gradation and this has a greater impact on porosity than the range of shapes as shown in Section 3.4.4.3. For further details of layer thickness and porosity prediction including values for other slopes, see Stewart *et al* (2003).

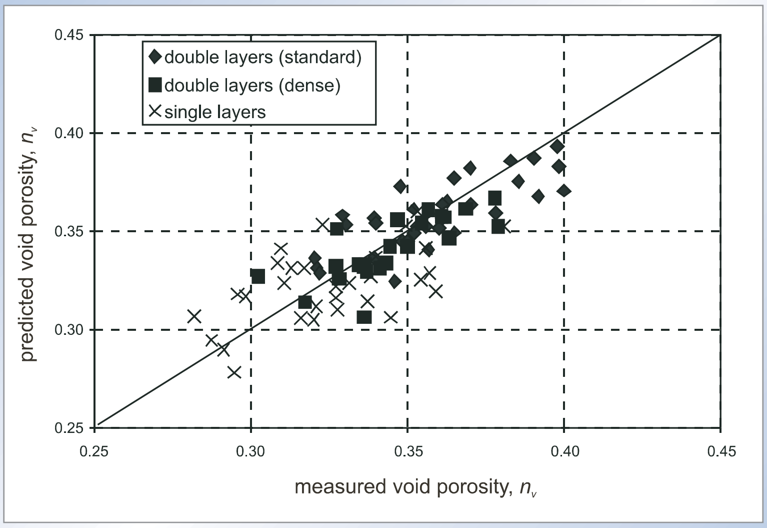



**Figure 3.28** *Predicted versus measured layer porosity, $n_v$, using Equations 3.29 – 3.31 and empirical coefficients*

## 3.5.2 Effect of rock density on design parameters

Where available, rock of alternative mass density to that assumed in the initial design may be considered for possible use in a project. Typically mass densities of up to 3.5 t/m³ can be obtained for dense rocks such as eclogite, and higher, eg > 4 t/m³, for manufactured armourstone obtained from recycled copper and steel slags. For an increase in density, an unchanged design gives a lower stability number $N_s = H_s/(\Delta D_{n50})$ and hence greater stability through an increase in $\Delta D_{n50}$ (m), where $\Delta$ is the relative buoyant density (-) (see Sections 5.2.1 and 5.2.2). The effect of water absorption can be significant and is discussed in Section 3.3.3, Box 3.5.

The designer may also wish to examine the various effects of substituting rock of alternative density $\rho_{app,alt}$ that achieves the same hydraulic stability (ie a constant value of the stability number, $N_s = H_s/(\Delta D_{n50})$ as the initial design density $\rho_{app,d}$. For identical stability, using subscripts "*d*" and "*alt*" for initial design mass density terms and alternative mass density terms respectively, graphs have been plotted using the Equations 3.32 and 3.33 for the median mass $M_{50}$ and the total mass of the armourstone $M_t$ respectively.

$$M_{50,alt}/M_{50,d} = (\rho_{app,alt}/\rho_{app,d})/(\Delta_{alt}/\Delta_d)^3 \qquad (3.32)$$

$$M_{t,alt}/M_{t,d} = (\rho_{app,alt}/\rho_{app,d})/(\Delta_{alt}/\Delta_d) \qquad (3.33)$$

The equations have been used to generate the contour plots of multiplication factors given in Figure 3.29, for both freshwater and seawater applications.

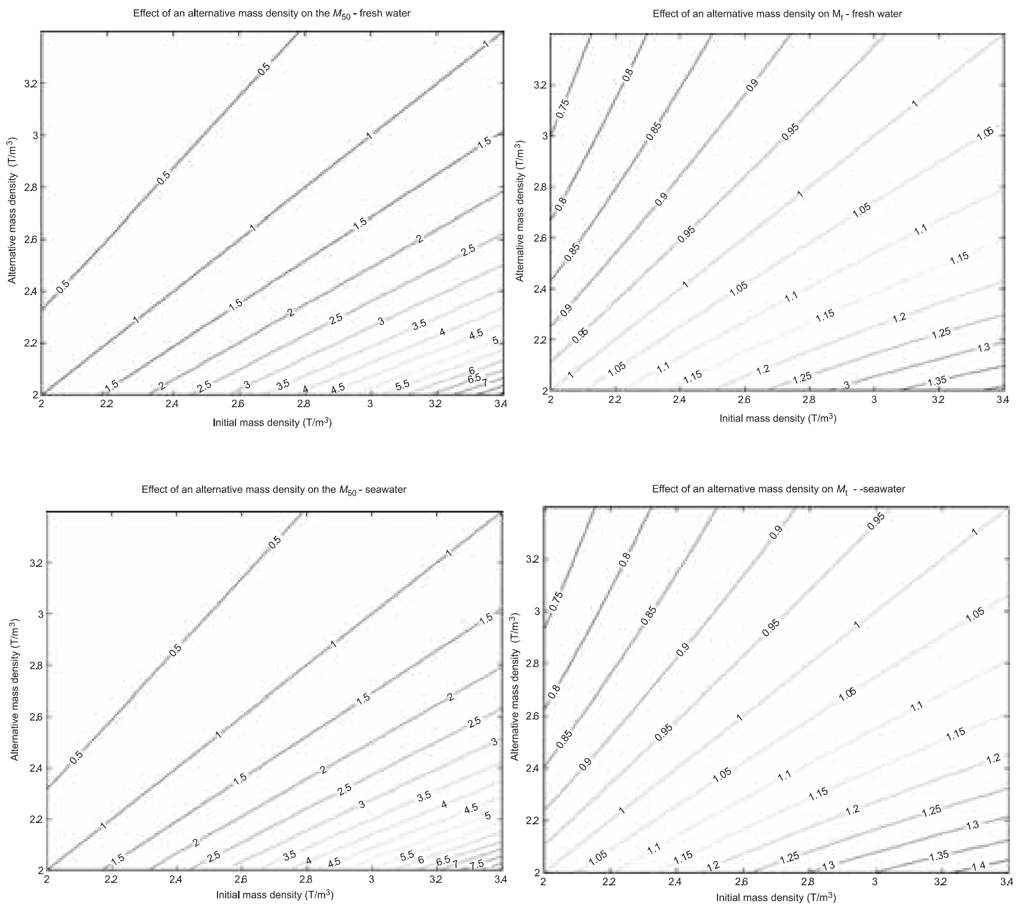



**Figure 3.29** *Contour plots of multiplication factors for change in density. Top: Fresh water, $\rho_w$ = 1.0 t/m³; bottom: Seawater, $\rho_w$ = 1.025 t/m³*

For identical stability, the multiplication factor for the total number of armourstone blocks, $N_a$ (for a narrow grading where $M_{50} \cong M_{em}$), is proportional to the factor $\Delta^2$, see Equation 3.34, while for armour layer thickness, $t_a$, the factor is proportional to the factor $1/\Delta$, see Equation 3.35.

$$N_{a,alt}/N_{a,d} = (\Delta_{alt}/\Delta_d)^2 \tag{3.34}$$

$$t_{a,alt}/t_{a,d} = \Delta_d/\Delta_{alt} \tag{3.35}$$

In summary, for the same hydraulic stability, substituting rock of greater density allows a smaller armour block size, reduced total mass in armour layer, reduced layer thickness and an increased number of units to place (possibly increasing the placing time).

If there are no design changes, an increased density will give increased stability and possibly increased durability. An advantage of using less dense material for core arises from its greater volume per unit weight of material transported to site, since it is the bulk volume making up the design levels that is attractive provided that the geotechnical properties are satisfactory.

**Box 3.9** *Influence of change of density on median mass, $M_{50}$, and total armourstone quantity, $M_t$*

**Example:** A project considers the use of 10 000 t of armourstone with $M_{50,d}$ = 8 t, with an initial design mass density of $\rho_{app,d}$ = 2.6 t/m³. An alternative source with a rock mass density of $\rho_{app,alt}$ = 2.3 t/m³ is locally available. The multiplication factor (= the right-hand side of Equation 3.32) is 1.65 (see Figure 3.29 top) and the alternative $M_{50}$ value (see Equation 3.32) is then: $M_{50,alt}$ = 1.65 × 8 t = 13.2 t.

Similarly, using Equation 3.33, the total amount of armourstone material is determined to be:

$M_{t,alt}$ = 1.09 × 10 000 t = 10 900 t

# 3.6 ROCK QUALITY, DURABILITY AND SERVICE-LIFE PREDICTION

## 3.6.1 Introduction

The information contained here (Section 3.6) is for consideration prior to specification (Section 3.7). The differences in possible demands on the performance of armourstone from one aggressive application to another mild one are substantial. Without knowledge of site conditions and the design application it is therefore not always possible to be confident from test results alone whether the rock materials will be either suitable or unsuitable. Degradation models can be used to take these differences into account and in some cases will suggest unacceptably rapid losses in performance. Fortunately, there are still many mitigating strategies (eg over-dimensioning, high maintenance etc; see Section 3.1.3) available to the design team, before finally preparing the material specification.

A key tool for the engineer in this manual is a multi-purpose and generalised look-up table of intrinsic properties (see Table 3.12). Each property is classified into bands **indicative** of excellent, good, marginal or poor armourstone durability considering all conceivable rock types and quarry sources. Such a classification is independent of design and site conditions, and therefore cannot provide categorical assurances for suitability or service life outcomes. Each attribute (each row in Table 3.12) has a direct or indirect consequence for the resistance to a particular type of loading that may or may not actually be present for the application. For the same application, relative outcomes for different rock sources can be inferred from the classes. In this relative sense, the four classes given for each specific attribute or property have the following tentative interpretation.

**Excellent** – ideal and sometimes available. This material, with reference to this specific attribute, can be used without any risk of degradation with time over a typical design life.

**Good** – better than average. In normal situations, no specific attention need be paid to this attribute. It will generally not lead to any significant degradation, although it may show progressive signs of degradation over a typical design life in certain circumstances.

**Marginal** – lower than average. Without specific attention, the attribute may lead to significant degradation. It should be studied. If necessary, production, construction or design should be adapted (see Section 3.1.3.1) by using appropriate blasting techniques (see Section 3.9), increased quality control (see Section 3.10) or by oversizing armourstone size using appropriate prediction of the degradation (see Section 3.6.4), for example. This may be associated with short periods where loss of performance is more severe.

**Poor** – much lower than average. If possible, the material should not be used where exposure may affect the attribute and lead to rapid degradation. If it is used, specific attention should be paid, as for *marginal* attributes. However, a specific survey of the structure will generally be required and heavy maintenance may be necessary.

Using such classes for specification purposes without paying due regard for the application is not recommended. For the designer or contractor to evaluate optimised solutions, it is important to specify a good match of materials requirements with the degradation conditions on site. To achieve such a match requires systematic approaches that take account of:

- key factors in the quarry and the rock material itself
- project site variables
- a model to help quantify the effect of degradation factors active at the structure site.

Prediction of degradation and damage with time can facilitate the use of whole-life cycle approaches, with further potential added benefits to the environment.

**NOTE:** Rock degradation prediction is by its nature inexact and burdened with difficult judgements. This section of the manual provides systematic methodologies for degradation prediction. Further validation and refinement of these recently proposed degradation models, eg by back analysis of case histories is required. However, the tools described do reduce the amount of guesswork that would otherwise be involved, especially in cases where less than ideal armourstone has to be used.

Section 3.6.2 introduces the concept of durability, modes of degradation in different parts of a structure and symptoms of rock that may have poor durability. Section 3.6.3 provides a system for assigning, in numerical terms, the overall armourstone quality designation, termed *AQD,* of a source, using quarry evaluation criteria as well as laboratory test results. The principles common to all degradation models are described in Section 3.6.4. Full details of a general degradation model and its application are presented in Section 3.6.5. Degradation specifically caused by breakages is treated in Section 3.6.6.

## 3.6.2 Durability and degradation

The durability of armourstone on a given project is quantified by the rate of loss of material performance (such as reduction of mean mass or interlock) attributable to changes in armourstone property in engineering time. This means that poor-quality materials exhibiting low resistance to weathering may stand up well in mild energy environments, with low exposure to climatic conditions, where degradation forces are virtually non-existent, for example in the permanently submerged part of the core of an impermeable breakwater.

Degradation processes can be broadly classified as wear, fracture and pervasive disintegration, see Lutton and Erikson (1992), Fookes and Poole (1981). These depend on the position of armourstone in the structure.

- In the **armour layer**, armourstone may be exposed to weathering such as freeze and thaw, salt crystallisation, wetting and drying, temperature cycling when above water. Dissolution below water is rarely significant. For coastal structures, the intertidal zone is the area most vulnerable to such physico-chemical effects. In permanently submerged armour layers, effects are negligible. For structures designed to adjust dynamically, impacts from armour stones may lead to breakage, attrition and greater overall wear. For these structures, the resistance to the forces induced by rocking or rolling is important. The main performance requirement is to minimise any decrease in $M_{50}$. Prediction of $M_{50}$ reduction is therefore sought by demand-based designers wishing to set quality requirements high enough, or by supply-led designers wishing to build in degradation-compensating measures within the design philosophy.
- In the **underlayer**, armourstone is exposed to weathering effects to a lesser degree than the armour layer. The main concern is that degradation may lead to breach of filter rules.
- **Core** material is less exposed to weathering agents, so the consequences are likely to be less critical. **Dissolution** may take place below water or be induced by intermittent water circulation above water level. This may lead to voids and reduction of the bearing capacity. The solubility is highly dependent on the water chemistry as well as mineral content and rock porosity. For example, most types of limestone will not dissolve in the chemical environment of most sea waters but will dissolve slowly in acidic fresh water.

1 2 3 4 5 6 7 8 9 10

**Indicators of possible poor durability**

Petrography, mass density, porosity, mineral fabric strength, armourstone production method and discontinuity pattern in the quarry, provide a good indication of relative durability when comparing sources. For any durability concerns, appropriate testing should be performed. Magoon and Baird (1991), McElroy and Lienhart (1993) and Latham (1992) are recommended sources for further details.

- **Petrographic examination**, based on visual observation or thin sections, generally provides a first evaluation of durability. Weathered rocks, breccias and conglomerates are most susceptible to displaying poor durability when exposed to salt or freeze action. Specific attention should be paid to schists, phyllites, chalk and marls, to rock containing clay minerals or with weak cements. Some geologically recent sources of basalt are known to display a specific weathering degradation mechanism known as "sonnenbrand". Rock containing pyrite minerals have been observed to display early breakage caused by oxidation of pyrite under water and heat action.
- **Water absorption (*WA*)** is a good indicator of in-service durability. Armourstone with a low *WA*, less than 0.5–1 per cent, will display a good resistance to severe cycling stresses such as salt crystallisation or freeze and thaw. For significantly higher values of *WA*, appropriate accelerated weathering tests should be performed to evaluate concerns about resistance to weathering of the rock. If taken in isolation, *WA* can be misleading, since rocks with *WA* greater than 4 per cent may have a free-draining pore structure and thus perform well in service for certain applications. A high proportion of microporosity as a percentage of the absolute porosity is detrimental. Rock that is porous but free draining is less prone to breakdown by freeze-thaw action and salt crystallisation. In the USA, the Mississippian-age Salem Limestone (Indiana Limestone) and Berea Sandstone both have absorptions exceeding 6 per cent. Both have been used in breakwaters on the Great Lakes where weathering intensities are extreme ($MCWI > 300$, see Table 3.15). The Salem Limestone in the Chicago Breakwater is still performing satisfactorily after 80 years. The Berea Sandstone in the Cleveland Breakwater is still in good condition after almost 100 years.
- Rock with **mass density** lower than 2.3 $t/m^3$ is considered to have unacceptable durability for normal use. For rock of low density and high water absorption, the low resistance to weathering is sometimes less of a problem than the low resistance to breakage.

Armourstone characteristics were introduced in Sections 3.2–3.5. Predicting the future response of armourstone with given characteristics in the quarry, under the wide range of possible lifetime loadings remains a subject in need of further research. Presented below are guidance tables and modelling tools that may be useful in the process of evaluating the quarry source, the site aggressiveness and the service-life of the armourstone.

## 3.6.3 Procedure for source evaluation of armourstone quality

**Assessment of the attributes affecting quality of the rock source**

Table 3.12 provides a summary of the most significant quality-related intrinsic attributes of a source of armourstone, based on field and laboratory data. The table has three uses:

- to provide a guide to four classes of quality for each attribute that affect the global relative durability
- to provide numerical input data for an overall rating system for comparing armourstone sources
- to provide data needed for the application of a degradation model.

The criteria recommended in the table are adapted from Lienhart (1998), established practice, and in some instances are specifically adjusted to maintain compatibility with the category settings in EN 13383 and recent experience.

When using Table 3.12, it must not be assumed that these rock types have the results shown in the columns below where mentioned. In addition, the following points should be considered.

- the table draws on quantitative and semi-quantitative assessment criteria. It is not designed for specification purposes
- requirement categories for specific tests that have been selected for specification purposes in EN 13383 and other national standards may be set with fewer than four categories and at different values to the above guide
- national guidance for setting specifications often prefers fewer categories and higher test performance levels, for simplicity and conservatism
- the guidance offered in this table is intended for detailed semi-quantitative general durability evaluation with an option to determine overall quality of a source in terms of the armourstone quality designation AQD, using the system in Table 3.13. It is therefore important to provide an appropriately sensitive rating, four classes being considered reasonable
- the range of test results in one quality class may not correlate with the range of results of another test in the same quality class (eg tensile and compressive strength values).

**Table 3.12** *Guide to quality and durability of armourstone from a quarry source using field and laboratory criteria*

| | Quality and durability guide (not intended for specification purposes) | | | | | |
|---|---|---|---|---|---|---|
| | **Criteria** | **Reference** | **Excellent** | **Good** | **Marginal** | **Poor** |
| Field evaluation in the quarry | Lithological classification | EN 932-3 | Unfoliated igneous and metamorphic rocks, quartzites and high silica cement sandstones, compact crystalline limestones | Crystalline dolomites, crystalline limestone and moderately well cemented sandstones | Argillaceous limestones, poorly cemented sandstones, dolomite reef rock with void cavities | Shaly limestones, reef breccia, shale, siltstone, slate, schist, chalk, gypsiferous carbonates |
| | Regional *in situ* stress | Lienhart (1998) | Low stress, no folds, no faults | Medium stress, unloading features may be present | High stress. Release fractures parallel to face may be present | Very high stress. Faults may be present in quarry face. Rock bursts may be present in floor |
| | Weathering grade | BS 5930:1999 | IA – fresh, unweathered | IB – faintly weathered (staining on major surfaces) | II – slightly weathered (staining persists through a greater part of the rock mass) | III – moderately weathered (less than half the rock mass is decomposed) |
| | Discontinuity analysis (IBSD) | Wang *et al* (1990) | $D_{i80}$ > 2 m **** | $D_{i80}$ = 1.5–2.0 m **** | $D_{i80}$ = 1.0–1.5 m **** | $D_{i80}$ < 1.0 m **** |
| | Groundwater condition | Lienhart (1998) | Dry | Moist | Seepage from quarry walls | Water flowing from walls and pooling on floor |
| | Production method | Lienhart (1998) | Non-blasting methods: eg dimension stone quarry production methods | Tailored single row blast, low shock energy, specific charge < 0.2 kg/m³, blast hole diameter ~ 75 mm | Conventional blasting with ANFO, specific charge 0.2–0.4 kg/m³, blast hole diameter ~ 100 mm | Aggregate blasting with large stone as by-product, specific charge > 0.4 kg/m³ |
| | Stone shape and weathering grade | Lienhart (1998) | < 5 per cent of stones have *LT* > 3, 95 per cent of stones are weathering Grade IA, free of unfilled cavities and are extremely high strength | 5–10 per cent of stones have *LT* > 3, 95 per cent of stones are weathering Grade IB or better, dense or free-draining, very high strength | 10–15 per cent of stones have *LT* > 3, 95 per cent of stones are at least weathering Grade II, either micro-porous or with unfilled cavities, high strength | >15 per cent of stones have *LT* > 3, 95 per cent of stones are at least weathering Grade III, argillaceous or micaceous |
| | Set-aside | Lienhart (1998) | Armourstone is stockpiled for three months for curing and release of stress | Armourstone is stockpiled for two months | Armourstone is stockpiled for one month | Freshly extracted armourstone is transported directly to project site for placement |
| | Armourstone integrity (visual) | Lienhart (1998) | > 95 per cent of stones are free of incipient fractures, flaws or cracks due to stress relief, rough handling, overblasting or other causes after two months set-aside in stockpile | 90–95 per cent of stones are fracture free after two months set-aside in stockpile | 85–90 per cent of stones are fracture-free after two months set-aside in stockpile | < 85 per cent of stones are fracture-free after two months set-aside in stockpile |
| | Block integrity (drop test) | See Section 3.8.5 | $I_{M50}$ < 2%<br>$B_n$ < 5% * | $I_{M50}$ = 2–5%<br>$B_n$ = 5–10% * | $I_{M50}$ = 5–15%<br>$B_n$ = 10–35% * | $I_{M50}$ > 15%<br>$B_n$ > 35% * |
| | Block integrity (FSST) | Dupray (2005) see Section 3.8.5 | **NOTE:** FSST is a design tool to assess the effect of the actual integrity of a source. As such, classification of $C_{FSST}$ values should be avoided | | | |
| | Block integrity (sonic velocity: $I_c$ and $D_f$ ) | Tourenq *et al* (1971) | $I_c$ > 80<br>$D_f$ < 20 | $I_c$ = 80–70<br>$D_f$ < 20 | $I_c$ = 70–50<br>$D_f$ < 20 | $I_c$ < 50<br>$D_f$ ≥ 20 |

**Table 3.12** *Guide to quality and durability of armourstone from a quarry source using field and laboratory criteria (contd)*

| | Quality and durability guide (not intended for specification purposes) | | | | | |
|---|---|---|---|---|---|---|
| | Criteria | Reference | Excellent | Good | Marginal | Poor |
| Laboratory Tests | Petrographic evaluation | Trained petrographer | ** | ** | ** | ** |
| | Mass density, $\rho_{rock}$ (t/m³) | EN 13383-2:2002 | > 2.7 | 2.5–2.7 | 2.3–2.5 | < 2.3 |
| | Water absorption (%) | EN 13383-2:2002 | < 0.5 | 0.5–2.0 | 2.0–6.0 | > 6.0 |
| | Microporosity/total porosity (%) | Lienhart (2003) | < 2 | 2–6 | 6–20 | > 20 |
| | Methylene blue adsorption (g/100g) | Verhoef (1992) | < 0.4 | 0.4–0.7 | 0.7–1.0 | 1.0 |
| | Compressive strength (MPa) | EN 1926:1999 | > 120 | 120–80 | 80–60 | < 60 |
| | Schmidt impact index (% rebound) | ISRM (1988) | > 60 | 50–60 | 40–50 | < 40 |
| | Sonic velocity (km/s) | EN 14579:2004 | > 6 | 4.5–6 | 3–4.5 | < 3 |
| | Point load strength (MPa) | ISRM (1985) | > 8 | 4–8 | 1.5–4 | < 1.5 |
| | Fracture toughness (MPa.m$^{1/2}$) | ISRM (1988) | > 1.7 | 1.0–1.7 | 0.6–1.0 | < 0.6 |
| | Indirect tensile (Brazilian) strength (MPa) | ASTM D3967-95a (2004) ISRM (1978) | > 10 | 5–10 | 2–5 | < 2 |
| | Los Angeles (% loss) | EN 1097-2:1998 | < 15 | 15–25 | 25–35 | > 35 |
| | Micro-Deval (% loss) | EN 1097-1:1996 | < 10 | 10–20 | 20–30 | > 30 |
| | $MgSO_4$ soundness (% loss) | EN 1367 | < 2 | 2–10 | 10–30 | > 30 |
| | Freeze-thaw (% loss) | EN 13383-2:2002 | < 0.5 | 0.5–1 | 1.0–2 | > 2 |
| | Sonic velocity reduced by freeze-thaw (% change) *** | Section 3.8.6 | < 5 | 5–15 | 15–30 | > 30 |
| | Wet-dry (% loss) | ASTM D5313-04 | < 0.5 | 0.5–1 | 1.0–2 | > 2 |

**Note**

* breakage rate, $B_n$, may be estimated visually by counting without weighing or derived accurately by weighing, see Section 3.8.5.1

** no criteria established, see Section 3.3.2

*** provisional criteria needing confirmation from further research

**** $D_{i80}$ = 80 per cent passing *in situ* block size.

**Assessment method for overall rating of quality of a rock source**

Table 3.13 shows an example of a completed quality rating assessment worksheet where the use of integer ratings gives maximum and minimum values of 4 Excellent and 1 Poor. The objective is to derive an overall rating for the armourstone source. In this manual, Lienhart's overall rating applicable to quarried rock is termed "Armourstone Quality Designation" (*AQD*).

In this example, column (d) provides six precise weighting values (58, 73 etc). These arise from Lienhart's (1998) detailed research on armourstone for the Great Lakes (USA). Designers working with experienced engineering geologists may prefer to assign alternative weightings for each of the criteria listed separately. For example, keeping to four alternative weighting values for the criteria importance as follows: **essential** = more than 90; **important** = 80–90; **equal** = 70–80; **minor** = 50–70, rounded weighting values could be assigned. In this way, *AQD* values pertinent to a specific application could be developed, but care should be exercised when introducing customised weightings if the *AQD* value is to be used in degradation modelling.

Many different implementations of Lienhart's systems approach are possible depending on the ease of acquiring data. For example, one based entirely on laboratory results using six factors is presented in Lienhart (2003), whereas six quarries with overall ratings of between 2.45 and 3.41, using quarry site and laboratory criteria, were described in Lienhart (1998). The determination of *AQD* is recommended for comparing the overall intrinsic quality of a source of armourstone that will be indicative of durability given similar site applications. The user who understands the basis of the quality criteria, the principles of generating an importance weighting, and the use of parameter rating systems for rock engineering may use it and adapt it to good effect. For example, substituting continuously varying ratings instead of integers within each category would allow greater accuracy and for the range of *AQD* to extend below a value of 1 for a poor source and above 4 for an excellent source. These numerical values of *AQD* can then be used to compare sources. The application of *AQD* for durability prediction modelling is described in Section 3.6.5.

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**Table 3.13** *Example of a completed quality rating assessment worksheet (after Lienhart, 1998)*

| | a | b | | | | c | d | e |
|---|---|---|---|---|---|---|---|---|
| | Criterion | Quality rating | | | | Rating value | Weighting | Weighted rating |
| | | Excellent | Good | Marginal | Poor | | | |
| | | (=4) | (=3) | (=2) | (=1) | Average | % | {(c) × (d)}/ mean of (d) |
| Field-based indicators | Lithological classification | | √ | | | 3 | 58 | 2.12 |
| | Regional *in situ* stress | | | √ | | 2 | 73 | 1378 |
| | Weathering grade | | √ | | | 3 | 73 | 2.67 |
| | Discontinuity analysis | | √ | | | 3 | 95 | 3.48 |
| | Groundwater condition | | | √ | | 2 | 73 | 1.78 |
| | Production method | | | | √ | 1 | 95 | 1.16 |
| | Rock block quality | | | √ | | 2 | 80 | 1.95 |
| | Set-aside | | √ | | | 3 | 73 | 2.67 |
| | Petrographic evaluation | | | √ | | 2 | 95 | 2.32 |
| 1 | Block integrity test | | | | √ | 1.5 | 90 | 1.65 |
| | Block integrity visual | | | √ | | | | |
| 2 | Mass density | | √ | | | 3 | 80 | 2.93 |
| | Water absorption | | √ | | | | | |
| | Microporosity/total porosity | | √ | | | | | |
| | Methylene blue absorption | | √ | | | | | |
| 3 | Compressive strength | | | √ | | 1.67 | 88 | 1.79 |
| | Schmidt impact index | | | √ | | | | |
| | Sonic velocity | | | | √ | | | |
| 4 | Point load strength | | | √ | | 2.67 | 88 | 2.87 |
| | Fracture toughness | | √ | | | | | |
| | Los Angeles | | √ | | | | | |
| 5 | Micro-Deval | | | √ | | 2 | 88 | 2.15 |
| 6 | Freeze-thaw loss | | √ | | | 3.67 | 80 | 3.58 |
| | $MgSO_4$ soundness | √ | | | | | | |
| | Wet-dry loss | √ | | | | | | |
| | | | | | | Sum | 1229 | 34.9 |
| | | | | | | n | 15 | 15 |
| | | | | | | Mean | 81.9 | **2.33** |

**Notes**

1 This sheet includes 15 factors (nine field, six laboratory), hence overall rating or armourstone quality designation (*AQD*) is mean of column (e) based on all 15 factors. If no data are available for one or more factors, *AQD* should be based on the number of included factors. A complete and balanced set of data is ideal.

2 In addition to engineering geology indicators, each boxed grouping of tests 1 to 6, generates one average rating value in column (c) from one or more suggested tests. They refer to 1: resistance to major breakage; 2: mineral fabric physical quality; 3: resistance to minor breakage (compressive); 4: resistance to minor breakage (tensile, dynamic); 5: resistance to wear (shear and attrition); 6: resistance to in-service weathering.

3 Test results and field assessments can be used to generate continuously varying ratings from 0.5 to 4.5 rather than integer values. Similarly, *AQD* results can vary from 0.5 to 4.5.

### 3.6.4 Principles of degradation modelling

In simple terms, a degradation model is the application of mechanics consisting of:

- material **properties + loadings** (and boundary conditions) = deformation or damage **response**

  or:

- evolution of material **properties** + history **of loadings applied** = history of damage **response**

  or:

- average material **properties** + average **loading intensity** = average **rate of degradation**.

Degradation models use armourstone **properties** representative of the armourstone consignment at the point of leaving the quarry. This may be measured by a specific material property, such as armourstone integrity or abrasion resistance, or an overall quality index, such as *AQD*.

The model then predicts the **response** to future **loading intensity** of the rock armour with such properties. These may be short-term loads or long-term in-service loads. The model output gives the change in the performance parameter (such as $M_{50}$, or the complete mass distribution) for any number of handling events or storm/flood events or, alternatively, for the number of years in service including the design life of the structure.

The **loading intensity** or **project site aggressiveness** can be assessed in terms of:

- **attrition** loading intensity: a function of waterborne attrition agents, rocking, sliding and rolling loads (affected by stone size, wave energy, mobility in design, interlock due to shape and grading)
- **breakage** loading intensity: a function of rocking and rolling loads (affected by stone size, wave energy, mobility in design, interlock due to shape and grading)
- **physiochemical climatic** loading intensity: a function of zone on structure, meteorological climate, slope angle.

For static armour designs, mass loss is by both fast and imperceptibly slow or subcritical opening of cracks, spalling, rounding and by accelerated loss of interlock from wear. A comprehensively averaged model is currently considered most appropriate in such cases where wear is the dominant mechanism (see Section 3.6.5).

For a dynamic design, attrition and breakage loading intensity will be considerably higher than climatic loading intensity – a breakage model calibrated using armourstone integrity, mineral fabric strength and/or resistance to wear properties may be more useful.

Degradation models focusing specifically on wear mechanisms (Tomassicchio *et al*, 2003) and breakage mechanisms (Tørum and Krogh, 2000; Dupray *et al*, 2003) have also been proposed. Such models consider progressive mass reduction associated with repeated storm events where storm loading exceeds a threshold energy for start of damage, or where armour movement velocity is above a threshold value. Such models attempt to deal with mass loss by specific wear or breakage mechanisms that ignore climatic weathering intensity effects. The fewer the degradation mechanisms considered in a model, the more rigorous the model calibration approaches can be, but the less widely applicable is the model to long-term service life prediction.

Probabilistic methods have been proposed to assess accumulated structural damage (eroded profile area) due to probability of exceedance of the design condition (see Takahashi *et al*, 2003). Such design approaches also require an estimate of the reduction in $M_{50}$ of the armourstone due to rock material degradation. The degradation model tools described here may be tentatively applied to estimate changes in $M_{50}$ for such purposes.

### 3.6.5 In-service degradation models for general wear of armourstone

Two in-service degradation models for general wear of armourstone are outlined below.

**NOTE:** Accuracy is not guaranteed, but it is believed to be better than guesswork.

A brief introduction to the principles of the model and possible suggested improvements based on the work of Lienhart (1998) since its first presentation in 1991 are given here. For practical implementation of the two models, readers may skip directly to Sections 3.6.5.1 and 3.6.5.2.

These general wear models are designed to introduce a systematic approach to the forecasting of progressive degradation of armourstone with time. They are, however, based on the notional assumption that, over the long term, deterioration of armourstone during service life follows the same progressive form as would the mass loss of stone pieces during a laboratory wear test. In practice, mass loss locally or even over a large part of a structure may be episodic and relatively rapid (eg bursts by freeze-thaw, Sonnenbrand, or oxidation of pyrite etc) following long dormant incubation periods. Deterioration measured by mass loss may also begin to accelerate after a critical number of years, whereas the laboratory degradation shows a continuously decelerating degradation trend. Engineering experience and judgement, such as may be obtained following an examination of degradation and stone-rounding processes near the proposed site (eg see Fookes and Thomas, 1986), should always be taken as a primary indicator of service life. The models are no substitute for the expertise of a qualified and experienced engineering geologist's judgement.

With these limitations and provisos, the user is then in a position to incorporate these predictions into the design. The original 1991 model has been considered in several projects in Cartagena, Colombia (Assen, 2000); Brindisi, Italy (Tomassicchio *et al,* 2003); western Canada (Lienhart *et al*, 2002; Lienhart, 2003); Iceland (Tørum, 2003); and the Middle East, to help specify armourstone quality requirements or to improve understanding of maintenance needs in these coastal structures.

The original 1991 model was based on test results using a wet laboratory mill abrasion test with constant abrasive environment applied, which were presented as a plot of fractional mass remaining $M/M_0$ versus laboratory mill time, $t$, in units of 1000 revolutions. The gradient generates an index called the abrasion resistance index, $k_s$ (-), measured as a fraction of mass loss per 1000 revolutions.

The Micro-Deval test, termed here the MDE, is another (standard) mill test for wear resistance by a wet surface grinding action (EN 1097-1:1996). This test value, termed the Micro-Deval value written $M_{DE}$ , is highly correlated with $k_s$ . This test is now the standard wear test for aggregates and is specified for resistance to wear in the armourstone standard EN 13383. Test results needed to apply the model are therefore now widely available for rock used as armourstone. Equation 3.36, which is valid for $M_{DE} < 70$ (Latham, 1998b), is used to relate the abrasion resistance index, $k_s$ , and the Micro-Deval test value, $M_{DE}$ .

Having established the mass loss versus time curve, laboratory time is then converted to years on site using the **equivalent wear time factor**, $X$ (-), which is derived from the product of nine weighted parameter ratings given in Table 3.14 and which accounts for the site aggressiveness.

The model can be implemented in two ways, the MDE method (essentially identical to the 1991 model) and the AQD method. Both assume the long-term pattern of mass loss in service to be progressive and of the same form as a steady abrasion test.

### 3.6.5.1 Micro-Deval (MDE) method

The Micro-Deval method used in the model appears at first to be only relevant to armourstone that degrades by attrition and surface grinding mechanisms. To extend the model to other modes of degradation, the experience of researchers was used to score semi-quantitatively the strength of interactions between factors perceived to be most important for all the principal degradation mechanisms including spalling and fracturing. For an explanation of the coupled terms $X_4$, $X_6$ and $X_9$ where aggressive site factors preferentially weaken armourstone with certain intrinsic properties, see Latham (1991).

**Step 1**

Use Equation 3.36 to convert Micro-Deval $M_{DE}$ test results to $k_s$ values, or use previously published data for the abrasion resistance index, $k_s$ (-), which describes the intrinsic resistance to mass loss by abrasion.

$$k_s = 4.12 \cdot 10^{-5}\, M_{DE}^{1.485} \tag{3.36}$$

**Step 2**

Plot fractional mass remaining $M/M_0$ versus time, $t$ (in units of 1000 mill revolutions), using Equation 3.37 and compare result with the abrasion resistance classification chart, Figure 3.30:

$$M/M_0 = 0.05 \exp(-30 k_s t) + 0.95 \exp(-k_s t) \tag{3.37}$$

where $M$ is the mass remaining after time, $t$, and $M_0$ is the initial mass (kg).

It has been suggested that this double exponential decay plot may be made more representative of the mass loss profile of typical armourstone shapes if the pre-factor 30 in Equation 3.37, governing the initial fast decay, is raised to about 200.

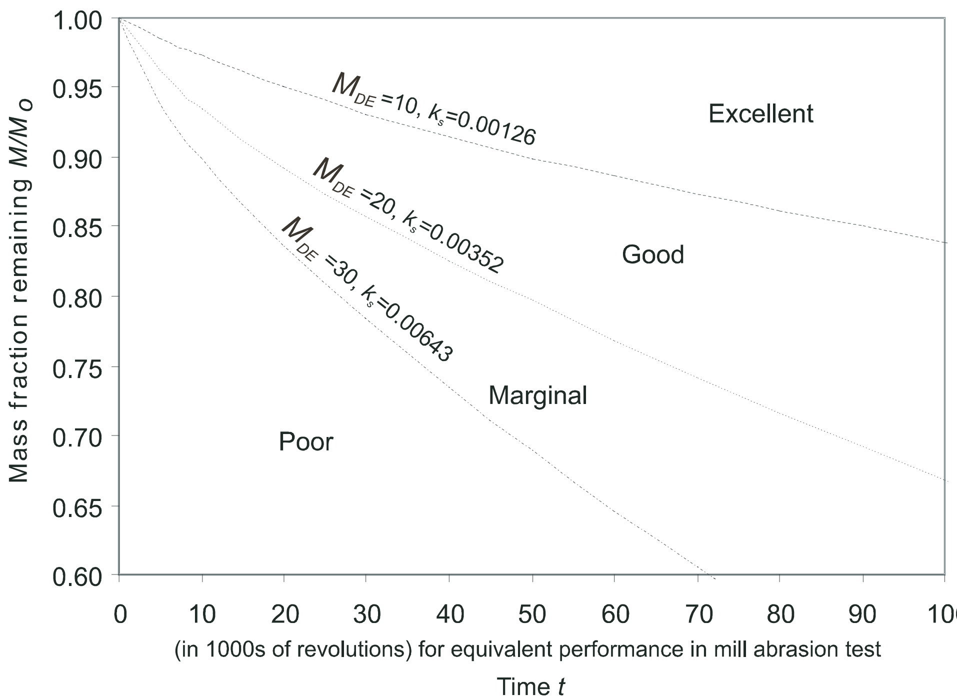


**Figure 3.30** *Abrasion resistance classification chart based on Micro-Deval test results. $M_{DE}$ values have been converted using Equations 3.36 and 3.37 to mass loss plots indicative of the equivalent mill abrasion test results. The quality boundaries for abrasion resistance have been revised from earlier published positions for compatibility with the European standard $M_{DE}$ specification categories (courtesy J van Meulen)*

**Step 3**

To determine the site aggressiveness, calculate $X$, the *equivalent wear time factor* using Equation 3.38:

$$X = X_1 \times X_2 \times X_3 \times X_4 \times X_5 \times X_6 \times X_7 \times X_8 \times X_9 \qquad (3.38)$$

where $X_1$, $X_2$ … $X_9$ are a series of site aggressiveness loading parameters obtained from Table 3.14.

Note the slight revisions to the former ratings for the site loading parameters (Latham, 1991) given here in the light of further research and case history experience. To obtain $X_6$, substitute the project site weathering intensity factor, *MCWI*, given in Table 3.15, based on work of Lienhart (2003). Care is required because of the unusual input parameters, which yield *MCWI* units in degrees² × cm / number of days². Also substitute water absorption test results.

**NOTE:** The drop test breakage index $I_{M50}$ , is also used to quantify the block integrity and how its value is coupled with the wave energy term ($X_4$) and mobility in the design term ($X_9$). The accuracy of the suggested ratings for these coupling effects is uncertain and could be low. Breakage rate values, $B_n$ (%) (see Table 3.12), can be used as a guide to $I_{M50}$ values required for $X_4$ and $X_9$.

**Step 4**

Finally, to determine the service life prediction, plot $M/M_0$ curve against time ($T$ in years on the structure) by multiplying the time scale (t in thousands of revolutions) in Step 2 by $X$. Or, equivalently, plot the change in mass, $M/M_0$ (-), against service life time, $T$ (years), using Equation 3.39. This plot gives the fraction of original mass remaining for any period of service life or design life.

$$M/M_0 = 0.05 \exp[-30(k_s/X)T] + 0.95 \exp[(-k_s/X)T] \qquad (3.39)$$

### 3.6.5.2 *Armourstone quality designation (AQD) method*

The AQD method (suggested here using parameter ratings given in Table 3.13) aims to scale the rate of loss of performance using an aggressiveness and design application factor that is totally independent of the global intrinsic property assessed by Micro-Deval method. It therefore differs from the MDE method.

**Step 1**

Perform a systematic quarry evaluation with a combination of field and laboratory assessments and obtain *AQD* using Tables 3.13 and 3.14. Use Equation 3.40 to convert *AQD* to $k_s$, where $k_s$ now describes the intrinsic resistance to mass loss of the armourstone quarry source in question (by consideration of all potential susceptibilities to possible degradation mechanisms that may be active in any structure over the long-term).

$$k_s = 0.032\ AQD^{-2.0} \qquad (3.40)$$

Equation 3.40 was derived empirically by Lienhart as a simple means to convert *AQD* values into plots with fraction of original mass remaining versus time $T$ in years on the structure, assuming the equivalent wear time factor $X = 1$. To derive the relationship in Equation 3.40, *AQD* values of 1.5, 2.5 and 3.5 were set by curve fitting to correspond with $k_s$ values that separate resistance to progressive degradation at three quality boundaries that are essentially similar to those given by abrasion resistance classes shown in Figure 3.30. For the AQD method, $k_s$ has the units of change in fraction of mass remaining per year, assuming the equivalent wear time factor on the structure $X$ is equal to 1.

**Step 2**

Use Equation 3.37 to plot reference curves for intrinsic armourstone performance with $AQD = 0.5$ to $AQD = 4.5$. These are given in Figure 3.31 where performance is plotted in terms of mass fraction remaining against time $T$ on the structure in years, assuming the equivalent wear time factor $X = 1$.

**Step 3**

Obtain $X$ using Equation 3.38 and Table 3.14, taking care with $X_4$, $X_6$ and $X_9$ to apply ratings that specifically apply to the AQD method (rather than the MDE method).

**Step 4**

Plot the change in mass, $M/M_0$ (-), against service lifetime, $T$ (years), using Equation 3.39. This plot gives the fraction of original mass remaining for any period of service life or design life.

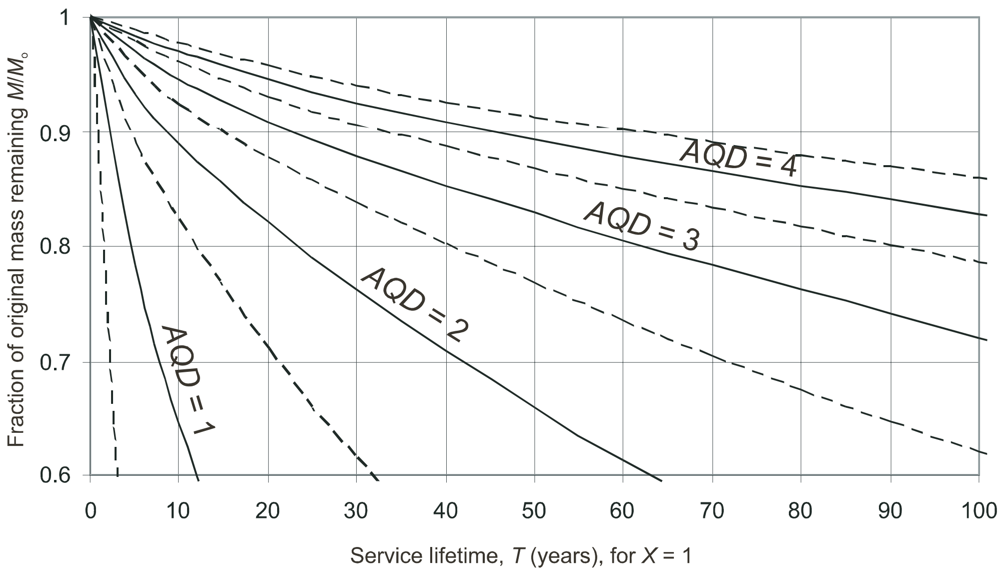


**Figure 3.31** *Intrinsic armourstone performance classification chart based on AQD, assuming equivalent wear time factor, X = 1 (courtesy J van Meulen)*

**Table 3.14** *Ratings estimates for parameters in armourstone degradation model, for input to Equation 3.38 (after Latham, 1991)*

| Parameter | Rating estimates | | | | | | Parameter influence $X_{max}/X_{min}$ | Calibration Reliability* |
|---|---|---|---|---|---|---|---|---|
| $k_s$ | **Rock fabric strength**<br>Use $M_{DE}$ test value and relationship: $k_s = 4.12 \times 10^{-5} M_{DE}^{1.485}$<br>or $AQD$ value and relationship: $k_s = 0.032\ AQD^{-2.0}$ | | | | | | ~500 | Excellent |
| $X_1$ | **Size**<br>Effect given by $0.5(M_{50})^{1/3}$ ($M_{50}$ in tonnes) | | | | | | ~10 | Good |
| | $M_{50}$ | 15.0 | 8.0 | 1 | 0.1 | 0.01 | | |
| | Rating | 1.23 | 1.00 | 0.50 | 0.23 | 0.11 | | |
| $X_2$ | **Grading width**<br>$(M_{85}/M_{15})^{1/3}$ | 1.1–1.4 | | 1.5–2.4 | 2.5–2.4 | | ~2.5 | Fair |
| | Rating | 1.2 | | 1.0 | 0.5 | | | |
| $X_3$ | **Initial shape** | | | | | | ~2 | Fair |
| | | | Angular/ irregular | Blocky/ equant | Semi-rounded | Rounded | | |
| | Rating | | 1.00 | 1.1 | 1.50 | 2.00 | | |
| $X_4$ | **Incident wave or current energy (treat as independent of size of stone)** | | | | | | ~10 | Fair |
| | | Significant wave height, $H_s$ (m) | | > 8.0 | 4.0–8.0 | < 4.0 | | |
| | Rating | If $I_{M50}$ > 15% | | 0.3 | 1.0 | 2.0 | | |
| | | If $I_{M50}$ = 5.0–15.0% | | 0.5 | 1.3 | 2.3 | | |
| | | If $I_{M50}$ = 2.0–5.0% | | 0.7 | 1.6 | 2.6 | | |
| | | If $I_{M50}$ < 2% | | 1.0 | 2.0 | 3.0 | | |
| | Rating | If using AQD method | | 0.7 | 1.6 | 2.6 | | |
| $X_5$ | **Zone of structure** | | | | | | ~10 | Good |
| | | | Intertidal | Supra-tidal /hot | Supra-tidal /temperate | Always submerged | | |
| | Rating | | 1.0 | 2.5 | 8 | 10 | | |
| $X_6$ | **Meteorological climate weathering intensity**<br>(Use *MCWI* index of Lienhart – see Table 3.15) | | | | | | ~7 | Good |
| | *MCWI* index | | < 100 | 100–300 | 300–600 | > 600 | | |
| | Rating | If *WA* > 2.0% | 0.8 | 0.6 | 0.4 | 0.2 | | |
| | | If *WA* = 0.5–2.0% | 1.0 | 0.8 | 0.6 | 0.4 | | |
| | | If *WA* < 0.5% | 1.4 | 1.2 | 1.0 | 0.8 | | |
| | Rating | If using AQD method | 1.0 | 0.8 | 0.6 | 0.4 | | |
| $X_7$ | **Waterborne attrition agents** | | | | | | ~7.5 | Poor |
| | Sediment type | shingle | gravel | sand | silt | none | | |
| | Rating | 0.2 | 0.5 | 1.0 | 1.2 | 1.50 | | |

**Table 3.14** *Ratings estimates for parameters in armourstone degradation model, for input to Equation 3.38 (after Latham, 1991) (contd)*

| Parameter | Rating estimates | | | | | | Parameter influence $X_{max}/X_{min}$ | Calibration Reliability* |
|---|---|---|---|---|---|---|---|---|
| $X_8$ | Concentration of wave attack | | | | | | ~2 | Fair |
| | *Tidal range (m):* | | | < 2.0 | 2.0–6.0 | > 6.0 | | |
| | Rating for slope angle of 1:2.5 or steeper | | | 1.0 | 1.2 | 1.5 | | |
| | Rating for slope angle of 1:3.0 or steeper | | | 1.5 | 1.8 | 2.0 | | |
| $X_9$ | Mobility of armourstone in design concept | | | | | | ~20 | Fair |
| | $H_s/(\Delta D_{n50})$ | | 1–2.4 | 2.5–3.9 | 4–6.9 | 7–20 | | |
| | Rating | If $I_{M50}$ > 15% | 1.5 | 0.6 | 0.3 | 0.1 | | |
| | | If $I_{M50}$ = 5.0–15.0% | 2.0 | 1.0 | 0.5 | 0.2 | | |
| | | If $I_{M50}$ = 2.0–5.0% | 2.0 | 1.5 | 1.0 | 0.5 | | |
| | | If $I_{M50}$ < 2% | 2.0 | 1.8 | 1.6 | 1.4 | | |
| | Rating | Rating If using AQD method | 1.5 | 1.3 | 1.1 | 0.7 | | |

**Note**

* calibration reliability of the ratings estimates is variable, ranging from a simple reasoning including qualitative field observations of factor influence (poor) to extensive confirmatory data (excellent).

**Table 3.15** *Meteorological Climate Weathering Intensity (MCWI) for rock (Lienhart, 2003)*

| Rock weathering intensity analysis | |
|---|---|
| *a* | Mean (max) – mean (min) temperature range over several years |
| *b* | Mean annual temperature |
| *c* | Mean number of days Max Temp > Freezing |
| *d* | Mean number of days Max Temp ≤ Freezing |
| *e* | Extreme max and min temperature range over several years |
| *f* | Mean number of days with precipitation > 0.25 mm |
| *g* | Annual precipitation, cm |
| *h* | Total normal degree-days, base 18 °C * |
| $MCWI = (a/b) \times (d/365) \times (e/c) \times ((g/f) \times h)$ | |

**Notes**

Care is required in calculating *MCWI* because of the unusual units of the various weather parameters. Units are degrees² × cm / number of days² as the second term "*d*/365" is dimensionless (365 = no days in a year).

* Total normal degree-days, base 18 degrees Celsius = sum of heating degree-days and cooling degree-days, and is measured in degrees. For each day where the outside temperature is such that a building may require heating, the heating degree-day (in degrees Celsius) = 18 minus the mean outside temperature for a 24-hour period. For each day with average temperatures above 18 degrees C, the heating degree-day is recorded as zero. The weather offices total these heating degree-day values for a specific weather station for a year and provide the "normal" total heating (in degrees C) for the average year. The cooling degree-day (in degrees C) = the mean outside temperature for a 24 hour period minus 18 degrees. The "normal" total cooling (in degrees C) is reported like the heating degree-days.

### 3.6.5.3 *Comparison between MDE and AQD methods*

An example where both methods are applied to the same dataset is given in Box 3.10. The remarkable similarity of the result is fortuitous. The AQD method is attractive because it draws upon many more intrinsic factors of relevance. On the other hand, the MDE method is probably better calibrated, being based on case history calibrations where abrasion test results were related to site case histories of degradation with time. It is suggested that in practice, results of both methods be examined along the lines discussed in Box 3.10 and illustrated in Figure 3.32. The user is encouraged always to perform a sensitivity analysis considering the range of parameter values that may be applicable. There is too little case history data to give guidance on which of the two methods is to be preferred.

Both methods assume the long-term pattern of mass loss in service to be progressive and of the same form as a steady laboratory abrasion test. After some value that could be anywhere between 10 per cent and 50 per cent mass loss, an accelerated deterioration may be more realistic than the assumed continuously slowing rate given by the form of the abrasion test plot. Increasingly inaccurate predictions are likely for $M/M_0$ below, say, 0.7.

**Box 3.10** *In-service degradation model for general wear of armourstone: illustrative example of two methods*

This box considers data compiled for intrinsic properties of an armourstone source and site aggressiveness parameters and compares the results of the degradation model for general wear of armourstone using two methods. In Table 3.16, the column for the MDE method indicates three test results. The MDE test result of 20 per cent is used with Equation 3.36 to provide the $k_s$ value of 0.00352 (boundary between Marginal and Good in terms of abrasion resistance). The water absorption and integrity drop test results are also required to more accurately select the coupling of the different attributes of the source rock with the site aggressiveness parameters $X_4$, $X_6$ and $X_9$, as identified in Table 3.14. All nine parameters are scored according to Table 3.14 and the product X=1.12 is determined using Equation 3.38. The column for the AQD method takes a more in-depth assessment of the intrinsic properties of the source material using the assessment scheme in Table 3.12 and 3.13 and in this example gives an *AQD* = 2.33, (top of Marginal range), which from Equation 3.40 yields the $k_s$ value of 0.00589. The parameters in Table 3.14 this time yield the product $X$ = 1.80, using Equation 3.38. The resulting service life predictions plotted using Equation 3.39 and shown in Figure 3.32 are similar for both methods. They suggest that $M_{50}$, originally of 8 tonnes, will have fallen to 7.2 t (90 per cent) in about 20 years.

**Table 3.16** *Application of armourstone degradation model for in-service mass loss to cover layers*

| Parameter* | Site loading information relating to degradation | MDE method eg $M_{DE}$ = 20%, *WA* = 1.2%, $I_{M50}$ = 12% | AQD method eg *AQD* = 2.33 based upon *AQD* for quarry source data given in Table 3.13 |
|---|---|---|---|
| $k_s$ | | 0.00352 | 0.00589 |
| $X_1$ | $M_{50}$ = 8 tonnes | 1 | 1 |
| $X_2$ | $(M_{85}/M_{15})^{1.3}$ | 1.2 | 1.2 |
| $X_3$ | Angular irregular shape | 1 | 1 |
| $X_4$ | Significant wave height for design storm $H_s$ = 5.0m | 1.3 | 1.6 |
| $X_5$ | Zone of concern is intertidal | 1 | 1 |
| $X_6$ | Meteorological climate weathering intensity, *MCWI* = 700 | 0.4 | 0.4 |
| $X_7$ | Attrition by silt | 1.2 | 1.2 |
| $X_8$ | Steep (1:2) slope with high (7m) tidal range | 1.5 | 1.5 |
| $X_9$ | Mobility in design expressed by $H_s/(\Delta D_{n50})$ = 3.0 | 1 | 1.3 |
| $X$ | **Equivalent wear time factor (Equation 3.38)** | **1.12** | **1.80** |

**Note**

* Refer to Table 3.14 for selection of appropriate parameters.

**Box 3.10** *In-service degradation model for general wear of armourstone: illustrative example of two methods (contd)*

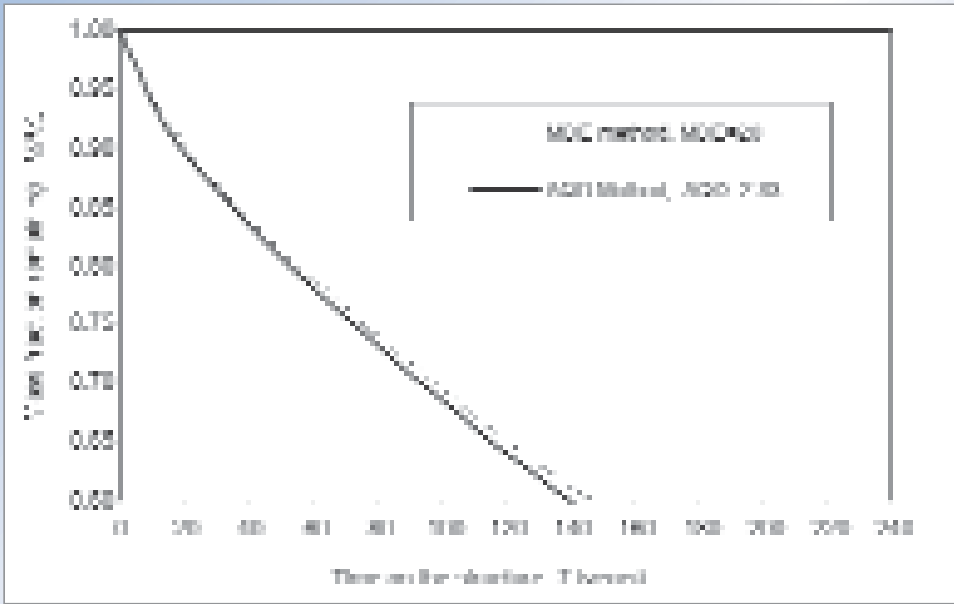

**Figure 3.32** *Service life predictions for the general in-service degradation model, using MDE and AQD methods. The very close agreement shown is somewhat fortuitous and not likely to be reproduced in practice (courtesy J van Meulen)*

## 3.6.6 Modelling degradation due to breakages

Minor and major breakages affect the mass distributions and also, to some extent, the shape of armourstone. For example, during the survey of a contract using a 6–10 t grading of armourstone, Laan (1992) observed that degradation related to transport and handling led to a production of pieces smaller than 3 t whose mass represented 9 per cent of the original material. In addition, he observed that the $M_{50}$ decreased from 8.5 t to 7.6 t. In a different situation, 1–3 t armourstone gradings, from different sources and exposed to different levels of quality control, were exposed to repeated routine handling events associated with stockpiling and loading. Dupray *et al* (2003) observed in each case a mass of small fragments, say smaller than 100 kg, totalling 5–8 per cent of the initial consignment and that the initial $M_{50}$ decreased by 14–21 per cent in certain cases.

This section discusses the effects of minor and major breakage on mass distribution, their quantitative contribution to mass distribution changes, and how to assess these changes from test results.

### 3.6.6.1 *Effects of minor breakages and major breakage*

Minor and major breakages have different effects on mass distribution of armourstone.

**Minor breakage** produces small fragments originating from breakage of stone edges or crushing of armourstone corners (see Figure 3.11). It has a limited effect on the values of $D_{n50}$ or $M_{50}$ compared with the effect of major breakage. Minor breakage modifies the mass distribution in the sense that the fragments appear in the form of a tail and a vertical shift of the lightest part of the grading curve, as shown on Figure 3.33. The amount of fines generated is expressed by the parameter $F_o$ (%).

Fragments resulting from minor breakage during transport or handling or structural loadings may be removed by further selection or by wave or current action. In this latter case the grading curve does not contain the fines, but only displays a general but small shift characterised by $\delta m$ (kg) (see Figure 3.33). Note that the steepness of the grading curve does not change in this case, but the mass of each stone decreases by an average value of $\delta m$. Methods to determine $\delta m$ and $F_o$, as well as equations that relate these two parameters, are discussed in detail in Dupray (2005) and Dupray *et al* (2007). However, a safe estimate of the value of $F_o$ (-) or (%) can be determined where the curvature of the post FSST grading changes (see Figure 3.33) and these parameters can be related by Equation 3.41:

$$F_o = \frac{\delta m}{M_{em}} \qquad (3.41)$$

where $M_{em}$ is the effective mean mass (kg).

**Major breakage** of individual blocks leads to a limited number of large fragments but does not lead to fines production (see Figure 3.10). If a significant proportion of stones display major breakage, $M_{50}$ may be diminished significantly. The $M_{50}$ decrease and occurrence of fragments induced by major breakage appears on the grading curve as a shift towards the smaller sizes and a decrease of its steepness (see Figure 3.33).

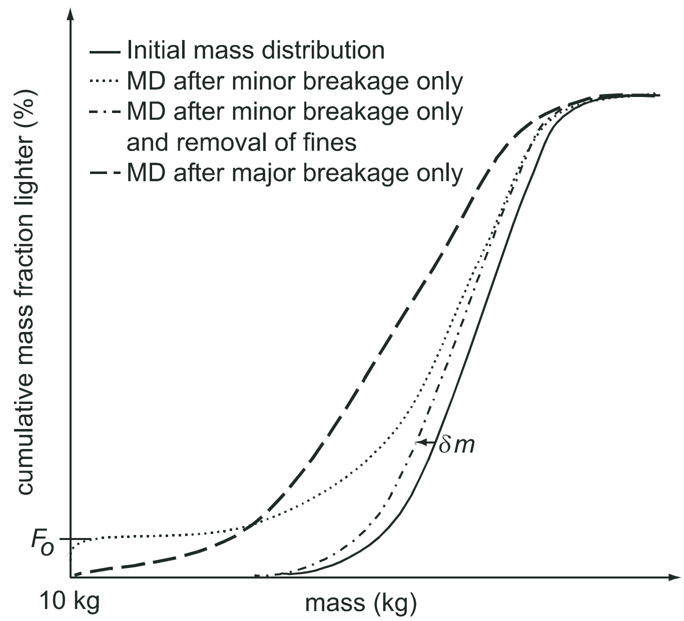


**Figure 3.33**

***Effects of minor breakage and major breakage on the grading curve (courtesy J van Meulen)***

In reality, the degradation induced by both poor integrity (major breakage) and by minor breakage may take place simultaneously. They can be separated out and Figure 3.34 shows schematically the combined effects of minor and major breakage. The grading curve to be expected if only minor breakage alone had taken place is also plotted. When considering a value of passing $x$, $I_{Mx,m}$ represents the relative mass decrease due to minor breakage whereas $I_{Mx,M}$ represents the part of the relative mass decrease due to major breakage. Similarly, the bounded areas between initial and breakage curves $\delta A_m$ and $\delta A_M$ represent the effect of minor breakage and major breakage respectively.

Figure 3.34 clearly shows that the common indicators of resistance to breakage such as $I_{Mx}$ (see Equation 3.4 in Section 3.3.4) are biased by the effect of minor breakage since $I_{Mx} = I_{Mx,M} + I_{Mx,m}$ , which in fact stands for the effect of major and minor breakage. Hence, using $I_{Mx,m}$ and $I_{Mx,M}$ or $\delta A_m$ and $\delta A_M$ is a means of separately assessing the effect of both types of breakage. Different methods to distinguish the effect of major and minor breakage from the global modifications of the mass distribution are discussed in Dupray (2005). A point-by-point method to determine the modification induced by minor breakage alone is given in Box 3.11.

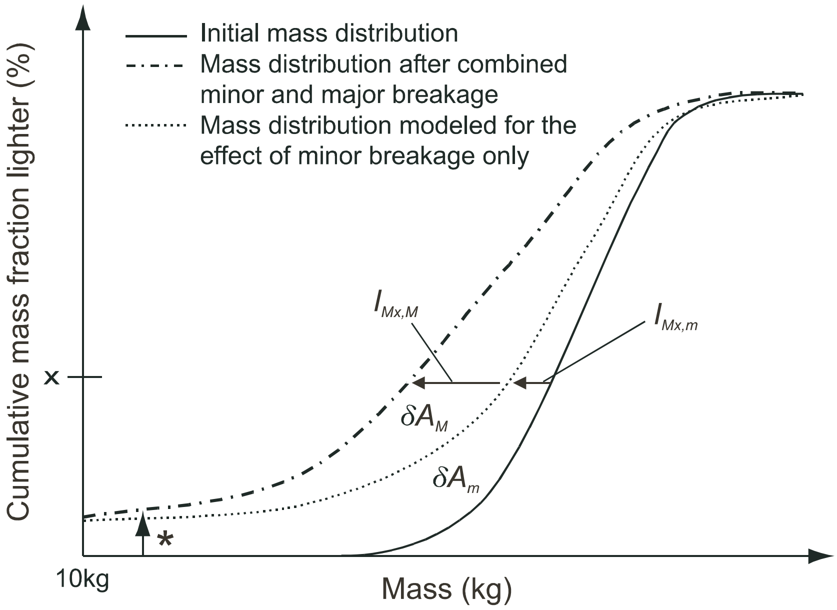


**Figure 3.34** *Separation of the effect of minor and major breakage from global modifications of the grading curve (* the effect of minor breakage)*

**Box 3.11** *Point-by-point method to determine the effect of minor breakage*

The amount of fines generated by minor breakage, $F_o$, is determined from the mass distribution affected by combined minor and major breakage at the point of curvature change. $\delta m$ can then be determined from Equation 3.41 where $M_{em}$ is determined on the population before degradation. The mass of each individual stone, assuming only minor breakage, can be determined from each initial mass, $m_i$, by retrieving the average mass broken off by minor breakage, $\delta m$. Thus, Equation 3.42 gives the mass of each particle after minor breakage, $m_f$:

$$m_f = m_i - \delta m \tag{3.42}$$

The mass distribution of the armourstone population after minor breakage can be determined from the new population of mass, $m_f$, as plotted in Figure 3.35.

**NOTE:** The total reference mass for the final population should include the mass of all fragments generated by minor breakage as well as the final mass of stones suffering minor breakages.

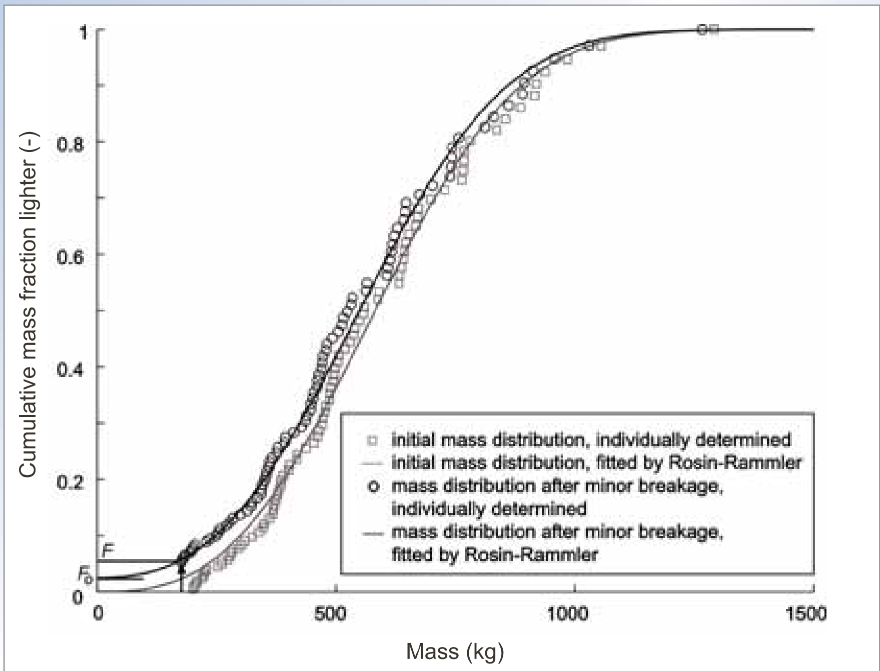


**Figure 3.35** *Separation of the effect of minor and major breakage from global modifications of the grading curve using a point-by-point approach*

### 3.6.6.2 Quantitative effect of breakages on armourstone grading using statistical model

Effects of minor and major breakage on gradings can be modelled using appropriate Monte Carlo simulation. The model whose results are presented here (see Figure 3.36) is based on a statistical fragmentation model as initially developed by Grady and Kipp (1985) modified into a one-dimensional Monte Carlo model to simulate the effect of breakage processes on a standard 300–1000 kg grading (Dupray, 2005). The model allows minor and major breakage to be handled separately or in combination. Such a graph allows the designer to estimate the expected value of $I_{M50}$, given reasoned assumptions for the expected number of pieces that would display major breakage, ie a good assumption of $B_n$, and the amount of minor breakage characterised by $F_o$ or $\delta_m$ (see Equation 3.41).

Using Figure 3.36 (left), a designer can determine the expected effect of major breakage on the shift in the value of the original $M_{50}$ in the quarry and use this information for setting tolerances in term of $I_{M50}$ for a given design. This will require the designer to select reasonable values for $F_o$ and $B_n$ as input to Figure 3.36:

- $F_o$ in service or during construction may be determined using the double exponential expression developed for attrition in Section 3.6.5 and applying Equation 3.39, which will provide $M/M_0$. $F_o$ can then be determined knowing $F_o = 1–M/M_0$
- $B_n$ can be determined from feedback from actual performance eg using a survey of breakage during contracts or on existing structures. Alternatively, a mechanically based field test method presented in Box 3.12 can be used.

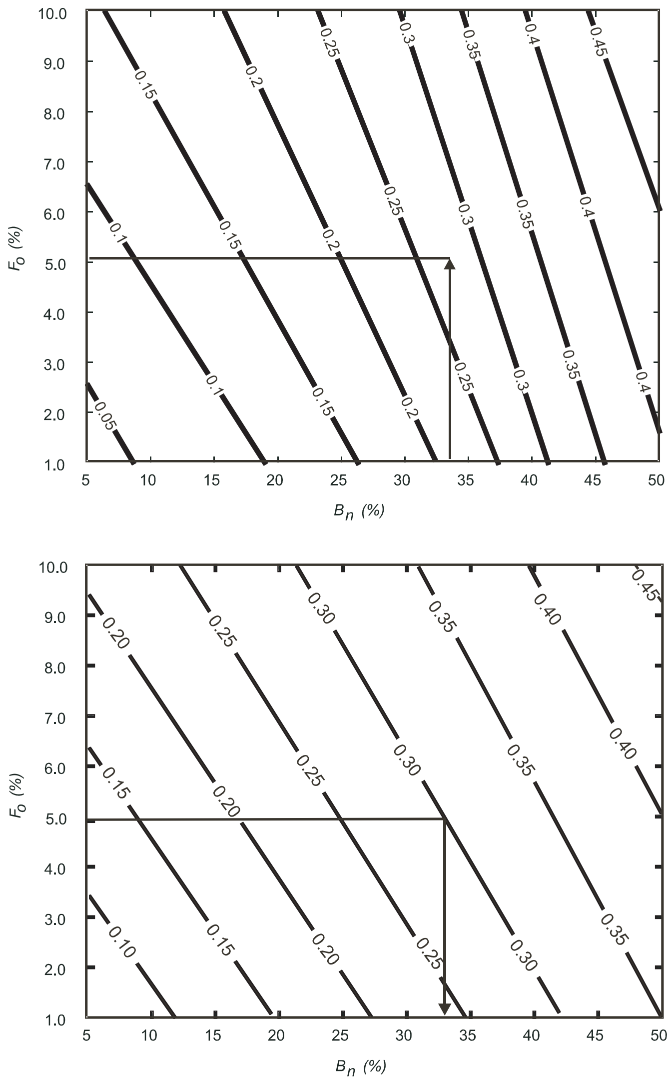


**Figure 3.36**

***Top: Values of $I_{M50}$, as a function of the breakage rate, $B_n$, and the amount of minor breakage estimated with $F_o$. Bottom: Values of $\delta A_M/A^*$, as a function of the breakage rate, $B_n$, and the amount of minor breakage estimated with $F_o$***

**Box 3.12** *Determination of the effect of minor breakage and major breakage*

An estimate of the relative number of pieces that may display major breakage during construction or in service, the $B_n$ value, may be based on the experience of the designer with the armourstone considered or feedback from performance of the same material in similar conditions. Alternatively, the results for the field-crushing test introduced by Tørum and Krogh (2000) may be used. This test provides the designer with characteristics of the material with regard to its breakage resistance expressed by parameters $k$, $\alpha$ and $\beta$. The energy required to induce major breakage in half of an armourstone population $P_{50}$ (J) can be determined with Equation 3.43:

$$P_{50} = k\left(\frac{M_{50}}{\rho_{rock}}\right)^{\alpha} \tag{3.43}$$

where the value of $k$ depends on integrity. In other words, the $k$-value expresses the energy amount (in Joules) required to crush 50 per cent of the blocks of 1 m³ volume.

The fraction by number of blocks that display breakage, $B_n$ (-), when exposed to a given level of energy $P$ can be determined using Equation 3.44:

$$B_n = \beta \ln\left(\frac{P}{P_{50}}\right) + 0.5 \tag{3.44}$$

Governing parameters have been determined on good igneous rock: the value of $\alpha$ (-) is close to 0.65; the value of $\beta$ (-) is within the range of 0.44–0.5; the value of $k$ (-) is within the range of 81 000–99 000. The reader should refer to the original work for further detail.

The determination of the appropriate energy to which armourstone is exposed, $P$ (J), is a difficult task that is still the subject of research. Extensive studies would be required to provide detailed guidance for the selection of the most appropriate value of $P$. This subject was partly investigated for berm breakwaters by Tørum and Krogh (2000) and for rubble mound breakwaters by Trmal (2004). To assist the designer, Equation 3.45 is provided as a means to determine a first estimate of $P$ (J):

$$P = 0.5 M_{50} K_i g H\left(\frac{V_A}{\sqrt{gH}}\right) \tag{3.45}$$

where $H$ is the wave height (m), $V_A$ is the characteristic velocity of armourstone piece during impacts (m/s) and $K_i$ is an impact parameter whose value may be between 0.6 and 0.9.

**NOTE:** The total reference mass for the final population should include the mass of all fragments generated by minor breakage as well as the final mass of stones suffering minor breakages.

### 3.6.6.3 Prediction of the effect of major breakages using a dedicated degradation model specific for breakage

This section discusses the use of Full-Scale Splitting Test (FSST) results in combination with an associated degradation model presented in Equation 3.46. Recent research proposed a new degradation model that is specific to major breakage. The parameter $\delta A_M$ (kg), which is the change in area under the grading curve due to major breakage (see Section 3.6.6.1), was identified as an appropriate indicator for major breakage that is not biased by the effect of minor breakage and that displays less variability than the usual breakage indicator, $I_{M50}$ (Dupray, 2005 and Dupray *et al*, 2007). The key relationship of the degradation model is given in Equation 3.46:

$$\delta A_M = \frac{A^* \cdot \left(\frac{E_D}{M_D}\right)^3}{C_{FSST}{}^3} \tag{3.46}$$

where:

$E_D$ = total degradation energy applied to the material (J)

$M_D$ = total mass of material exposed to degradation (kg)

$C_{FSST}$ = characteristic integrity (J/kg) determined using FSST (see Section 3.8.5.2).

$A^*$ = characteristic reference area (kg).

**On the use of the degradation model**

Starting with an armourstone consignment of known grading, defined by standard NLL and NUL limits, with a total mass of $M_D$, the designer can then use Equation 3.46 to assess the projected loss of mass by major breakage for an applied energy, using the term $\delta A_M$.

The determination of $\delta A_M$ requires values of:

- $A^*$, which is a characteristic reference area (kg) as required for dimensional consistency (see Step 1 below)
- $E_D$, which is the equivalent energy applied to the material that induces major breakage (J) and consequently the increase of $\delta A_M$ (kg). It is of interest to the designer to determine $E_D$ for both the construction situation and the situation in service. Recent research provides a way to determine $E_D$ for routine handling at the quarry or on site (see Step 2 below)
- $C_{FSST}$, which represents integrity. See Box 3.21 of Section 3.8.5 for a simplified method to determine its value from full-scale splitting tests in the field. For information, high integrity tends to correspond to values of $C_{FSST}$ greater than 35 and poor integrity to values smaller than 27. However, integrity of the armourstone may increase during routine handling where certain weaknesses are exposed and some breakages occur. It may therefore be more appropriate to use an updated value of integrity to take into account breakage that has already occurred, represented by using $C_H$ instead of $C_{FSST}$ (see Step 3).

Using Figure 3.36, $\delta A_M$ can be easily converted into the traditional integrity indicator $B_n$ or $I_{M50}$. For example, assuming the loss from attrition, $F_o$ , is estimated as 5 per cent, whether from experience or by using the degradation model due to attrition, and that $\delta A_M /A^*$ is found to be 0.3. This will correspond to a value of $B_n$ of 0.33, ie one-third of the blocks display major breakage as determined from Figure 3.36 (bottom). Using Figure 3.36 (top), the relative decrease due to major breakage of the $M_{50}$, ie $I_{M50,M}$ , is 27 per cent.

**Step 1: Determination of the characteristic area, $A^*$ (kg)**

This term $A^*$ is required for dimensional consistency of Equation 3.46. It could be determined as exact integration of the area below the grading curve. However, by assuming that the grading is linear (and not a Rosin-Rammler form, see Equation 3.12) $A^*$ can be simply determined using the grading limit masses. Thus, $A^* = (NLL + NUL)/2$.

**Step 2: Determination of the equivalent degradation energy associated with routine handling events**

Three field investigations including three different rock types were carried out. They consisted of measuring $C_{FSST}$ and mass distribution changes induced by routine handling events. This enabled Equation 3.46 to be calibrated against effective degradation measured in the field. The sources were tested using standard armourstone gradings of 1000–3000 kg. The degradation energy, $E_D$ (J), was determined from the actual potential energy of the armourstone consignment (converted into kinetic energy). Thus, the energy loss of the material during handling events is simply calculated from the height to which the armourstone material is lifted by the handling machine (see Equation 3.47). In the study, the wheel loader had an average lifting capacity of 3 m.

$$E_D / M_D = 1.98 \cdot gH_h \tag{3.47}$$

where $H_h$ is the height to which the armourstone material is lifted by the handling machine (m), and $M_D$ is the total mass of material exposed to degradation (kg).

**Step 3: Increased integrity during routine handling events**

During repeated handling events, major breakage of weak stones has two effects. First, it affects the mass distribution as discussed in Figure 3.33. Second, it breaks the weakest blocks that are then no longer available for further major breakage. It therefore tends to increase the integrity (Figure 3.37 right). In the service environment and over time, it is also possible that planes of weakness can be opened up that will not be fully revealed by handling events in the quarry. This risk should normally be covered by accelerated weathering tests performed on appropriate samples. If there are no concerns about a risk of breakage of armourstone, for example resulting from freeze and thaw processes, then the parameter $C_H$, as defined in Equations 3.49 and 3.50, should be a good assumption of the effective integrity of the consignment. If this is not the case, then the increase in integrity given by Equations 3.49 and 3.50 should not be applied.

The parameter $n_H$ may be used as an indicator of the number of handling events (see Equation 3.49). However, an objective measure of the relative amount of degradation induced by major breakage with reference to the amount of major breakage displayed during the FSST is the parameter $X_H$, defined by Equation 3.48. This applies to any type of loading events or loading history for which the mass distribution is known or given:

$$X_H = \left(\frac{\delta A_M}{\delta A_{FSST}}\right)\left(\frac{A^*_{FSST}}{A^*_H}\right) \tag{3.48}$$

where:

| | | |
|---|---|---|
| $A^*_H$ | = | value of $A^*$ before the first handling events. It can be approximated by $(m_{10} + m_{70})/2$ where $m_{10}$ and $m_{70}$ are the characteristic masses of the consignment that is handled |
| $\delta A_M$ | = | total change in area under the grading curve induced by major breakage from the beginning of the degradation process (kg) |
| $A^*_{FSST}$ | = | value of $A^*$ before the full-scale splitting test, equal to $(NLL + NUL)/2$ (kg) |
| $\delta A_{FSST}$ | = | total change in area under the grading curve induced by major breakage during the full-scale splitting test (kg). |

The integrity increase with handling events of this kind can be determined with a simplified approach (see Equation 3.49):

$$C_H/C_{FSST} = 1 + 11.19(n_H/20)^{1.93} \tag{3.49}$$

where: $n_H$ is the number of handling events. Alternatively, $X_H$ can be used to assess the increase of integrity (see Equation 3.50):

$$C_H/C_{FSST} = 1 + 7.28X_H^{4.02} \tag{3.50}$$

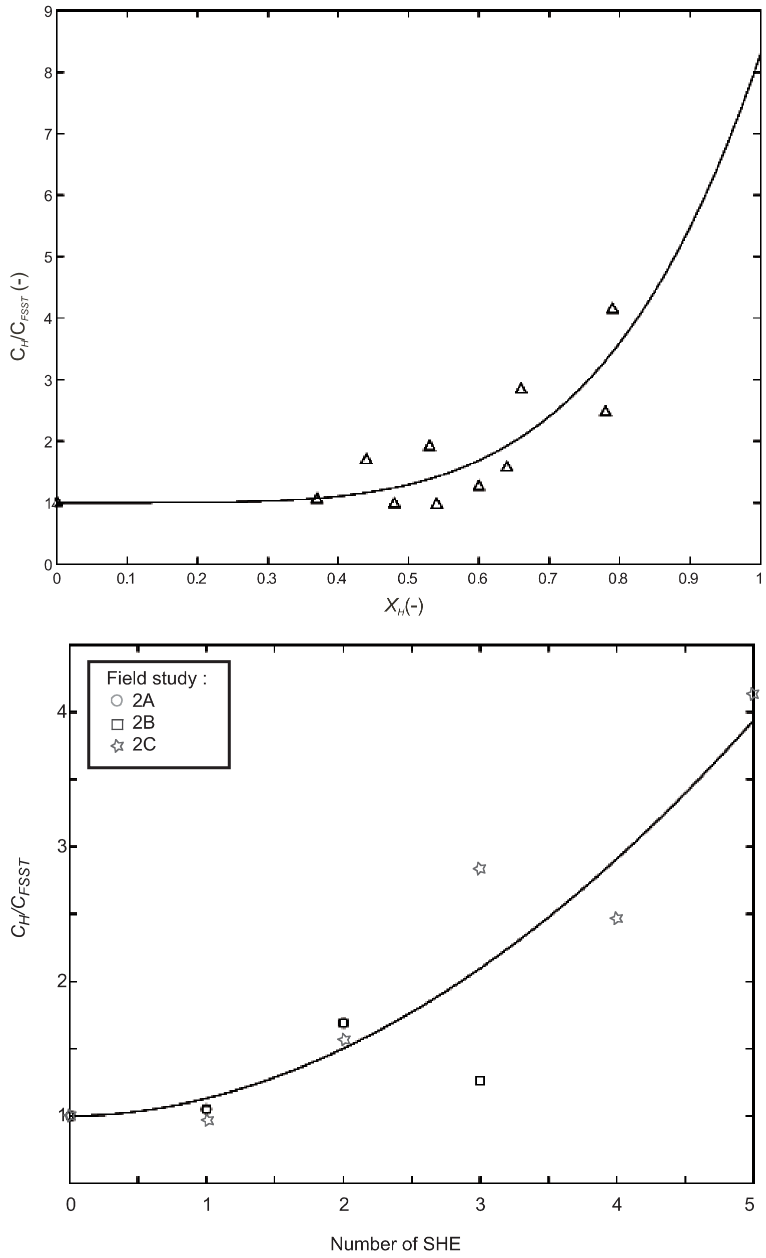


**Figure 3.37** *Variation of integrity as determined with the FSST with repeated standardised rough handling events; Top: as a function of $X_H$. Bottom: as a function of the number of handling events (SHE). A fourfold increase in integrity is seen after between four and six handling events*

## 3.6.7 Summary of recommendations for degradation modelling

If available, service record observations are the best guide for calibration of degradation models and validation of predictions. Damage prediction modelling is more complex where the armour is mobile during storms. Aggregated distances travelled by stones, possibly producing severe degradation by corner breakage and rounding, as well as by splitting, need to be considered. Both integrity and abrasion resistance are therefore extremely important. For dynamic structures such as berm breakwaters and other novel low-cost designs with expected movements, degradation models (Tørum and Krogh, 2000; Tomassichio *et al*, 2003) have advanced sufficiently to warrant application of calibrated stone integrity testing (full-scale splitting test results) and mineral fabric strength tests (eg point load strength index and $M_{DE}$) to assess mass losses during stone splitting and rolling. For berm breakwater analysis of mass losses, breakages and rounding with reshaping storm events, key research papers by Tørum and Krogh (2000) and Tomassichio *et al* (2003) should be considered.

For static designs, especially where marginal and poor armourstone is to be considered, the general degradation models that attempt a comprehensive average degradation assessment over the service life are recommended.

**NOTE:** Armourstone degradation models should only be applied with considerable caution and backed up by sensitivity analysis that will make clear the degree of uncertainty in the service life predictions.

## 3.7 PREPARING THE ARMOURSTONE SPECIFICATION

This section provides advice on preparing a specification for quarried rock. A specification template is provided in Table 3.17. Note that this does not include the specification for the workmanship of placing the armourstone on the construction site that is given in Appendix A1 and supported by the text in Chapter 9. Quarried rock specifications include **requirements** for materials to fall within given values of parameters when assessed using standard **test methods**. This section provides the general framework for setting the requirement levels as defined by European standard EN 13383 (see Section 3.1.4). Section 3.8 provides more detailed information on the test methods.

The manner in which EN 13383 describes armourstone differs from previous practice in some parts of Europe and the rest of the world, and in some cases it uses different test methods to evaluate their properties, but there is no change to the general quality of the armourstone in use.

The effect of the standard is that the specification process for materials has become considerably simplified. However, those specifying need to understand how to use this standard and incorporate it into their contract specifications.

The key to using EN 13383 is to understand that when selecting an armourstone grading or property the designer/purchaser must select the appropriate category. It is then the producer's responsibility to produce material complying with the requirements for that category. In all cases, as well as the specific categories laid down in EN 13383, other categories are possible.

It is possible for a specifier to select a "No requirement" (NR) category. Examples of NR categories are given in Table 3.17.

If properties are outside specified limits, the producer may declare a value, which may be accepted by a purchaser if these declared values are acceptable for the end use. For example, if the percentage of armourstone pieces with $LT$ > 3 for a coarse grading is 25 per cent (cf normal maximum of 20 per cent), the producer would state "$LT_{25}$". A client could buy this as an $LT_{NR}$ core material. Similarly, the producer might prepare for sale a non-standard heavy grading with, say, upper and lower nominal limits of 2000 kg and 4000 kg respectively. A grading category could then be declared as "$HMA_{2000/4000}$" (see also Section 3.4.3.9 on non-standard gradings).

Where a producer decides not to test for a particular property and still offer it for sale, then he may declare a category of "No performance determined". If this matches a "No requirement" on the part of the purchaser/specifier then the material can be used.

Grading categories follow requirements as already described in Section 3.4.3.

### 3.7.1 EU context

Within the European Union, a large proportion of armourstone projects will be constructed for public bodies. The Public Procurement Directive requires public bodies to use harmonised European standards in full and not to specify in other ways or to use other standards. National regulations in member countries provide the legal basis for enforcement of harmonised standards.

EN 13383-1:2002, Annex ZA addresses the provisions of the EU Construction Products Directive (89/106/EEC). Both EN 13383-1:2002 and its Annex ZA have been produced under a mandate given by the European Commission and the European Free Trade Association to CEN. Annex ZA is described as "informative", but its requirements become mandatory to ensure compliance with the mandate and/or where CE marking is applicable to armourstone. CE marking is a "passport" enabling a product to be legally placed on the market in any European member state. This does not necessarily mean that the product will be suitable for all end uses in all member states, but merely shows that the product addresses the regulatory requirements set out in a particular European Directive, in this case the EU Construction Products Directive (89/106/EEC).

Clauses identified in EN 13383-1:2002, Table ZA.1 indicate the characteristics that are subject to regulatory requirements for the specified application in one or more European member states. There is no obligation to determine or declare a value for a characteristic in a member state where there is no regulatory requirement for that characteristic unless it is subject to a "threshold" value.

Conformity to these identified requirements confers a prescription of fitness of the armourstone for the intended uses indicated in the scope of EN 13383-1:2002. However, to meet the provisions of the EU Construction Products Directive (89/106/EEC), armourstone is also required to conform to any transposed European legislation and national laws relating to dangerous substances referred to in EN 13383-1:2002.

Within the notes to Table ZA.1 in EN 13383-1:2002, reference is made to the type of compliance requirement, for example: fail threshold value, categories, declared value. EN 13383-1:2002 Annex ZA also details the allowed levels for attestation of conformity as "2+" or "4". If level 4 is selected the producer alone is responsible for factory production control and initial type testing. If level 2+ is selected then independent certification and surveillance of the producer's factory production control procedures are required.

CE marking is a legal requirement for armourstone supplied to or within most EU member states. The main exception is the UK, but industry in the UK has adopted a voluntary system of CE marking that makes it as effective as in other member states. In all cases, CE marks must be translated into the language of the member state supplied. Figure 3.38 illustrates the information required for CE marking.

| Marking | |
|---|---|
| CE | *CE conformity marking, consisting of the "CE"-symbol given in directive 93/68/EEC* |
| **01234** | *Identification number of the inspection body* |
| **Any Co Ltd, PO Box 21, B-1050** | *Name or identifying mark and registered address of the producer* |
| **02** | *Last two digits of the year in which the marking was affixed* |
| **0123-CPD-0456** | *Number of the EC certificate* |
| **EN 13383-1** | *No. of European standard* |
| Aggregates obtained by processing natural, manufactured or recycled materials and mixtures of these aggregates for use as armourstone | *Description of product and* |
| (characteristics below) | *Information on regulated characteristics* |

| | | |
|---|---|---|
| **Particle shape** | Category | (e.g. $LT_A$) |
| **Particle size** | Categories | (e.g. $CP_{63/180}$, $LM_A5/40$ $HM_B300/1000$) |
| **Particle density** | Declared value | (Mg/m³) |
| **Resistance to fragmentation/crushing** | } | |
| **Resistance to breakage** | } Category | (e.g. $CS_{60}$) |
| **Resistance to attrition** | Category | (e.g. $M_{DE}10$) |
| **Release of dangerous substances** | e.g. Substance X 0.2 $\mu m^3$ | |
| **Durability against weathering** | | |
| **Dicalcium silicate disintegration of air-cooled blastfurnace slag** | Declared value | (Visual - Pass/ fail) |
| **Iron disintegration of air-cooled blastfurnace slag** | Declared value | (Visual - Pass/ fail) |
| **Disintegration of steel slag** | Category | (e.g. $DS_A$) |
| **Durability against freeze/thaw** | Category | (e.g. $FT_A$) |
| **Durability against salt crystallisation** | Category | (e.g. $MS_{25}$) |
| **Durability against weathering** | Category | (e.g. $SB_A$) |

**Figure 3.38** *Requirements for CE marking and labelling (from EN 13383-1:2002, Annex ZA)*

If producers voluntarily or otherwise decide to CE mark their armourstone, the producers need to comply strictly with the indicated requirements. Where the CE mark identifies particular characteristics, the supplier is required to indicate the category or declared value appropriate to the armourstone. The user is responsible for confirming that the declaration of properties on the CE mark complies with their particular requirements.

It should also be noted that where armourstone is placed on the market in a European member state that has no regulatory requirement for a particular characteristic, the supplier is not required to determine the performance for this characteristic. In this case "No performance determined" should be stated in the CE marking information.

Typically all that will be required in a contract is a tabular specification of the format shown in Table 3.17. If steel slag or other slag types or basalt are specified then additional requirements will be necessary as set out in Table 3.18.

**Table 3.17** *Selection of categories for armourstone specifications*

| Property | Category to EN 13383-1:2002 |
|---|---|
| Grading | Selection of gradings should take account of the required grading width and average mass requirements with reference to guidance in the rest of this manual (see especially Chapters 5 to 8) |
| Volume-filling materials (see Section 3.1.2.1), such as quarry-run or tout-venant used in the core of breakwaters. (See also Section 3.4.4 for further explanation of ways of controlling such materials) | Where materials are not providing any significant protection or filtration function, the grading system in EN 13383-1:2002 is not appropriate. This includes the quarry run or tout-venant materials typically used in the core materials to a breakwater. Any attempt to impose the EN 13383 system on them will lead to waste of resource and substantially increased cost.<br>Opinions vary as to whether any control at all should be imposed on such materials, but the only control that has any engineering justification is limiting the fines content at the bottom end of the grading (see Section 3.4.4), although even this will have a cost and resource penalty associated with it. |
| Coarse grading – *CP* (see Section 3.4.3 for explanations of gradings) | Insert appropriate categories from EN 13383-1:2002, Table 1, but note that such materials should not be specified for applications only requiring a volume fill. |
| Light grading – *LM* (see Section 3.4.3 for explanations of gradings) | As far as possible, **standard gradings** (see Sections 3.4.3.4, 3.4.3.6) should be used from those listed in EN 13383-1. Unlike heavy gradings, which can be modified quite easily (as the pieces of armourstone are generally handled individually), light gradings are produced using standardised equipment (screens and crushers) and procedures that are difficult to modify without incurring significant cost. When selecting gradings, every opportunity should be taken to optimise quarry yields, especially for quarries dedicated to a particular large project (see Section 3.9.5 on quarry operations and the case history in Box 3.1).<br>When selecting the appropriate category, it is suggested that EN 13383-1:2002, Table 3 category B materials be used for all applications except cover layers (see below).<br>**Cover layer applications**<br>EN 13383-1:2002, Table 2 Category A gradings should normally be used for cover layers as these gradings have a control on the average mass of the grading.<br>When assessing the size of grading required for hydraulic stability, designers should be aware of the fact that the value of $M_{50}$ (and the associated value of $D_{n50}$) is greater than the corresponding average mass $M_{em}$. Conversion factors are given in Sections 3.4.3.7 and 3.4.3.8.<br>The width of the grading $LMA_{15/300}$ is believed to be unsuitable for cover layer applications. |
| Heavy grading – *HM* (see Section 3.4.3 for explanations of gradings) | Heavy gradings can be standard gradings or non-standard gradings (see Section 3.4.3.9.) When selecting the appropriate category, it suggested that EN 13383-1:2002, Table 5 Category B gradings be used for all applications except cover layers.<br>**Cover layer applications**<br>EN 13383-1:2002, Table 4 Category A gradings should normally be used for cover layers, as these gradings have a control on the average mass of the grading.<br>When assessing the size of grading required for hydraulic stability, designers should allow for the fact that the value of $M_{50}$ (and the associated value of $D_{n50}$) is greater than the corresponding average mass $M_{em}$. Conversion factors are given in Sections 3.4.3.7 and 3.4.3.8. |
| Shape (as assessed by length to thickness ratio, *LT*; see Section 3.4.1.1) | For cover layers it is suggested that the category $LT_A$ should normally be specified. However, where the armourstone is being used beneath more than two stone thicknesses of other armourstone, then $LT_{NR}$ will normally be acceptable. |
| Proportion of crushed or broken surfaces, *RO* (see Section 3.4.1.5) | Unless naturally rounded boulders of riverine or glacial origin are being used, $RO_{NR}$ will normally be acceptable. Where natural boulders may be used in structures in which rounded stones could lead to instability then category $RO_5$ should be selected. |

**Table 3.17** *Selection of categories for armourstone specifications (contd)*

| Properties | Category to EN 13383-1:2002 |
|---|---|
| Particle density, $x = \rho_{rock}$ (see Section 3.3.3.2 for definitions) | Should be selected in accordance with EN 13383-1:2002, Table 8, which allows the designer/specifier to select the most appropriate value for the oven dry particle density, $x = \rho_{rock}$ EN 13383-1:2002, Table 8, implies that such densities should not be less than 2.3. However, in some applications it may be reasonable to use lower densities. This particularly applies to materials used for volume-filling, which are not explicitly covered by EN 13383-1:2002. It may also apply to underlayer and cover layer applications in situations where the prevailing climate at its proposed place of use is sufficiently mild (Fookes and Thomas, 1986).<br>Designers should note that in calculations for hydraulic stability of armourstone used in cover layers (see Section 5.2) the apparent density $\rho_{app}$ should be used. Netherlands Ministry of Transport, Public Works and Water Management (Laan, 1999) indicates that $\rho_{app}$ can be calculated by multiplying the (oven-dry) particle density specified in accordance with EN 13383-2:2002, Clause 8 by factors:<br>• [1 + 0.005*WA*] where the armourstone is to be used in a structure of which all or part is permanently submerged. This factor is based on half the pore volume within individual pieces of armourstone being filled with water<br>• [1 + 0.0025*WA*] where the armourstone is to be used in a structure of which all or part is temporarily submerged. This factor is based on one quarter of the pore volume within individual pieces of armourstone being filled with water.<br>In the above formulae, *WA* is the percentage water absorption of the armourstone, determined in accordance with EN 13383-2:2002, Clause 8 (see also Section 3.3.3.3). |
| Resistance to breakage (as assessed by compressive strength, *CS*, in MPa) | For cover layer applications, it is recommended that category $CS_{80}$ is selected in order to avoid excessive breakage of the armourstone through the mineral fabric.<br>For cover layers where the loadings are limited and for filtering applications, category $CS_{60}$ will be sufficient, however.<br>For volume-filling applications where grading is not critical and the standard gradings in EN 13383-1:2002 do not apply (see "Volume-filling materials" above), it will be more appropriate not to set any requirements for resistance to breakage. |
| Armourstone integrity | Although EN 13383 states that armourstone integrity is of particular importance and states that armourstone should be free from significant discontinuities that could lead to breakage during loading unloading or placing, the property is very difficult to control. Nevertheless, to gain an estimate of the degree of breakage likely and whether it can be accommodated within the design, checks for armourstone integrity are strongly advised as part of initial type testing.<br>For guidance see Section 3.8.5 and also EN 13383-1:2002, Annex B. |
| Resistance to wear (as assessed by abrasion losses determined as Micro-Deval coefficient, $M_{DE}$, in the Micro-Deval wear test | For cover layers and dynamic structures such as beaches, specify:<br>• $M_{DE}10$ for very highly abrasive environment (eg frequently stormy seas with shingle-structure interaction, fluvial torrents, dynamic armour layers including berm breakwaters)<br>• $M_{DE}20$ for highly abrasive environment (eg occasionally stormy seas with shingle or sandy foreshore)<br>• $M_{DE}30$ for moderately abrasive environment (eg occasional wave or current action with suspended sediment load).<br>For most other applications specify $M_{DE}$NR. Such applications include:<br>• cover layers where insignificant sediment loads are present in the water<br>• filtering and volume filling applications, because there is insignificant wear in such applications. |
| Water absorption | It is recommended that water absorption, *WA*, is determined in accordance with EN 13383-2:2002, Clause 8. No requirement level needs to be set, but the results are needed for two reasons:<br>• for apparent density calculations for hydraulic stability (see density above)<br>• as a screening test for durability against salt crystallisation and/or freeze-thaw attack (see below). |
| Resistance to freezing and thawing, *FT* (as assessed by loss of mass in testing) | Where it is relevant to the climate of end use for the armourstone, testing for resistance to freezing and thawing should be undertaken and category $FT_A$ should be selected. However, EN 13383-1:2002, Clause 7.3 explains that where *WA* is determined not to be greater than 0.5 per cent (category $WA_{0.5}$), no further testing is required.<br>Where armourstone is permanently submerged, freezing and thawing processes are likely to be limited in effect even in cool climates, and $FT_{NR}$ may generally be selected for such stone. (See EN 13383-1:2002 Annex C for more information.) |
| Resistance to salt crystallisation (as assessed by the percentage loss of mass, *MS*, obtained in the Magnesium Sulphate soundness test) | Where it is appropriate to test for resistance to salt crystallisation, category $MS_{25}$ should be selected. However, EN 13383-1:2002 Clause 7.3 explains that where *WA* is determined not to be greater than 0.5 per cent (category $WA_{0.5}$), no further testing is required.<br>Where armourstone is permanently submerged, salt crystallisation processes are likely to be limited in effect and $MS_{NR}$ may be selected for such stone. (See EN 13383-1:2002 Annex C for more information.) |

**Table 3.18** *Additional requirements for particular armourstone sources*

| Source | Property | Recommended EN 13383-1 category |
|---|---|---|
| Source: air-cooled blast furnace slag | Di-calcium silicate disintegration | Free, when tested in accordance with EN 1744-1:1998, 19.1 |
| | Iron disintegration | Free, when tested in accordance with EN 1744-1:1998, 19.2 |
| Source: steel slag | Disintegration | $DS_A$ (see EN 13383 for details) |
| Source: basalts | Signs of sonnenbrand | $SB_A$ (see EN 13383 for details) |

### 3.7.2 Non-EU context

It is recommended that the approaches of EN 13383 continue to be adopted for applications outside the EU. However, the following important differences in approach need to be noted.

There will be a need for external audit and confirmatory testing, since CE marking or producer declaration will not apply. It may not always be possible to achieve the level of quality control that can be enforced in Europe. In this situation there may be much greater significance for drop testing for integrity (see Section 3.8.5). The drop test will give a useful indication of the extent of the problem. The full-scale splitting test will enable designers to allow for the change in grading between initial production and final placement in the structure.

There is more freedom to use armourstone of lower density than 2.3, eg high-porosity low-density rock, which can in fact perform perfectly satisfactorily in certain applications.

In developing countries, it is much more likely than in Europe that dedicated quarries, such as those for breakwaters, will be opened up. In this case ther will be a far greater need for non-standard gradings to ensure that the design matches the quarry yield (see Section 3.9.5).

In many parts of the world, local geological maps reveal that the available construction materials are of types and geological ages (eg Tertiary) that are not normally associated with armourstone of high quality. It is therefore important to specify armourstone quality using clauses and categories that recognise the quality that is likely to be economically available. It may be very expensive to exclude materials of poorer quality from a source of mixed quality. Supply-based design approaches, using armourstone quality evaluation, durability and degradation modelling tools (see Section 3.6), together with cost-benefit analysis that includes greater maintenance options, will be needed. These combined approaches can provide a rational framework for evaluating the consequences of specifying relatively marginal or poor quality materials in circumstances where there is no viable alternative.

## 3.8 TESTING AND MEASURING

This section includes instruction and comment on the tests required by EN 13383. Annex G of this standard requires that some tests should be performed with a frequency that aims at delivering CE marking of the production. However, for specific needs within a contract or specific project, other test schedules may be required and the frequency of testing modified to fit with the need to assess variability of the deliveries. This section also provides details on complementary or alternative tests, many of which are identified in Table 3.12. The use of alternative tests to those in EN 13383 has greater significance for initial source evaluation and specifications falling outside the scope of CE and other trade-marking schemes for construction materials (see Section 3.7).

As discussed in Section 3.1.4, the choice of test methods for armourstone in Europe is quite tightly prescribed compared with the standard practice for evaluation of armourstone to be used for erosion control in the USA. In the non-EU context, ASTM test methods referred to in ASTM D4992-94 (2001) that could be used for evaluation and specification purposes where there is not a corresponding EN or ISRM (International Society for Rock Mechanics) standard, are indicated in this section or in Table 3.12. Other US publications that refer to test details are EM 1110-2-2302 (1990) Construction with large stone and ASTM D6711-01 on stones for filling gabions.

The client should consider the ability of the laboratory to carry out the testing in accordance with the general requirement. COFRAC, NAMAS, UKAS or other types of laboratory accreditation schemes will confirm the ability of the laboratory to conduct the testing with the required confidence and authority. A visit to the testing laboratory may be useful to ensure that the quality of the equipment and the qualifications of the operators are satisfactory.

### 3.8.1 Sampling

The aim of sampling in an existing quarry is to obtain material representative of the average properties available to the purchaser. The properties may be properties of the mineral fabric of the armourstone (aggregate and hand-sized pieces) or properties of the armourstone itself.

The purpose of sampling for initial evaluation of a greenfield site is mostly directed towards geological site investigation. Such sampling will differ from that described in this section, which is concerned with control and verification of the production quality.

Sampling methods are described in EN 13383-2:2002 Clause 4. They include sampling from stockpiles, bucket conveyors, bucket loaders or grabs, stationary conveyor belts, silos, floating equipment, wheeled transport and at belt and chute discharge points. Care in sampling, labelling and transport of the samples is essential if the analysis is to give reliable results. A variety of equipment is used to avoid sampling bias. The possibility of human bias, most easily introduced by visual selection, can be avoided by preparing a sampling plan.

This plan should introduce randomisation (see EN 13383-2:2002) for the sampling increments (ie sub-samples) to cover all parts of the batch that the samples are to represent. For moving material, it is recommended to sample at regular increments during loading or unloading. Sampling variation caused by the heterogeneity of the source of samples should be reduced to an acceptable level by taking an adequate number of sampling increments. In certain cases, a source supplying armourstone may consist of two or more distinct rock types. In such cases, the purchaser will require results from sample suites for each rock type. This enables the purchaser to evaluate the merits of all rock types and the scope offered by accepting unplanned or planned blends from the one source.

The sampler should be informed of the aim of the sampling. Once a representative sample of armourstone is obtained, it must be reduced to the relevant test specimen sizes and numbers. The reduction should be carried out so that no artificial bias is introduced into the test pieces or test specimens (see EN 13383-2:2002 guidance on sample reduction). Examples of good sampling practice are given in Box 3.13 and sampling work flow for selecting test portions for the various tests is given in Figure 3.39 and Table 3.19.

1 2 3 4 5 6 7 8 9 10

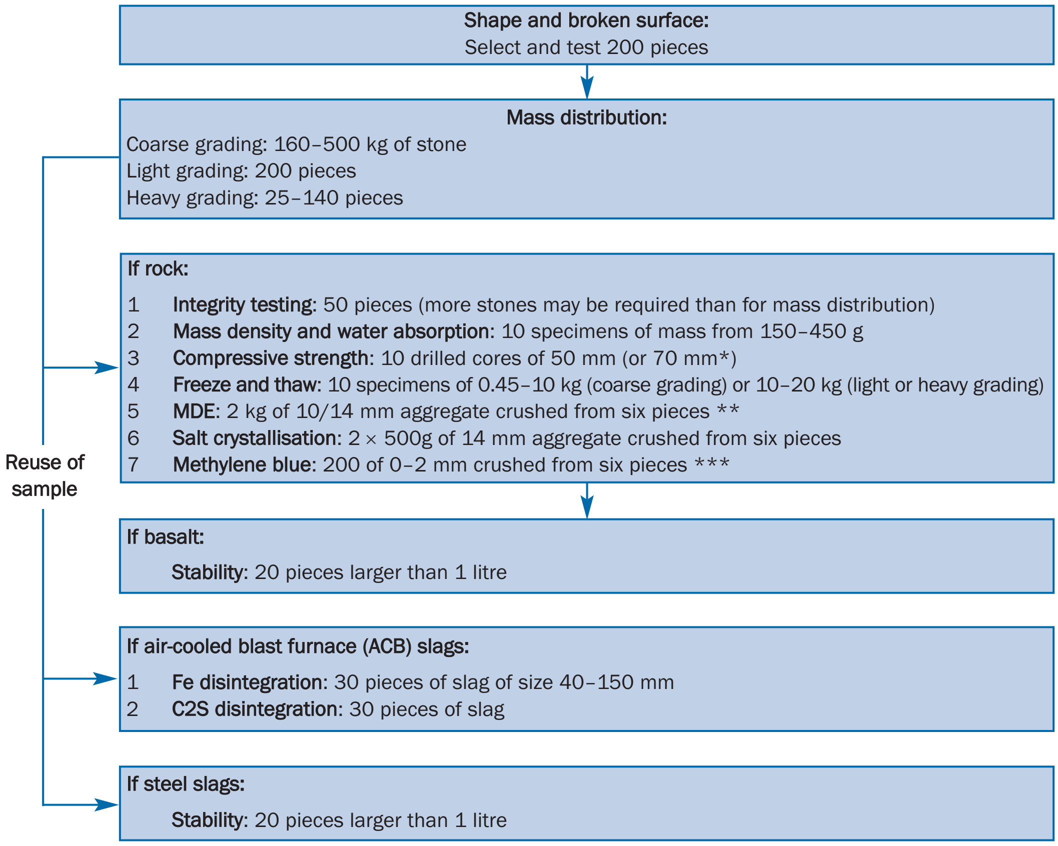


**Figure 3.39** *Sampling chart identifying possible multiple uses of the same samples and test pieces leading to economies in the testing programme*

**Notes**

* if UCS is expected to be less than 40 MPa; ** or from representative aggregate; *** not compulsory in European but recommended when concerned with clay minerals.

Specific national standards relating to use of gabions, eg those in France and USA, may introduce sampling requirements compatible with this scheme.

**Box 3.13** *Examples of sampling for moving and static stocks of heavy gradings*

**Case 1:** Sampling for the control of the mass of deliveries for a coastal contract, where $HM_{B3000\text{-}6000}$ is required (ie, a 3–6 t heavy mass grading of category B and therefore no control of the average masses). It is loaded on to a barge for further shipment to the construction site. The loading process consists of 20 000 t of material loaded from several stockpiles on the quayside into the barge. Loading takes place over 24 hours. The sampling of stones is carried out as follows: (i) every 15 minutes the wheel loader ready to empty its bucket on the barge is asked to empty it at the grading measurement point, (ii) after emptying its bucket the wheel loader takes the previously weighed sub-sample and places it on to the barge. In some circumstances, the purpose of such sampling during loading may be achieved equally well by a client's representative being present one day before loading is due to start, and weighing from parts of the stockpile. This may satisfy concerns over possible delays to the loading operation caused by weighing.

**Case 2:** Sampling of $HM_{A1000\text{-}3000}$ at a static stockpile in the quarry. A sample for mass distribution (EN 13383 requires ≥ 90 stones), shape testing (EN 13383 requires ≥ 50 stones) and initial type testing of block integrity testing is also required (≥ 50 stones) to be taken. The scope to reuse the same samples and test specimens for different tests is further illustrated in Figure 3.39. The long and thin layout of most stockpiles usually makes access practical from only one side. The number of bucket-loads needed to produce a little over the 90-stone sample is estimated. For example if nine bucket-loads of a 10 m³ wheel loader are taken: one from each end of the stockpile, one at the centre of the face of the stockpile and three equally spaced in the middle of each half of the stockpile, the nine loads emptied on the floor of the quarry consist of about 90 stones or 200 t. If the total sample is still much larger than needed it can be reduced by dividing the circular heap into eight "cake-portions" and taking the required number of portions for the near-perfect sample size. The blocks can then be numbered and weighed for input to the mass distribution test. Systematic and unbiased methods such as removing every nth block in the sequence can reduce the test portion to give a 50-stone sample for integrity testing and shape testing. The sample is ideal for providing initial type testing to give the additional shape information for integrity and blockiness, as all stones have been weighed and stone dimensions can be assessed. Note that for the full-scale splitting test for integrity (see Section 3.8.5), stones below 1 t and above 3 t as well as stones with more extreme shapes are discarded to produce a test sample of 50 stones.

**Table 3.19** *Summary of samples and test specimens required for armourstone testing (see also EN 13383-2:2002 Annex G)*

| | Coarse grading | Light grading | Heavy grading |
|---|---|---|---|
| Petrography | Drill cores, aggregate from stockpiles or exposed faces of quarries. In the case of a rock sample, the mass of material delivered for the examination shall be not less than 5 kg. | | |
| Methylene blue absorption, *MBA* | Sample: 200 g of 0–2 mm from representative aggregate. If aggregate is not available, aggregate shall be prepared by jaw-crushing of six representative armourstone pieces of similar size. | | |
| Grading | Sample mass in kg of the test specimen = NUL (mm) × 2 | 200 AS | 10–15 t: 25 AS; 6–10 t: 30 AS; 3–6 t: 60 AS; 1–3 t: 90 AS; 0.3–1 t: 140 AS |
| Shape, eg *LT* | 200 AS | Same sample and AS as grading | Same sample and AS as grading |
| Broken surfaces *RO* | Same sample and AS as grading | Same sample and AS as grading | Same sample and AS as grading |
| Mass density $\rho_{app}$ ($S_r$ = 0 and 100%) Water absorption *WA* | Sample: 10 p; if mass density is expected to be lower than 2.3 t/m³ take 40 p in one go | | |
| | Test specimen: mass between 150 g and 450 g, sawn or drilled from each different AS | | |
| Resistance to wear $M_{DE}$ | Sample: 2 kg of 10–14 mm representative aggregate. If aggregate is not available, aggregate shall be prepared by jaw-crushing fragments of 6 AS of similar size. All test aggregate to have removal of extremely flaky and cubical shaped pieces. | | |
| Resistance to minor breakage, eg *UCS* | Sample: 10 p | | |
| | Test specimen: drilled cores of 50 mm diameter and length (or 50 mm cubes). **NOTE:** 70 mm cubes and cores required if *UCS* < 40 MPa expected. | | |
| Resistance to major breakage, eg DT or FSST | | | DT: 50 AS from ELL-EUL FSST: 30 AS from NLL-NUL, good shapes |
| Dicalcium silicate disintegration of ACBS | Sample: 30 p | | |
| Iron disintegration of ACBS | 30 p of slag, with a nominal size between 40 mm and 150 mm | | |
| Disintegration of steel slag | Sample: 20 p larger than 1 litre | | |
| | Test specimen: pieces with a sawn surface larger than 0.005 m² | | |
| Resistance to freezing and thawing, eg *FT* | Sample: 10 p each to produce one p. If low resistance to freeze and thaw is expected, take 20 AS pieces instead of 10. Laboratory test piece is linked to water absorption test piece, see EN 13383-2:2002 for details. | | |
| | Test specimen: 0.45–10 kg | | Test specimen: 10–20 kg |
| Resistance to salt crystallisation, eg *MS* | Test specimen: 2 × 500 g of 10–14 mm representative aggregate. If aggregate is not available, aggregate shall be prepared by jaw crushing of material obtained from 6 AS of similar size. | | |
| Sonnenbrand *SB* | Sample: 20 p, each to produce one p larger than 1 litre | | |
| | Test specimen: pieces with a sawn surface larger than 0.005 m² | | |

**Notes**

ACBS: air-cooled blast-furnace slag, AS: armourstone pieces, p: test pieces or test specimens from different AS, DT: drop test, FSST: full-scale splitting test.

## 3.8.2 Testing of physical properties

### *3.8.2.1 Petrography*

EN 932-3:1997 gives guidance on the simplified description of petrography that shall only be used for simple identification. Detailed petrographic analysis by the ISRM method (Brown, 1981), is always advisable for evaluation of a new source, and should be performed by a qualified geologist. The methylene blue staining technique for thin sections will further help to identify minerals that may be deleterious. When clay minerals are evident from thin section analysis of the rock, the methylene blue test may be performed in accordance with EN 933-9:1999, to evaluate their significance, see also Verhoef (1992).

### *3.8.2.2 Aesthetic properties*

As mentioned in Section 3.3.1, the colour of natural armourstone should not be defined or specified more precisely than the shade of the colour. Use of colour charts for specification purposes is not recommended. Visual observation of the shade may be instructive and stockpiles should be available for inspection.

### *3.8.2.3 Rock density, water absorption and porosity*

ASTM D5779-95a (2001) on field determination of apparent specific gravity of rock for erosion control is a means for field-testing using a portable balance and system for weighing immersed specimens. It is ideal when a rapid appraisal of density and its variation is required, as no oven-drying is necessary.

The wide variety of terms in use worldwide provides considerable scope for confusion. Care has been taken to provide details (see Box 3.14) of the calculations of apparent density, $\rho_{app}$, water absorption, $WA$ (-), and degree of saturation, $S_r$ (-), as defined in Section 3.3.3.2.

Apparent mass density, water absorption and porosity, $p$ (-), are generally determined simultaneously. These properties may be determined on aggregate representative of the armourstone, samples such as cores prior to mechanical testing or pieces of armourstone. Test methods consist of weighing the test sample in an oven-dry (OD) state and saturated-surface dry state (SSD) and determining its volume either by direct measurement of a well-defined geometry or indirect measurement such as by the mass of displaced water (hydrostatic weighing). As a general rule of thumb, porosity values are about twice the values of water absorption.

A selection of useful test methods is presented in Table 3.20, see also Figure 3.8. The method defined in EN 13383-2:2002 Clause 8 is recommended in Europe.

**Table 3.20** *Methods to determine mass density, water absorption and porosity*

| Test method | Test specimens | Method used | Comments |
|---|---|---|---|
| EN 13383-2:2002 Clause 8 | Ten pieces of 150–450 g | Dry and saturated-surface dry weighing<br>Hydrostatic weighing | Test specimens can have irregular shape<br>Volume is determined indirectly |
| EN 1936:1999 | Six prismatic or cylindrical pieces larger than 25 ml | Dry and saturated-surface dry weighing<br>Geometric determination of the specimen volume | The standard provides guidance on determining the real mass density<br>Test specimens for resistance to breakage may be used |
| EN 1097-6:2000 | Minimum of 7 kg of aggregate smaller than 45 mm or minimum of 15 kg of aggregate smaller than 63 mm | Dry and saturated-surface dry weighing<br>Hydrostatic weighing or pycnometer method | Aggregate should be representative of armourstone |

**Box 3.14** *Calculation of mass density and water absorption during testing*

Masses of the test specimen, $M_T$, are determined by weighing, which is generally carried out at two extreme values of water content or degree of saturation, $S_r$:

- $S_r$ = 0 or oven-dried state, OD; in that case $M_{T(Sr=0)} = M_M$ where $M_M$ is the mineral mass (see Figure 3.8)
- $S_r$ = 100 per cent or saturated surface dry state, SSD; in that case $M_{T(Sr=1)} = M_M + \rho_w \times V_p$, where $V_p$ is the pore volume (see Figure 3.8).

The volume is either indirectly determined by hydrostatic weighing, $V_{TH}$, or directly (geometrically) measured on cores or cubes, $V_{TG}$, before carrying out other tests such as the compressive strength test.

a. **Direct measure of the volume of the test specimen:** If the volume is geometrically determined and its value is $V_{TG}$, then the apparent mass density is defined as:

$$\rho_{app(Sr=0)} = M_{T(Sr=0)}/V_{TG} \qquad (3.51)$$

$$\rho_{app(Sr=1)} = M_{T(Sr=1)}/V_{TG} \qquad (3.52)$$

b. **Non-direct measure of the volume of the test specimen, $V_{TH}$:** Hydrostatic weighing is a useful method for test specimens or aggregates with irregular shape. Equation 3.53 gives the relationship, based on:

- $V_H$ is the volume of water displaced by the specimen; $V_H = V_M$
- $M_H$ is the hydrostatic mass of the specimen determined by weighing while suspended in water

$$V_{TH} = [M_{T(Sr=1)} - M_{T(Sr=0)}]/\rho_w + V_H \qquad (3.53)$$

**Apparent mass densities are determined as follows:**

$$\rho_{app(Sr=0)} = M_{T(Sr=0)}/V_{TG} \cong M_{T(Sr=0)}/V_{TH} \cong \rho_w \times M_{T(Sr=0)}/[M_{T(Sr=0)} - M_H] \qquad (3.54)$$

$$\rho_{app(Sr=1)} = M_{T(Sr=1)}/V_{TG} \cong M_{T(Sr=1)}/V_{TH} \cong \rho_w \times M_{T(Sr=1)}/[M_{T(Sr=0)} - M_H] \qquad (3.55)$$

In natural conditions on site, the actual apparent mass density of the rock depends on its actual water content as implied by the symbol $\rho_{app}(S_r)$. The designer should make the appropriate substitution of $S_r$ in Equation 3.56 (see Section 3.3.3.3, and Table 3.17):

$$\rho_{app}(S_r) = \rho_{app(Sr=0)} \times (1\text{-}S_r) + \rho_{app(Sr=1)}\ '\ S_r \qquad (3.56)$$

**The water absorption and porosity are given by:**

$$WA = [M_{T(Sr=1)} - M_{T(Sr=0)}]/M_{T(Sr=0)} \qquad (3.57)$$

$$p = [M_{T(Sr=1)} - M_{T(Sr=0)}]/[\rho_w \times V_{TG}] \quad \text{for geometric measurement of the volume} \qquad (3.58)$$

$$p = [M_{T(Sr=1)} - M_{T(Sr=0)}]/[M_{T(Sr=1)}) - M_H] \quad \text{for hydrostatic measurement of the volume} \qquad (3.59)$$

## 3.8.3 Testing properties of individual pieces of armourstone

### *3.8.3.1 Shape*

For shape specification compliance, factory production control in EN 13383 uses the test: determination of the percentage of pieces of armourstone with a length-to-thickness ratio $LT$ greater than 3. The method to determine $l$ and $d$ uses two straight laths positioned parallel to each other at right-angles to the longest dimension $l$ and then to the smallest dimension $d$. $l$ and $d$ are measured using a carpenter's rule, a tape measure or, to achieve greater accuracy, callipers (see Figure 3.82).

Shape indicators including length-to-thickness ratio, $LT$, cubicity, $(L+G)/2E$, and blockiness, $BLc$, are discussed in Section 3.8.4.

### *3.8.3.2 Mass and size*

The mass of individual armourstone pieces is rarely determined alone but rather to determine:

- the mass distribution by combination of individual masses
- the input and output data for armourstone integrity tests that use destructive testing
- the blockiness index of armourstone pieces (relevant for individually placed armour layers).

For coarse armourstone EN 13383-2:2002 recommends the use of steel rod sieves, with square openings of 250 mm, 180 mm, 125 mm, 90 mm and 63 mm, fitting on receivers, and a single opening sieve, 360 mm. Test sieves with apertures conforming to ISO 3310-2:1999 are necessary for openings smaller than 63 mm. As an alternative to the very practical steel rod sieves shown in Figure 3.40, perforated steel plates of the same sizes as recommended in EN 933 may be satisfactory for testing.

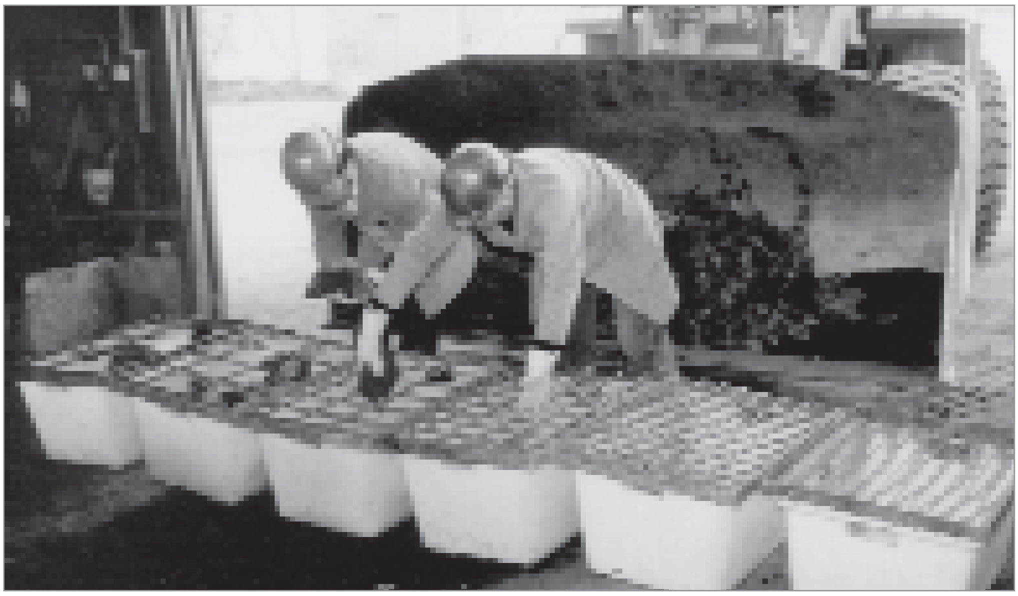

**Figure 3.40** *Steel rod sieves in use for determination of size distribution of a coarse grading (courtesy G Laan)*

For light and heavy armourstone weighing of individual pieces is needed both for the reference and alternative methods of EN 13383-2:2002. For pieces lighter less than 60–100 kg, weighing can be carried out satisfactorily using a laboratory scale. For heavier pieces, weighing scales may be used on site or in the quarry, provided they meet EN 13383 requirements on the precision (see Figure 3.41). Load cells or spring-type scales may be used (see Figure 3.42), but, again, specific attention should be given to the measurement precision. In addition to the standard certification of the equipment, it is recommended to have available a series of reference blocks of known mass for regular calibration checks during the weighing or at least for verification before each measure.

**Figure 3.41** *View of high capacity weighing scale made of portable weigh beams, used for blocks with a mass of less than 6 tonnes (courtesy S Dupray)*

**Figure 3.42**

*View of load cell and fisherman's spring-type scale (courtesy G Laan)*

## 3.8.4 Testing geometrical properties of armourstone as a granular material

### *3.8.4.1 Shape*

EN 13383 offers two tests to constrain unwanted stone shapes in armourstone deliveries.

**Determination of the percentage of pieces of armourstone with a length-to-thickness ratio *LT* greater than 3.** The standard requires percentage $LT > 3$ to be controlled for all gradings but introduces different ways of calculating the percentage so that there is no bias, eg towards the shape of the smaller particles. The test method requires $LT$ to be estimated visually and measured only on borderline blocks.

**Proportion of crushed or broken surfaces, *RO*.** Clearly, freshly blasted or crushed pieces of quarried rock are angular and can be said to have greater than 50 per cent surface area that is joint-bounded or newly crushed or broken. Rounded glacial boulders, cobbles and core stones from basalt and dolerite quarries have a completely different visual appearance. The test is by visual assessment and counting of these non-angular stones. The proportion of stones without crushed or broken surfaces can then be declared by the producer or restricted by the specifier.

**Measurement of shape parameters.** The measurement of mean length-to-thickness ratio and mean blockiness is based on the determination of specifically defined dimensions. For blockiness, in addition to determining the $X$, $Y$ and $Z$ dimensions of the enclosing cuboid of the stone, stone masses and rock density are required (see Box 3.15). It is therefore recommended to carry out shape determination at the same time as the other properties, such as mass distribution or integrity, are determined. It is advisable to measure $X$, $Y$, $Z$, $l$ and $d$ of all 50 pieces in the sample. This provides for greater accuracy in the EN 13383 test. It also generates the additional information for mean and standard deviation of $LT$ and $BLc$ as may be requested for initial type testing by designers and contractors for the layer thickness and void porosity prediction (see Section 3.5.1.1). Tape measures are sometimes used, but the use of a custom-made calliper is greatly preferred if the required accuracies are to be achieved. The maximum dimension, $l$, is often given by the long diagonal in more tabular and blocky rocks. It is sometimes best computed by means of Pythagoras's Theorem when callipers are not practical.

**Box 3.15** *Shape assessment including measurement of blockiness*

This box provides necessary information for executing assessment of blockiness and includes discussion of variability of shape measurement descriptors. For definition of blockiness, *BLc*, and length-to-thickness ratio, *LT*, see Section 3.4.1.

For heavy armourstone that cannot be manipulated easily, the determination of dimensions *X*, *Y*, and *Z* involves subjective judgement. *X*, *Y*, and *Z* are theoretical dimensions corresponding to the axial dimensions of the minimum volume enclosing box. To the operator, the directions of *X*, *Y*, and *Z* may be immediately apparent and the dimensions easily estimated, or, for less blocky stones, the directions may be difficult to visualise. Values of *l* and *d* are more objectively defined. *LT* is still subject to large operator errors during test conditions for irregular blocks because of uncertainty with *d*, which can lead to significant errors in the ratio *l*/*d*.

To execute the blockiness assessment test, a representative sample of 50 stones is selected. For each stone to be assessed in turn, first locate the minimum thickness (bar spacing through which the stone could just pass) *d* and record this as the *Z* dimension and direction. Then view (or imagine viewing) parallel to the *Z* dimension. Consider different possible directions for orthogonals *X* and *Y* in the plane perpendicular to *Z* (and *d*). Choose the directions for *X* and *Y* that enclose the block in an imaginary box that has a minimum for the product *XY* and thus for the whole block. Record these as *X* and *Y*.

**NOTE:** The French system for cubicity measurement uses an alternative, though again potentially subjective, set of orthogonal dimensions to characterise the form of a block. First, the length *l* (=*L*) is measured, then *E* and *G* are set orthogonal to the direction of *L* where *L* may be the long diagonal on a blocky rock. It is possible that in practice the requirement that *L* is set to be the longest dimension is relaxed in the case of obviously blocky rocks.

Report values of *X*, *Y*, and *Z* (and *l* if requested) on a spreadsheet, making a descriptive note of the use of callipers, laths and tapes. Note that to measure *BLc* also requires mass and density determination, which is usually available if the testing is combined with grading control or armourstone integrity tests.

**Discussion of variability**

Blockiness measurement is generally considered more subjective than length-to-thickness ratio, but in a field study (Newberry, 2003) accuracy was greater than expected. The coefficient of variation of *BLc* and *LT* was determined per typical block from a sample taken from a heavy grading. Each stone was measured by seven operators using pocket tape measures. For both shape descriptors, the standard deviation divided by the mean from all seven operators (issued with the same instruction guides and of varying experience) was determined. Between the seven operators, the coefficient of variation *CoV* was obtained and then averaged over the total number of stones. The average *CoV* for *BLc* and *LT* was 0.13 and 0.11 respectively, assuming no influence from variability in weighings and density determination. This suggests that field conditions may lead to comparable accuracy for *BLc* and *LT* determinations even though *l* and *d* are more objectively defined than *X*, *Y*, and *Z*. It appears that variation in assessing the value of *d* is high. The average *BLc* for the sample determined by each operator ranged from 61.0 per cent to 57.2 per cent and average *LT* ranged from 2.03 to 2.21. With correct use of callipers and laths as described in EN 13383-2:2002, greater reproducibility for *LT* would be expected. This sample consisted of only 46 blocks and a mix of two rock types, suggesting more research is required to examine the apparent similarity in accuracy of assessing mean *LT* and mean *BLc*.

### 3.8.4.2 Mass distribution

EN 13383-2:2002 specifies the following two methods for determining the mass distribution of light and heavy gradings:

- the *reference method*, which should be used in cases of dispute
- the *alternative method*, which is quicker and more suitable for production control than the reference method but is less precise.

The minimum number of pieces of armourstone, excluding fragments, required to be used in a test portion depends on the grading category the armourstone material appears to fall into on initial visual inspection.

The reference method weighs all the stones individually and uses the mass of weighed stones. In the alternative method, bulk weighing may be carried out on stones visually sorted into categories. EN 13383-2:2002 describes both these methods. Box 3.16 illustrates the fundamental methods behind plotting grading results. In Box 3.17, results of these are shown together with results of another method that can be used for production control, based on visual comparisons.

Further consideration of methods for testing gradings can be found in ASTM D6092-97 (2003) on standard practice for specifying size of stone for erosion control and the US Army Corps EM 1110-2-1601 (1994) for rip-rap.

**Box 3.16** *Guidance on calculations for generating mass grading curves*

A sample of natural armour stones will display a range of stone masses or sieve sizes. The percentage of total mass lighter or smaller than a given mass or size is used to construct cumulative curves in the assessment of mass and size distributions. $M_y$ expresses the stone mass for which y per cent of the total sample mass is lighter. For example, $M_{50}$ is the mass of a theoretical stone for which half of the mass of the sample is lighter. The distribution of particle masses or sizes can be represented by cumulative curves with reference to percentage of (i) total mass or (ii) total number of pieces. These differences have been a source of confusion. The characterisation of granular materials in geotechnics and coastal engineering refers to percentage of total mass. It is instructive to give an example showing how the different results are generated from first principles using real figures obtained for a sample of 25 stones. In the example, shown in Table 3.21, the results generated by inserting discrete values are also compared with those produced by grouping similar masses into intervals (bins) before forming the cumulative curve. Differences in the results are shown plotted in Figure 3.43 and summarised in Table 3.22.

**Table 3.21** *Calculation of cumulative curves*

| C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | C12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone masses (tonnes) | Cum mass | Cum % by mass less than | Cum % by number less than or equal to stone mass | Bin mass range | Mass in range | Cum mass | Cum % by mass less than ref mass | Number in range | Cum number less than ref mass | Cum % by number less than ref mass | Ref mass |
| 0.65 | 0.65 | 1.26 | 4 | | | | | | | | |
| 0.71 | 1.36 | 2.65 | 8 | 0.00-0.49 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 | 0.5 |
| 0.91 | 2.27 | 4.42 | 12 | | | | | | | | |
| 1.14 | 3.42 | 6.64 | 16 | 0.50 - 0.99 | 2.27 | 2.27 | 4.42 | 3 | 3 | 12 | 1.0 |
| 1.27 | 4.69 | 9.11 | 20 | | | | | | | | |
| 1.39 | 6.07 | 11.80 | 24 | 1.00-1.49 | 5.27 | 7.54 | 14.65 | 4 | 7 | 28 | 1.5 |
| 1.47 | 7.54 | 14.65 | 28 | | | | | | | | |
| 1.59 | 9.13 | 17.73 | 32 | 1.50-1.99 | 10.68 | 18.22 | 35.40 | 6 | 13 | 52 | 2.0 |
| 1.67 | 10.79 | 20.97 | 36 | | | | | | | | |
| 1.73 | 12.52 | 24.33 | 40 | 2.00-2.49 | 13.45 | 31.66 | 61.53 | 6 | 19 | 76 | 2.5 |
| 1.82 | 14.34 | 27.87 | 44 | | | | | | | | |
| 1.89 | 16.23 | 31.54 | 48 | 2.50-2.99 | 5.38 | 37.04 | 71.98 | 2 | 21 | 84 | 3.0 |
| 1.99 | 18.22 | 35.40 | 52 | | | | | | | | |
| 2.02 | 20.24 | 39.33 | 56 | 3.00-3.49 | 9.68 | 46.72 | 90.80 | 3 | 24 | 96 | 3.5 |
| 2.09 | 22.33 | 43.39 | 60 | | | | | | | | |
| 2.19 | 24.52 | 47.64 | 64 | 3.50-3.99 | 0.00 | 46.72 | 90.80 | 0 | 24 | 96 | 4.0 |
| 2.26 | 26.78 | 52.04 | 68 | | | | | | | | |
| 2.39 | 29.17 | 56.68 | 72 | 4.00-4.49 | 0.00 | 46.72 | 90.80 | 0 | 24 | 96 | 4.5 |
| 2.50 | 31.66 | 61.53 | 76 | | | | | | | | |
| 2.64 | 34.31 | 66.66 | 80 | 4.50-4.99 | 4.74 | 51.459 | 100 | 1 | 25 | 100 | 5 |
| 2.74 | 37.04 | 71.98 | 84 | | | | | | | | |
| 3.02 | 40.06 | 77.84 | 88 | | | | | | | | |
| 3.25 | 43.30 | 84.15 | 92 | | | | | | | | |
| 3.42 | 46.72 | 90.80 | 96 | | | | | | | | |
| 4.74 | 51.46 | 100.00 | 100 | | | | | | | | |

C1 are the masses of 25 individually weighed armour stones that have been placed in ascending order. C2 gives the progressive sum as each new mass is added to the previous one. C3 divides C2 by the total mass and expresses it as a percentage. C4 gives the proportion of stones with masses lighter than the one in C1 and therefore goes up by 4 per cent for each new stone as there are 25 blocks in all. For a 90-stone sample, C4 entries would go up by 100/90 or 1.1 per cent. C1 to C4 generate data for cumulative plots that show one data point for each mass. They are therefore the most accurate and are termed discrete cumulative plots.

**Box 3.16** *Guidance on calculations for generating mass grading curves (contd)*

C5 to C12 show calculation stages to create binned cumulative plots. C5 shows the selected mass intervals and their upper value represents the reference mass given in C12 required for plotting binned cumulative lighter plots. C6 to C8 develop data for the binned plots for cumulative percentage by mass, while C9 to C11 develop data for the binned plots of cumulative percentage by number of stones.

The plots of C1 versus C3 and C4 are shown together with plots of C12 versus C8 and C11 in Figure 3.43. All four plots are different: binned plots place curves further to the right of discrete plots and curves based on percentage by number are generally shifted to the left of curves based on percentage by mass. In summary, binning makes a small but sometimes significant change to the discrete results: the fewer bins, the larger the significance. Cumulative plots by mass are fundamentally different to cumulative plots by number. Readers should be warned that graphing software has automatic functions to generate cumulative plots and these invariably make the assumption that it is the cumulative **plot by number** (ie the frequency of occurrence of the mass or other parameter in question) that is required in histograms and cumulative plots.

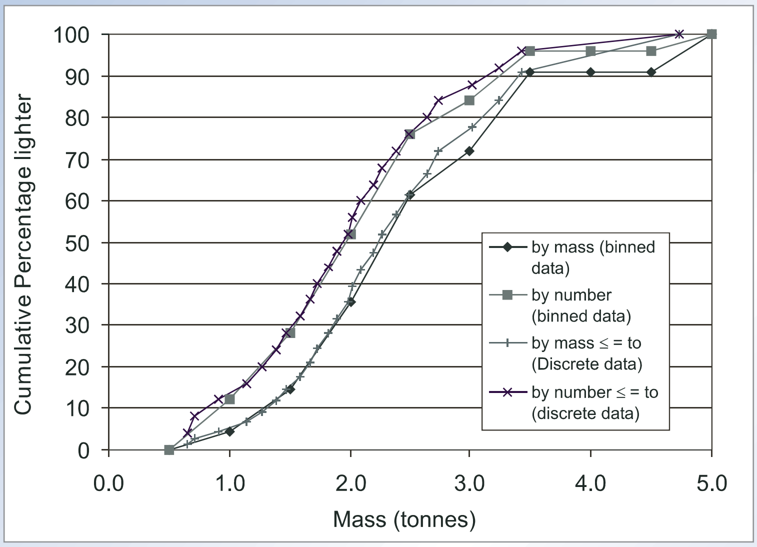


**Figure 3.43**

*Examples of different mass distribution cumulative plots obtained from the same mass values*

Having created any one of the four curves, specific percentiles of the cumulative curve such as $M_{50}$, $M_{85}$ and $M_{15}$ can be obtained, eg by graphical linear interpolation from an enlarged plot, by mathematical linear interpolation of adjacent points spanning the specific percentile, or by curve fitting. Using linear interpolation, Table 3.22 shows how the percentiles, such as those used for design, can have different values depending on whether the percentage data is discrete, binned, by mass or by number. For mass distributions in coastal engineering, the correct values to use are percentage by mass, the discrete data being more accurate. Note that the arithmetic average mass $M_{em}$ is the same in each case and the ratio $M_{50}/M_{em}$ by mass is considerably above unity and by number it is considerably below unity.

**Table 3.22** **Variation in design parameters resulting from different calculation methods**

| | Discrete data | | Binned data | |
|---|---|---|---|---|
| Parameter | By mass | By number | By mass | By number |
| $M_{50}$ (t) | 2.23 | 1.94 | 2.28 | 1.93 |
| $M_{15}$ (t) | 1.48 | 1.09 | 1.51 | 1.09 |
| $M_{85}$ (t) | 3.27 | 3.18 | 3.08 | 3.04 |
| $M_{85}/M_{15}$ (-) | 2.21 | 2.84 | 2.04 | 2.78 |
| $M_{em}$ (t) | 2.06 | 2.06 | 2.06 | 2.06 |
| $M_{50}/M_{em}$ (-) | 1.08 | 0.94 | 1.11 | 0.94 |

For sieve size distributions, particles cannot in general be counted and there is only one possible analysis method, namely that based on percentage by mass using bins corresponding to available sieve intervals. The percentage by mass and binning methods are therefore used together to create particle size distribution statistics and curves. An example of when percentage by number is used is when analysing the distribution of shape descriptors within a sample of blocks. Percentage by number gives a more meaningful expression of the occurrence of extreme shapes.

**Box 3.17** *Alternative methods for the determination of mass distribution*

The following box presents the mass distribution (see Figure 3.44) determined in accordance with the standard method (curve a) and the alternative method (curve b) of EN 13383. Curve c shows the mass distribution determined without weighing but by sorting armourstone pieces visually into four separate mass ranges (ie four bins) defined by the five limits: ELL, NLL, (NLL+NUL)/2, NUL and EUL. This task may be made easier by sourcing five witness blocks with approximately the same limit masses that should then be prominently displayed for visual comparison and checking.

Bin 1 contains blocks of mass visually estimated to be between ELL and NLL; the number of blocks is called $N_1$. Similarly, Bin 2 contains $N_2$ blocks from NLL to (NLL+NUL)/2; Bin 3 contains $N_3$ blocks from (NLL+NUL)/2 to NUL; Bin 4 contains $N_4$ blocks from NUL to EUL. Each bin is supposed to contain blocks with an average mass equal to the average mass of the bin limits. Bin 1 would then contain $N_1$ blocks of mass $m_1$ = (ELL+NLL)/2 and have a total estimated mass of $N_1 \times m_1$. The cumulative proportion in each bin is given by $X_1 = m_1/M_T$; $X_2 = X_1 + m_2/M_T$; $X_3 = X_2 + m_3/M_T$, where $M_T$ is the total mass of armourstone. The cumulative mass lighter is determined by plotting $X_i$ as a function of the upper limit of the bin. The average mass is estimated by $(N_1 \times m_1 + N_2 \times m_2 + N_3 \times m_3 + N_4 \times m_4)/(N_1 + N_2 + N_3 + N_4)$. Curve d shows the mass distribution determined similarly for eight bins.

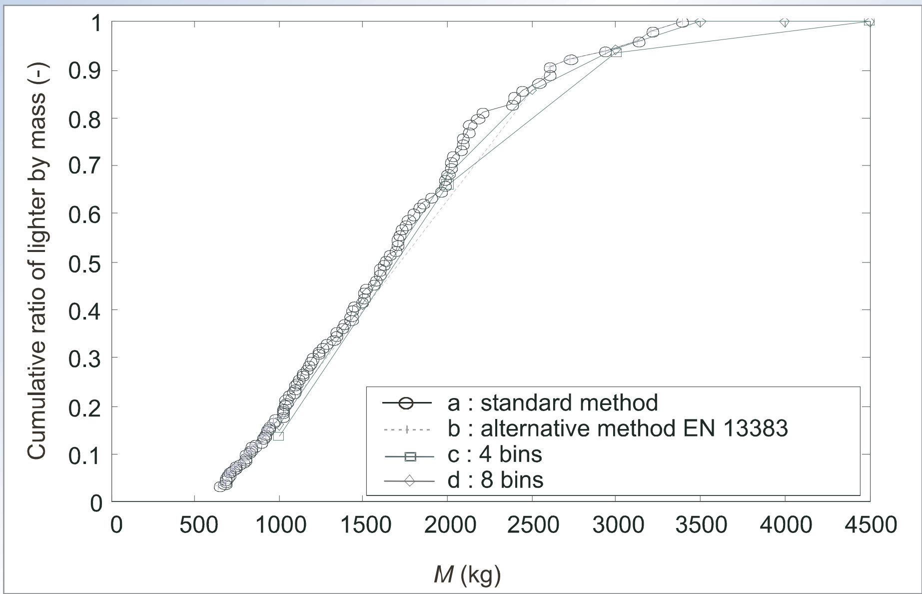


**Figure 3.44** *Mass distributions determined with (a) the reference method and (b) the alternative method of EN 13383, (c) and (d) by visual sorting in bins with estimation of the mass of each bin*

## 3.8.5 Mechanical properties

### *3.8.5.1 Resistance to breakage*

In EN 13383, tests under the heading resistance to breakage refer only to strength of the mineral fabric determined on hand-sized specimens or aggregates. As such resistance to breakage is only appropriate to assess the risk of minor breakage of armourstone and will not necessarily indicate armourstone integrity as discussed in Section 3.3.4. EN 13383 requires that the resistance to breakage of the mineral fabric of armourstone shall be determined using the compressive strength test according to EN 1926 Annex A. This test method differs only marginally from more conventional rock mechanics test methods for unconfined compressive strength, termed *UCS*.

For testing with EN 1926 Annex A, 10 specimens are prepared from separate pieces of armourstone. They should be cubes with 50 mm edge or cylinders whose diameter and height are equal to 50 mm. Note that for material with an expected compressive strength lower than 40 MPa, the use of test specimens with characteristic sizes of 70 mm is allowed. Test specimens should be tested in their saturated condition that is reached after soaking in water for (48 ± 4) h. If any existing plane of anisotropy is identified, it shall to be clearly indicated on each specimen by means of two parallel lines and mentioned in the test report. Results from the test on 10 test pieces enables (i) the mean of the best nine and (ii) the strength of the two weakest specimens, to be compared with the specified requirements.

The **point load strength test** (ISRM, 1985) is a portable, rapid means to assess the resistance to breakage of the rock that can be performed on cores, sawn blocks or rough chiselled lumps. Results are corrected to the equivalent value for 50 mm cores and expressed as the point load strength index $I_s$ (sometimes written $I_{s(50)}$), which correlates well with *UCS*, where $UCS \approx 22I_s$ (EN 1926 Annex B). Since it is easy and cheap to use, this test may be appropriately used for quarry evaluation and quality control purposes.

Further tests are indicative of the strength of mineral fabric:

- indirect Brazilian tensile strength (ASTM D3967-95a, 2004; ISRM, 1978), whose ratio to the compressive strength gives an indication of the rock brittleness
- fracture toughness (ISRM, 1988), which indicates resistance to crack propagation and is sometimes recommended but is difficult to perform
- Los Angeles (EN 1097-2:1998) is currently performed on aggregates for factory production control and could be used as a quality control means provided a proven and sure correlation with *UCS* is given
- Schmidt impact (ISRM, 1988) and sonic velocity (EN 14579:2004) are indirect non-destructive tests that provide indicators of the existence of cracks.

Values of these various tests are given in the guide to durability (Table 3.12).

### 3.8.5.2 *Armourstone integrity*

Standard integrity clauses based on subjective visual criteria alone have often failed to provide sufficient safeguard against "unfair" rejection by the purchaser as well as "unfair" acceptance. No standard test for armourstone integrity is currently recommended in EN 13383. Guidance on approaches to assess integrity is given in Annex B of EN 13383. There are two approaches for the quantification of the likelihood of major breakage that can improve the subjective visual assessment.

**Destructive testing** aims at (i) reproducing the characteristic loading to which the armourstone may be exposed such as for the drop test (DT), or (ii) exposing the test specimen to standard loading such as for the full-scale crushing test (FSCT) or the full-scale splitting test (FSST). Whereas the drop test is a routine quality control test to perform at the quarry, it does not allow prediction of the grading changes. Designers prefer to have FSCT or FSST results, as they may be used with design tools to predict grading changes. Such standard loading tests may be performed as an initial type test when selecting a quarry.

**Non-destructive testing** is based on auscultation of armour stones using sonic waves. Unexpectedly slow sonic velocities through a piece of armourstone indicate the presence of open cracks or flaws. Note that the test results are highly sensitive to the test conditions, notably existence of small cracks in the vicinity of the measuring device and the coupling media. Test methods are detailed in Box 3.18. Non-destructive testing is appropriate for quality control during deliveries especially for borderline strength large stones. It is recommended to calibrate threshold values against destructive test results.

While in principle, non-destructive methods for integrity are preferable and they may eventually prove superior since they are a suitable means to evaluate the quality of the material that is used, none is currently more reliable than existing destructive tests.

**Box 3.18** *Assessment of armourstone integrity using non-destructive sonic velocity test methods*

Based on the success of sonic velocity detection of cracks in small specimens, full-scale methods have been developed in France and in the Netherlands. The principles of each approach are given in this box together with details of the method to evaluate armourstone integrity using the **continuity index**, $I_c$, based on more than 15 years of French experience with armourstone specification and testing.

The continuity index, $I_c$ (%), is defined as:

$$I_c = \frac{V_p}{V^*} \cdot 100 \tag{3.60}$$

where $V_p$ is the P-wave velocity (m/s) measured through the armourstone test piece and $V^*$ (m/s) is a theoretical sonic value determined from the mineral composition of the rock as given in Table 3.23.

For other rock types, $V^*$ may be determined from detailed petrographic analysis (Denis *et al*, 1979). $I_c$ values decrease with both cracks and porosity and the degree of fissuration, $D_f$ (%), is a means of separating the effect of discontinuities from the effect of natural porosity, *p* (%), and is given by (Tourenq *et al*, 1971):

$$D_f = 100 - 1.4 \times p - I_c \tag{3.61}$$

**Table 3.23** *Theoretical sonic velocity V* values used for $I_c$ calculation (Denis et al, 1979)*

| Rock type | Granite Gneiss | Diorite | Gabbro Amphibolite | Quartzite Sandstone | Schist | Limestone | Dolomite |
|---|---|---|---|---|---|---|---|
| $V^*$ (m/s) | 6000 | 6500 | 7000 | 6000 | 5800 | 6600 | 7200 |

The characteristic value of $I_c$ to be reported for each stone is the minimum value determined after measuring in three orthogonal directions. The measurements should be performed on 30 blocks at least. For a sample to be assigned to an armourstone integrity category such as $I_c(60)$ or $I_c(80)$, two conditions should be verified: (i) the mean value is greater than *x* and (ii) less than 10 per cent of the blocks display a value lower than *x*, where *x* is the number in the brackets (expressed as a percentage). Suggested integrity ranking based on values of both the degree of fissuration, $D_p$ (%), and the continuity index, $I_c$ (%), are given in Table 3.24.

A Dutch method is presented by Niese *et al* (1990). It requires 20 measurements of the P-wave velocity, $V_p$ (m/s), per individual stone (the research used between 17 and 25). The spread of results is then plotted as the cumulative percentage of stones by number (y-axis) with velocity less than a certain velocity (x-axis). Both a larger spread and a lower average velocity imply poorer integrity. Thus, a **normalised velocity anisotropy index**, $I_d$ (-), was defined for each stone as:

$$I_d = (R_{90}/R_{10})/R_{50} \tag{3.62}$$

where $R_y$ is the velocity represented at *y* (-) per cent, equal to $V_{p,y}/V_{p,max}$, where $V_p$ is the P-wave velocity (m/s).

Practical difficulties include: length of time to take each reading, methods are limited to armourstone gradings below about 6 t, and obtaining technical equipment and trained personnel. Suggested integrity ranking based on the normalised velocity anisotrophy index, $I_d$ (%), is also included in Table 3.24.

**Table 3.24** *Proposed ranking of integrity from non-destructive measurement*

| Excellent integrity | Good integrity | Marginal integrity | Poor integrity |
|---|---|---|---|
| $D_f < 20\%$ | $D_f < 20\%$ | $D_f < 20\%$ | $D_f < 20\%$ |
| $I_c(80) \le I_c$ | $I_c(70) \le I_c \le I_c(80)$ | $I_c(50) < I_c \le I_c(70)$ | $I_c < I_c(50)$ |
| $I_d \le 1.25$ | $1.25 \le I_d \le 2$ | $2 \le I_d \le 3$ | $I_d > 3$ |

Destructive testing is the most direct approach to assess the resistance of the armourstone population to major breakage. Of the many such test methods reported, the **drop test** or **DT** (Latham and Gauss, 1995), **full-scale crushing test** or **FSCT** (Tørum *et al*, 2000) and **full-scale splitting test** or **FSST** (Dupray, 2005 and Dupray *et al*, 2007) are the only tests to have descriptions or field results recorded in sufficient detail to permit widespread use.

For the drop test, the degradation process is pragmatically reproduced by dropping individual pieces of the armourstone population from a height that is representative of the average loading experienced during construction. For the full-scale splitting test, a better control of impact conditions occurs: an impactor is released from a standard height on to the test specimen, leading to a test result that is not directly representative of degradation experienced but may be used for the prediction of grading changes.

The test configurations are presented and discussed in Box 3.19. The detailed approaches for testing and analysing for drop test and full-scale splitting test are given respectively in Box 3.20 and Box 3.21.

It is recommended that the reference test for factory production control of integrity is the drop test (Box 3.20). When more accurate prediction of the effect of integrity at a new source is required and a designer wishes to predict degradation caused by breakages, then the FSST (Box 3.21) is to be recommended as part of initial type testing. FSCT may also be used, although it is not presented here since the equipment required makes it difficult to perform. For further details refer to the key report, Tørum *et al* (2000).

Combining the results of any breakages suffered by each stone tested into a result for the whole sample provides a characteristic value of integrity for the armourstone population. Useful indicators to analyse destructive test results but also to characterise degradation experienced by an armourstone population in the field are summarised below.

- $B_n$ is the ratio of the number of pieces that display major breakage to the number of pieces in the population. For an objective determination of $B_n$, Equations 3.63 and 3.64 are recommended

  $$B_n = (\text{number of stones with } L_m \geq 10 \text{ per cent after testing})/(\text{number of stones tested}) \quad (3.63)$$

  $$L_m = (M_i - M^*_f)/M_i \quad (3.64)$$

  where $L_m$ is the loss of mass (%), $M_i$ is the mass of the stone prior to testing (kg), and $M^*_f$ is the mass of the largest piece remaining after the test (kg)
- $I_{Mx}$ is the relative decrease of a characteristic mass with reference to the initial mass prior to degradation, at a given fraction or percentage passing value on the cumulative plot (see Equation 3.4).

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**Box 3.19** *Configurations for full-scale destructive tests for integrity*

The test configurations are presented in Figure 3.45.

For the drop test (DT), individual armourstone pieces are dropped onto an anvil made of a bed of other armourstones of similar size. The surface of the anvil should be levelled and laid in a single compact layer on a 0.5 ± 0.05 m thick layer of crushed rock aggregate.

For the full-scale splitting test (FSST), an impactor is dropped on to the top of the individual armourstone piece to be tested, which is positioned on an anvil. The anvil consists of one block of the same rock type and its mass, $M_A$, should be $M_A$ = EUL ± 5 per cent. The anvil should be buried within quarry-run rockfill, compacted and levelled at ground level.

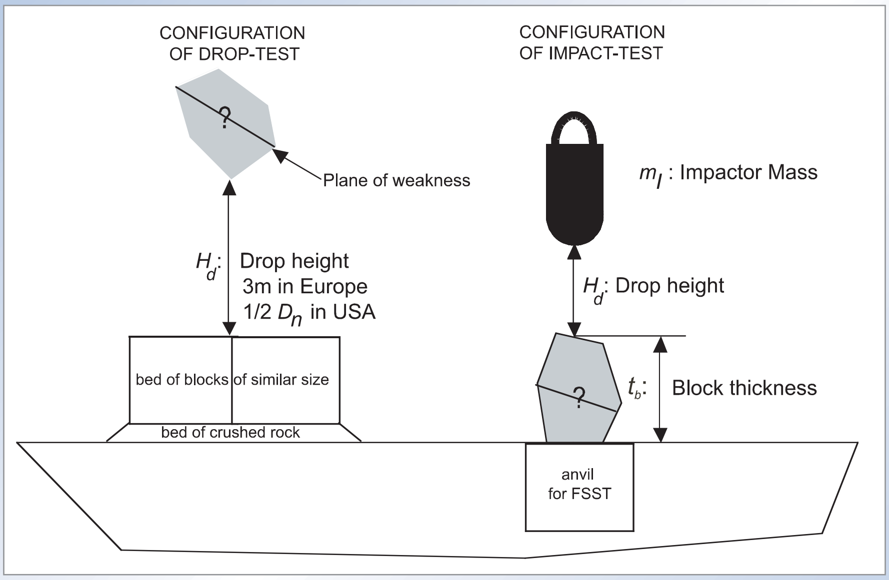


**Figure 3.45** *Comparison of test configurations for drop test and full-scale splitting test*

When performing these tests, specific attention should be paid to the height and alignment of the stone (for the drop test) or of the impactor (for FSST). This may be achieved by using a control chain fixed to the grab (for the DT) or along the impactor (for the FSST) with appropriate length. For the drop test, spinning or undesired rotation of the block during the fall should be avoided by using appropriate machinery such as an orange-peel grab.

**NOTE:** Performing these tests in a quarry is an unfamiliar activity that may be repeated only every two to five years. Specific risk assessment and safety procedures must be devised and adhered to. Operators should be instructed to wear appropriate protection and personnel kept at sufficient safe distances to avoid flying rock fragments. Machinery will also need to be protected. A suggested template for risk assessment is included in Appendix A2.

**Both types of destructive test are rather time-consuming to perform and require some assistance from the quarry, preparation, time and equipment, space and safety attention. Destructive tests should therefore be specified and performed only where necessary.**

**Box 3.20** *Determination of the drop test breakage index, $I_{d50}$*

The drop test is used on heavy gradings to reproduce degradation related to construction. Its results are expressed in terms of the breakage number $B_n$ or drop test breakage index, $I_{d50}$. The **sample** should contain at least 50 pieces, using sampling in accordance with EN 13383-2 from masses above the ELL of the grading in question. **Equipment and other aids** consist of a suitable hydraulic grab (the orange-peel type is recommended), weighing equipment accurate to within 2 per cent of ELL, and an anvil (see Box 3.19).

**To execute the test**

1 Before the test, determine the individual masses of each armourstone piece and also the initial mass distribution using the standard method of EN 13383.

2 Subject each block in the test sample in turn to a drop on to the anvil, ensuring a fall height of 3 m ± 0.1 m.

3 Set aside all resulting pieces whose mass is greater than the ELL mass, or whose mass is assessed to be close to the ELL mass, for further weighing.

4 Record the result of each drop, noting the number and type of visible flaws in blocks and the number and type of blocks or broken pieces resulting.

5 Clear all rock fragments from the anvil, leaving clean surfaces before dropping the next stone.

6 On completion of the drop test for each stone in the test sample, individually weigh and record the mass of each stone piece heavier than the ELL. Record the mass of the heaviest of these pieces, $m_f$*, corresponding to each dropped stone.

**Calculate the value of $B_n$** using Equation 3.63 and 3.64.

**Calculate the drop test breakage index, $I_{d50}$** as follows. Plot the cumulative mass distribution curves for the total (50-block) sample before drop testing and the cumulative mass distribution after drop testing for all pieces heavier than the ELL. By linear interpolation of the cumulative plot, calculate the median sample mass before testing $M_{i50}$ and the median sample mass of pieces above ELL after testing $M_{fELL50}$. The **drop test breakage index**, $I_{d50}$, is given by:

$$I_{d50} = (M_{i50} - M_{fELL50})/M_{i50} \tag{3.65}$$

**NOTE:** After the drop test, there is usually only one piece remaining that is larger than ELL, although it is just possible to have two. Therefore the cumulative mass distribution derived from each largest piece after each impact, $M_f$*, is practically identical to that including all pieces heavier than ELL, but may differ. Particular care should therefore be taken when inspecting the cumulative mass distribution curves using all pieces larger than ELL or if using $M_f$*. They will both be different from the actual mass distribution after testing because they exclude the finer fragments. Thus, $I_{d50}$ underestimates the expected decrease of $M_{50}$ during construction.

**NOTE:** $I_{d50}$ assesses both integrity and resistance of the mineral fabric to breakage.

**Report** the following data: the drop test breakage index, $I_{d50}$; a reference to this box; a description of the sample including its mass grading; the source of the sample; the date of testing. If agreed beforehand, the cumulative mass distributions before and after testing shall be provided (it is recommended that this be on a single graph), together with the value of $B_n$.

The drop test is a quality control tool that may be performed in two days (including sampling) with equipment available at the quarry. The drop test result is highly variable, however, because of the lack of impact geometry control such as block motion, discontinuity orientation and location of impact on the block.

The full-scale splitting test is a tool for the designer to predict mass distribution changes. The test takes longer to perform (maximum three days including sampling) and requires an impactor. However, it provides a good control of the test conditions on impact and yields results that show up the effects of discontinuities. It provides a means to relate the degradation during routine handling and during service life to the results of an integrity test (FSST), as explained in Section 3.6.6.

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**Box 3.21** *Determination of the full-scale splitting test index, $I_{FSST50}$, and characteristic integrity, $C_{FSST}$*

The FSST is used to determine the maximum effect of discontinuities on the mass distribution. The test result yields both an FSST index value, $I_{FSST50}$, and an FSST strength value, $C_{FSST}$. The actual mass distribution change of the grading can be determined using the degradation model of Section 3.6.6. The **test sample** shall contain at least 30 blocks sampled in accordance with EN 13383-2, with masses larger than the NLL mass. Stones with *LT* above 3 should be discarded during preparation.

**Equipment and other aids**. The mass of the **impactor**, $M_I$, is close to the average nominal limits of the grading considered, $M_I$ = (NLL+NUL)/2 ± 5 per cent, and the radius of the impactor should be close to the radius of the average nominal limits $r_I = 0.5\,(M_I/\rho_{app})^{(1/3)}$. The release equipment of the impactor should allow a good control of the height and position of the impactor. The use of tyre and sling to handle the impactor is a simple but effective method. Alternatively, a dedicated shackle whose opening is controlled from a crane may be used. **Weighing equipment** should be accurate to within 2 per cent of ELL.

**Test procedure**

1. Each stone is weighed before testing and its mass, $M_i$, recorded.
2. Each stone is visually examined to detect any possible planes of weakness. Sonic measurement can be carried out to quantitatively determine the weakest direction, should any exist in the test specimen.
3. The test specimen is placed on the anvil with the plane of weakness as vertical as possible.
4. The impactor is lifted to the required height, $H_d$, above the centre of the sample and released.
5. All fragments (as defined in Section 3.4.3.5) larger than 10 per cent of NLL are individually weighed and their individual mass recorded.
6. The total number of FSST sample test stones subjected to impacts, $n_{FSST}$, is recorded.

**NOTE:** The FSST has been performed and verified in the field for the standard grading 1–3 t, with an impactor mass, $M_I$, of 2 t and an anvil mass, $M_A$, of 4.5 t. The drop height $H_d$ was 2 m (Dupray, 2005).

**Calculate the value of $B_n$** using Equations 3.63 and 3.64.

**Calculate the FSST index**. Plot the point-by-point cumulative mass distribution curves for the sample prior to drop testing. Plot the point-by-point cumulative mass distribution after FSST using the total initial mass as the reference mass for the standard method of EN 13383-2 – ie in Clause 6.5.1 of EN 13383-2. Calculate the median sample mass before testing, $M_{i50}$, and the median sample mass of pieces above ELL after testing, $M_{f50}$. The FSST index, $I_{FSST50}$ (-), is given by:

$$I_{FSST50} = (M_{i50} - M_{f50})/M_{i50} \tag{3.66}$$

**NOTE:** $I_{FSST50}$ represents the maximum mass distribution decrease that may be expected from discontinuity propagation. As with $I_{d50}$ in the drop test, $I_{FSST50}$ includes the effect of minor breakage.

**Calculate the FSST characteristic integrity, $C_{FSST}$**. Plot both pre- and post-FSST mass distributions. Determine the vertical of the post-FSST mass distribution curve at mass *M* = *0.1.NLL* to determine the value of *F* (see also Section 3.6.6.1). Determine the area below the mass distribution curve pre-FSST, $A_i$ , and post-FSST, $A_f$ . An approximate value of $C_{FSST}$ (J/kg) can be determined using Equation 3.67.

$$C_{FSST} = \frac{g n_{FSST} M_I H_d}{M_T} \sqrt[3]{\frac{A_f - A_i - F \cdot (NLL + NUL)/2}{(NLL + NUL)/2}} \tag{3.67}$$

where $M_T$ = total mass of the consignment tested; $n_{FSST}$ = number of stones tested. $A_f$ and $A_i$ can be determined by numerical integration of the area below the mass distribution curves. Alternatively, the reader may refer to Figure 3.34.

**NOTE:** $C_{FSST}$ accounts specifically for the effect of discontinuities. Populations of blocks displaying open cracks tends to have a value of $C_{FSST}$ smaller than 27 J/kg whereas others with no significant discontinuities tend to display $C_{FSST}$ larger than 35 J/kg.

**Report** the following data: the breakage rate, $B_n$, the full-scale splitting test index, $I_{FSST50}$, and the full-scale splitting test characteristic integrity, $C_{FSST}$; a reference to this box; a description of the sample including its mass grading; the source of the sample; the date of testing. If agreed beforehand, cumulative mass distributions before and after testing should be provided, eg to predict degradation. It is recommended that this be on a single graph.

### 3.8.6 Durability and accelerated weathering tests

Ideally, cyclic stressing simulation tests (for example, freeze-thaw, sulphate crystallisation, wetting and drying, thermal cycling), should be carried out on sample stones of the same size as those to be used on site. This is impractical, however, so a compromise for routine testing is necessary. Specially designed test procedures using large pieces (eg greater than 20 kg) may sometimes be recommended in the material evaluation process for a source with no service history. There is a greater need to use non-standard large test pieces if the recommended test piece size will not capture the features of the rock texture that are of concern. The integrity test on full-scale armourstone is another way of detecting such large-scale features, although possible weakening by cyclic stressing leading to opening of macro-flaws will not have been reflected by integrity tests. The largest test specimen size in the EN 13383 standard freeze-thaw test uses 10–20 kg pieces. Many specialist tests and investigations of armourstone degradation were described in the volumes by McElroy and Lienhart (1993) and Magoon and Baird (1991).

#### 3.8.6.1 Freeze and thaw test

Only very rarely has degradation induced by freeze and thaw occurred in rock with water absorption, *WA*, lower than 0.5 per cent. EN 13383 considers that rock with *WA* < 0.5 per cent is resistant to freeze and thaw.

The test method (EN 13383-2:2002 Section 9) is based on visual assessment and a threshold value for the loss of mass of armourstone pieces undergoing 25 freeze and thaw cycles between +20°C and -17.5°C with a period at 0°C. For the material to be considered resistant to freeze and thaw, no more than one piece among the 10 tested should display signs of degradation.

Refinements to this method, based on widespread practice for rock and concrete durability testing have been proposed, where additional sonic velocity measurements are taken before and after freeze-thaw cycles (see Box 3.22). They have been suggested by several countries, eg France and Austria, and should be considered for source evaluation in aggressively cold environments.

#### 3.8.6.2 Salt crystallisation test

The European test method recommended for resistance to salt crystallisation of armourstone, EN 1367-2:1998 Clause 8, sometimes referred to as the *magnesium sulphate soundness test*, is based on the standard test for 10–14 mm aggregate samples using magnesium sulphate solution. Repeated immersion in saturated solutions of magnesium sulphate is followed by oven-drying to partially or completely dehydrate the salt precipitated in permeable pore spaces. The internal expansive force, derived from the rehydration of the salt upon re-immersion, was originally intended to simulate freeze-thaw action. It is considered more representative of the precipitation of sea salt from intertidal and splash zones of hot dry coastal environments than the freeze-thaw test using fresh water. The test uses five precipitation cycles and may take three weeks. It attempts to measure only the weaknesses in the armourstone at the mineral fabric grain-scale. If there is a requirement for rock with *WA* > 0.5 per cent to have resistance to salt crystallisation, it is to be set at *MS* < 25 per cent according to EN 13383-1:2002 Annex C and measured according to the test for thermal and weathering properties in the EN 1367-2:1998 magnesium sulfate test. In the USA, it is common to conduct the test using sodium sulphate in place of magnesium sulphate. The percentage loss in the latter test is usually 1.5 to 2 times higher than in the former, the factor depending upon rock type.

The equivalent US test, ASTM C88-99a, is more labour-intensive and also takes three weeks to perform. It uses a range of aggregate sizes up to 125 mm and weights the results of the test according to size fraction. This permits the effect of possible meso-scale flaws in the larger pieces to be detected. The EU standard for railway track ballast (EN 13450:2002) introduces a magnesium sulphate test with 31.5–50 mm aggregates. Such a test would also give meaningful results for comparing armourstone sources.

The chemical reaction that occurs between carbonate and sulphate in solution is a concern. The test may not be suitable for all rock types, and reservations have been expressed elsewhere in respect of some carbonate aggregates and some aggregates having a high

1 2 3 4 5 6 7 8 9 10

proportion of magnesium bearing minerals or of cryptocrystalline quartz. There is therefore always a high variability associated with the sulphate soundness test and usually at least a three-week reporting time. When the strength of visible microcracks is in question, an experienced geologist's visual examination of cored specimens that have been subjected to a five-cycle sulphate soundness test can be more useful than the numerical result of the standard test.

**Box 3.22** *Outline of alternative French freeze-thaw test method using sonic velocity*

A representative sample is selected at the quarry consisting of at least five stones. Test specimens are prepared by coring a cylinder of at least 15 cm diameter and 30 cm length or by sawing so that two sawn faces are perpendicular and display an area for visual examination greater than 15 cm × 15 cm and 10 cm thickness (see Figure 3.46). Before the test, photographs of the sawn faces are taken and the P-wave velocity is measured in three perpendicular directions. The size of the sample is small enough to use a sonic velocity tester of the type used routinely for concrete testing. The samples are exposed to 25 freeze and thaw cycles as required in EN 1367-1:2000. The armourstone is considered to be resistant to freeze and thaw if (i) no open crack is observed after the cycles and (ii) less than 20 per cent of the pieces tested display a decrease of sonic velocity larger than 15 per cent.

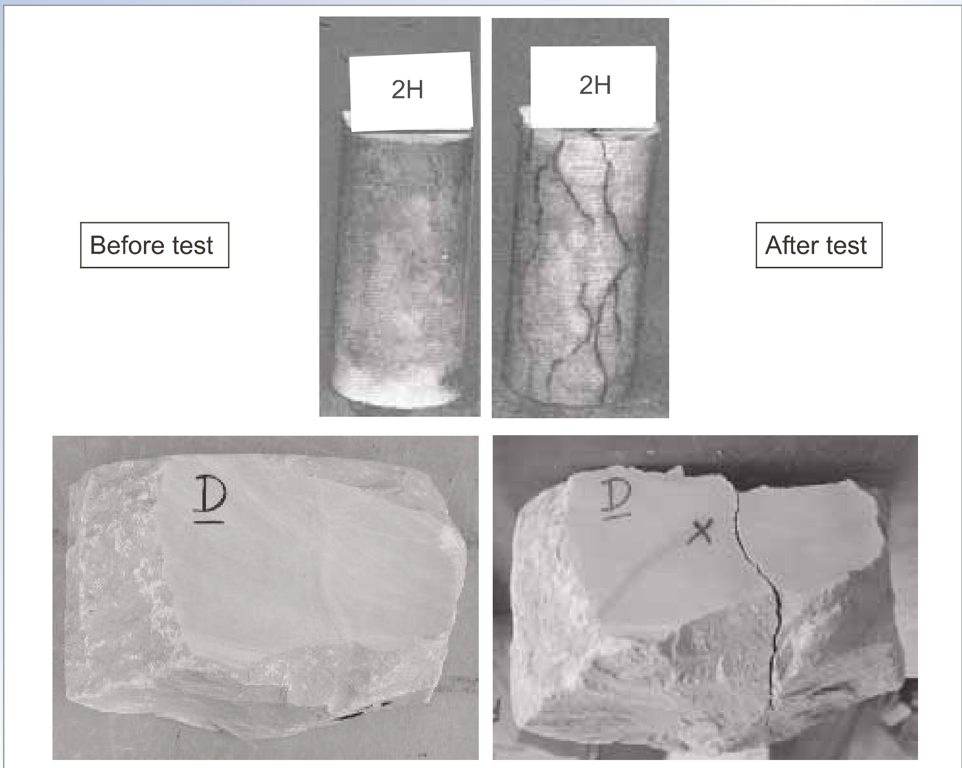



**Figure 3.46** *Samples before and after freeze-thaw test using sonic velocity. Top: specimen with wet surface displaying discontinuities and significant decrease of sonic velocity after test. Bottom: specimen displaying open cracks and significant decrease of sonic velocity. Before test: Sonic velocity, $V_p$ = 5100 m/s, continuity index, $I_c$ = 76 per cent; after test: $V_p$ = 2600 m/s, $I_c$ = 40 per cent (Top: courtesy S Dupray, bottom: courtesy J Perrier, CNR)*

### 3.8.6.3 Test for breakdown by Sonnenbrand

***Sonnenbrand*** is defined in EN 13383-2:2002 as a type of rock decay that can be present in some basalts and which manifests itself under the influence of atmospheric conditions. Sonnenbrand starts with the appearance of grey or white star-shaped spots. Usually hairline cracks are generated, radiating out from the spots and interconnecting them. This reduces the strength of the mineral fabric, and as a result the rock decays to small particles.

The laboratory sample for testing for Sonnenbrand consists of a single piece of basalt armourstone, which is cut to give two test portions, each with a sawn surface equal to or greater than 0.005 m². One test portion is examined for signs of Sonnenbrand after boiling for 36 h. A record is made of any formation of grey/white star-shaped spots and cracks (both hairline and larger) and any breakage of the test portion. As an aid to examining the boiled test portion, a comparison can be made with the unboiled test portion. The star-shaped spots and associated cracks of rocks exhibiting deterioration by Sonnenbrand are shown in Figure 3.47.

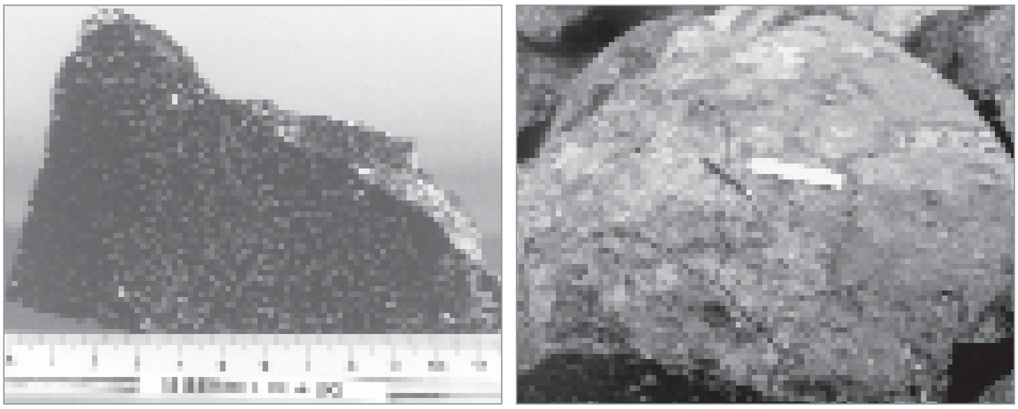


**Figure 3.47** *Stones affected by the "Sonnenbrand effect" (courtesy G Laan). Left: pattern on the surface of basalt rock, leading to severe failure; right: considerable cracking interpreted as being caused primarily by Sonnenbrand effects*

### *3.8.6.4 Non-European tests and other source evaluation tests*

The geometry of pore spaces contributing to the microstructure of the mineral fabric is strongly indicative of susceptibility to weathering in engineering time. When the ratio of microporosity to macroporosity is relatively high, cyclic stressing caused by water penetration and crystallisation effects is much more severe because the solutions do not drain away rapidly. This can be discovered by testing using a procedure described in Lienhart (2003).

Tests designed to reveal weakness resulting from the effects of clay minerals may be particularly appropriate for argillaceous sedimentary rocks, impure micritic limestones, and many igneous rock showing signs of weathering. Examples of such tests include: wetting and drying, ASTM D5313-04, and methylene blue absorption, EN 933-9:1999. A novel testing approach for degradation prediction in hot climates based on thermal cycling is described in Box 3.23.

### *3.8.6.5 Chemical analysis, organic matter and leaching tests*

Such analysis and tests are not generally relevant for armourstone derived from quarried rock but may be used where organic matter or significant soluble minerals are thought to be present in the rock. Organic content may be determined by removing it from the sample by heating or by chemical means (EN 1744-1). For leaching, EN 1744-3 may be used. Rock samples from mining areas suspected of having potentially toxic minerals may be sent to geological laboratories for an elemental analysis of constituents.

**Box 3.23** *Thermal cycle testing for hot climate applications*

The test presented in this box was developed by CNR for riverbanks in the south of France to predict degradation of fine-grained impure limestones as well as some granites caused by day/night heating/cooling cycles and rapid cooling during summer storms. The test aims to reproduce these conditions.

The test specimens of 20 × 10 × 10 cm parallelepipeds are prepared by sawing individual pieces. The bottom of the test sample is locked while the top is heated. A single identified face is regularly exposed to water spray. The specimen is exposed to 160 cycles of 4 hours composed of:

1. 3 hours of heating from room temperature to 80°C by putting the specimen in a isolated container heated by a set of electrical resistors.
2. 10 minutes without heating.
3. 40 minutes of violent cooling by water spray from a series of nozzles.
4. 10 minutes without wetting or heating.

Every 10 minutes, the vertical and horizontal lengths and internal and surface temperature of the specimen are measured. It is then possible to compare visual observations of the specimens, modes of degradation, dilatancy and temperature. Temperature variations inside the sample may vary from 25°C to 60°C.

This test is proposed as an important complement to petrographic analysis for projects where the hot site environment carries a risk of causing thermal degradation. It is relevant for selecting rock sources displaying a certain degree of weathering or containing minerals that may evolve with time. The test takes more than a month to perform but can provide an objective understanding of predicted degradation, the mechanism involved and the selection of alternative rock sources. Example results of indicative behaviour are shown from micritic limestones in Figure 3.48.

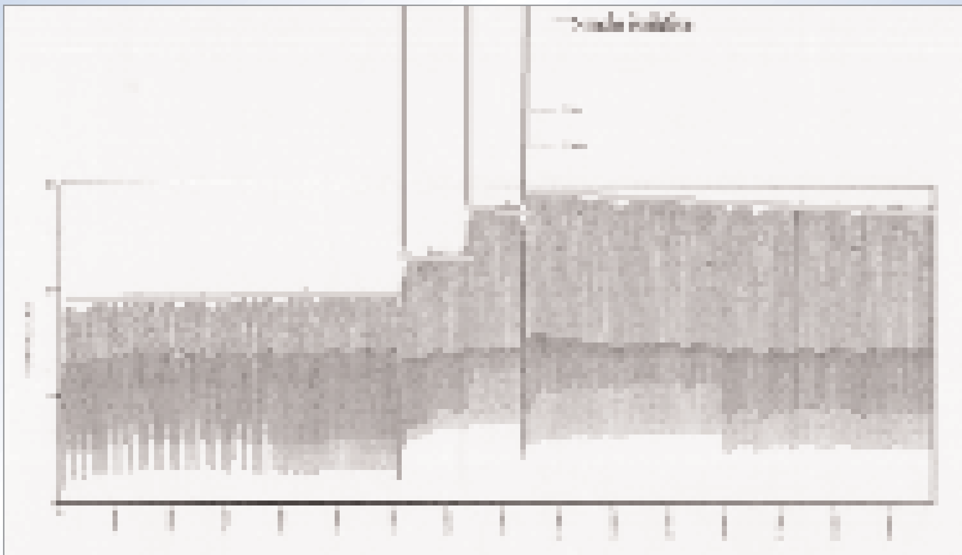


**Figure 3.48** *Trace recording of thermal cycling. The lower trace indicates the inside temperature, the upper trace the surface temperature; the steps reveal the rock has undergone degradation (courtesy J Perrier, CNR)*

## 3.9 QUARRY OPERATIONS

For the purpose of sourcing armourstone, quarries fall into three categories.

**Aggregate quarries.** In general, activity in these quarries focuses on procedures for roadstone and concrete aggregates production. Aggregates production and processing is core business so any armourstone production is undertaken with minimum possible disruption to normal markets. Quarry operators will however, consider on commercial merit all trading opportunities and additional costs associated with armourstone production, handling, storage, quality control and quality certification. Aggregate quarries willing to adjust blasting and processing to improve armourstone yields are ideal for the contractor and the material costs may be very reasonable since all excess material from an armourstone blast is processed along with routine aggregates production. What makes armourstone from a dedicated quarry expensive is the set-up cost and the amount of materials that cannot be used. By adapting procedures in an aggregates quarry in this way, the problem is solved.

**Dedicated quarries in greenfield sites.** These quarries are set up specifically to be the source of rock for a particular contract. The rate of production of armourstone can therefore be geared to the scale of the quarry operation, so there are no delays for the construction team. The major disadvantage is that a considerable amount of excess material, such as the fines and sizes not required, will be left over. The cost of producing these excess materials has to be recouped and is usually reflected in a higher price for the products sold. Furthermore, it is becoming increasingly difficult worldwide to open a quarry in a greenfield site, particularly at short notice, considering all the permits and the environmental impact assessment required. For large breakwater projects, adapting existing quarries is becoming increasingly favoured.

**Dimension stone quarries**. Reject blocks from dimension stone quarries are ideal for the supply of very large armourstone. Typically, dimension stones are cut out or pneumatically split using a row of closely spaced holes. Many blocks extracted in this way have to be disqualified from further processing, ie cutting and polishing, either because of visual appearance or flaws. Similarly, natural blocks that are bounded by several angled joints are of no use as dimension stone products. If very large, these are further broken up by a breaker. Such *rejects* are manoeuvred into big waste heaps from where they need to be recovered if they are to be sold as armourstone by-product. Where these uneconomic waste blocks of the dimension stone industry are near coastal waters, they often make excellent sources of heavy armourstone. The production of smaller gradings generally requires secondary breakage. The distribution of shapes within a consignment, some pieces being very blocky, may need careful consideration for certain applications.

Section 3.9 is organised in two parts: Sections 3.9.1–3.9.5 deal mainly with quarry evaluation and yield prediction while Sections 3.9.6–3.9.9 cover the practical aspects of running armourstone operations in the quarry.

## 3.9.1 Exploration and evaluation

The principles of locating and evaluating a quarry are summarised in this section. An important part of this process is the discontinuity survey and the *in situ* block size distribution assessment, which are presented in Section 3.9.2. Blast design specific to armourstone production is briefly outlined in Section 3.9.3, while in Section 3.9.4 emphasis is given to the use of Rosin-Rammler curves and the prediction of quarry yield curves. For large projects requiring dedicated sources of armourstone, quarry yield prediction is a critical part of design optimisation. To check whether the proposed design will result in higher or lower utilisation of the quarried rock, yield-matching methods are described in Section 3.9.5.

### *3.9.1.1 Quarry evaluation of armourstone in general*

Analysis of *in situ* block sizes and analysis of rock quality (covered in Section 3.6) are essential and distinct tasks. In practice, they are addressed together at the time of the quarry site evaluation. Information should be gathered and processed in a systematic manner – see for example the generalised scheme applicable to both greenfield sites and existing quarries shown in Figure 3.7 in Section 3.2.3. The assessment of data and the analysis tools required to prepare an armourstone evaluation report for a potential source should draw upon details found in many parts of this Chapter, eg Sections 3.2, 3.3, 3.4, 3.6, as well as Section 3.9, which includes *in situ* and blast size analysis.

### *3.9.1.2 New armourstone quarry in a greenfield site*

The process of exploration and evaluation leading to the decision to set up a new armourstone resource aims to:

1 2 3 4 5 6 7 8 9 10

- locate a target resource
- determine the quality and production rate for different sizes of armourstone
- determine the economics of extraction
- determine the cost of processing up to the quarry gate
- assess the planning and environmental costs of extraction, restoration and processing
- optimise the distance from site or transport facilities
- ensure the facilities around the quarry have the capacity to transport armourstone to load-out facilities. This includes considerations such as road capacity and crane capacities in the local harbour
- for small quarries, the stocking area might be an issue
- obtain the quarry production engineer/quarry operator.

Many of these points are developed in Smith (1999). The literature search and field *reconnaissance* is focused on areas constrained by suitable geology for block size and quality and by economic distance of the resource from the project site. Opening a new armourstone resource follows the same basic process as for any mineral resource, irrespective of the scale of the material requirements, and has much in common with the search for rock-fill and construction materials in highway and dam engineering works. In most countries, project engineers should be aware that it is increasingly difficult to obtain planning permission to open a new quarry or even to open a *borrow pit* for a small project.

The primary objective is to locate a source with large enough natural blocks (ie one with a suitable *in situ* block size distribution, IBSD). Large discontinuity spacings averaging greater than 1 metre usually indicate an *in situ* rock mass that will yield sufficient volumes of large blocks (see Table 3.25). In general, sources that can yield large blocks will also be of satisfactory physical and durability properties. Exceptionally, this is not the case. Rock sources are inherently variable and evaluation of rock quality using tests is always necessary. Many insights into the practicalities of setting up a dedicated armourstone quarry in a greenfield site and advice on delivering armourstone gradings efficiently for a large breakwater project can be found in Van Meulen (1998).

### 3.9.1.3 Principles of armourstone yield assessment

Predicting the blasted block size distribution (BBSD) is the key to assessment of armourstone potential in new temporary (ie dedicated) quarries as well as in the adaptation of aggregates quarries for armourstone production. Modern approaches to modelling blasting, increasingly applied to aggregates and ore blasting, require an estimation of the size distribution of blocks in the rock mass that exists prior to blasting and certainly an indication of the maximum *in situ* block size. Such approaches are even more applicable to armourstone production because large blocks cannot be produced if they are not there in the first place. Once it is established that a good proportion of large blocks naturally exist in the rock mass before blasting, many of the *in situ* blocks will be liberated and remain unbroken to produce heavy armourstone if the blast is designed correctly. This natural block size distribution, due to intersecting discontinuities, is termed the *in situ* block size distribution, IBSD (sometimes referred to as ISBD).

To assess the top sizes and yield curves of armourstone, the rock engineering investigation has the following logic, as illustrated in Figure 3.49:

*In situ* discontinuity analysis → IBSD prediction → blast modelling → BBSD prediction and assessment.

The range of methods of IBSD assessment and the underlying importance of IBSD were explained in a recent review of rock mass blastability and fragmentation by Widzyk-Capehart and Lilly (2002). While there are many blasting engineers and geotechnical consultants with expertise in quarrying techniques, experience in armourstone operations remains relatively scarce. Production methods and yield prediction techniques applicable to armourstone have proven difficult to find from literature. Various suitable approaches have therefore been brought together here in Sections 3.9.2–3.9.4. It should be noted that blast design and yield prediction are not exact sciences and the approaches suggested below are essentially qualitative, subject to large possible errors and should be supplemented with genuine blasting experience whenever possible. Nevertheless, they do represent methodologies that can significantly help a production team constrain the cost of a project and achieve its objectives.

### 3.9.2 Assessment of *in situ* block size distribution, IBSD

The most directly relevant set of initial geotechnical data needed for planning production is a 3D survey of the discontinuities of the rock mass to be blasted, leading to an IBSD prediction. If such a survey and analysis from surface outcrop is not practical or too expensive, there are several possible field techniques giving measurements that correlate with the degree of jointing or the mean size of *in situ* blocks such as drill core recovery, rock quality designation and seismic velocity. Palmström (2001) presents a practical overview of these methods to assess the degree of jointing and the conversion to mean *in situ* block volumes. Logging of borehole drilling rate and resistance force or down-hole sonic velocity measurements (Rat, 1973; Allard and Blanchier, 1980) are alternative indirect approaches. These are sometimes referred to as measurement while drilling (MWD) techniques (Segui and Higgins, 2001).

Discontinuities in most rock masses can be classified into sets according to their orientations. There are usually three sets, because rock masses of orthogonally jointed bedded sedimentary sequences are common. For a greenfield site investigation, with poor outcrop exposure, borehole orientation is critical if discontinuity spacing data is to be recovered from all major discontinuity sets. In many circumstances, vertical drilling is the only practical approach to sampling the rock mass. Such investigations will focus on the plan-shape variability of vertical spacings and intact rock strengths deduced from drill core recovery. In general, a more extensive site investigation yields greater cost savings. Data from core recovery can be used to assess the average *in situ* block dimensions using the weighted joint density method of Palmström (2001) if both spacing and obliquity of the discontinuity to the core axis is logged. This method is given as the final IBSD method, see below.

In addition to logging discontinuity spacings from recovered solid cores, down-hole visualisation surveys of joint traces using open-hole drilling can be a fruitful investment. These provide the data needed to assemble an IBSD prediction as the discontinuity orientations in space are detected.

With the rapid advances in digital imaging, semi-automated geological face mapping, including joint mapping, is being developed for input to many rock mechanics application software packages. These systems may soon enable IBSD to be determined rapidly from computer software, without manual mapping of joints. Related research and commercial software can easily be located using internet searches with terms such as services, automated, joint, “rock slope”, laser, imaging, technology, software. Until these systems become more robust and can generate joint set and spacing data (an example of such technology developments is described by Slob *et al*, 2005), manual, photo-analysis and laser-assisted scanline mapping offer the best practical means to obtain complete IBSDs.

Assessment of test blasting in a potential quarry area is of limited value unless the 3D variability of discontinuity spacing, eg to depths and in regions that are of potential interest, is also evaluated.

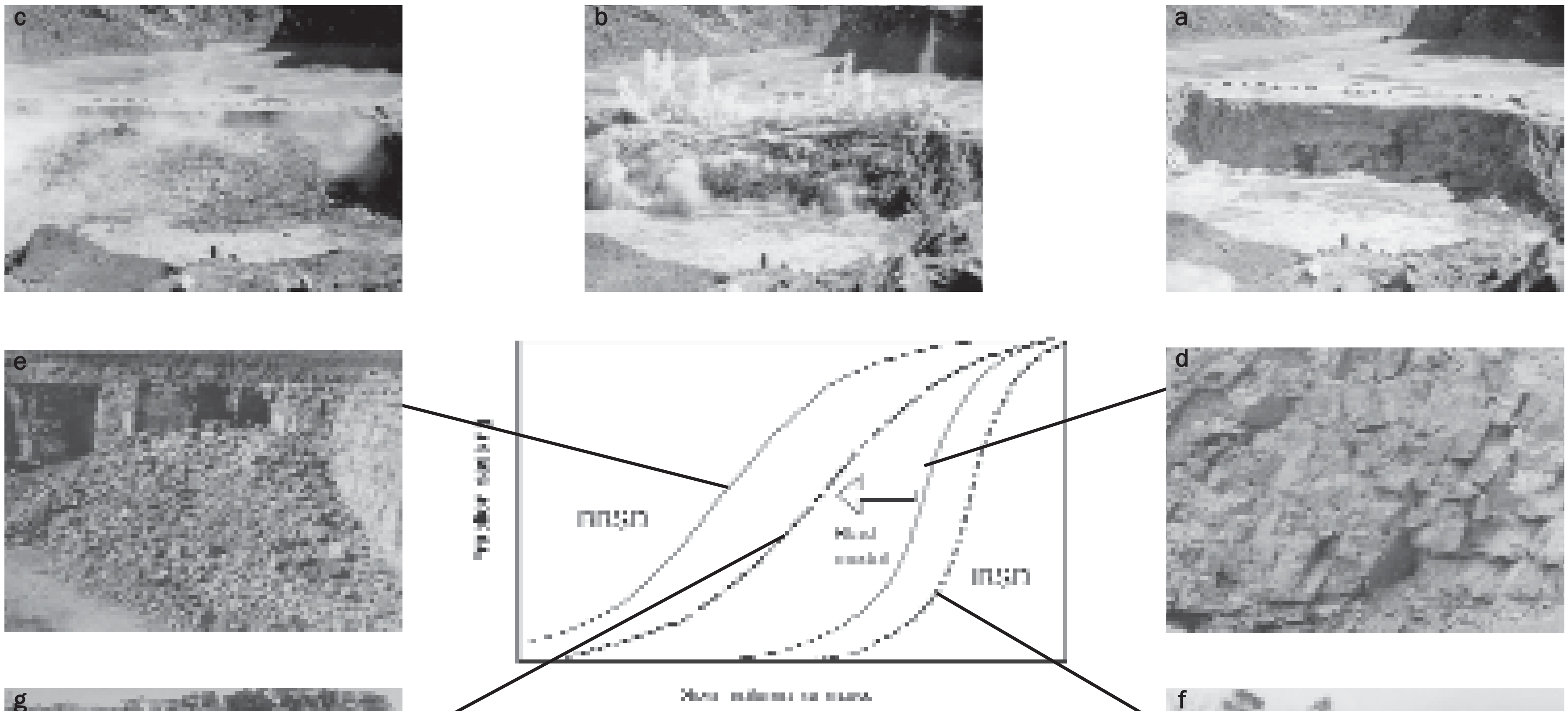


**Figure 3.49**

*Schematic illustration of quarry yield prediction. a,b,c: before, during and after multi-row high-fragmentation blast in aggregates quarry; d: in situ blocks in intensely jointed quartzite showing two discontinuity sets with mean spacing of ~0.4 m, which indicates that this aggregates quarry cannot produce heavy armourstone (1 m scale bar bottom right); e: aggregates blast and high fragmentation in aggregates quarry, low armourstone yield mainly from blocks liberated from stemming section; f: in situ blocks in outcrop of gneiss from proposed greenfield site for armourstone quarry with mean joint spacing of ~2m; g: armourstone blast in aggregates quarry, large armourstone yields from loosened blocks*

### 3.9.2.1 *Scanline mapping of discontinuities*

IBSD assessment begins with discontinuity data acquisition and analysis. The method described here in brief is the scanline method (Figure 3.50). Wang (1992) divided the scanline methods into two kinds.

- Quick scanline. This just gives the location of each joint intersection along a scanline, with respect to an origin taken at one end of the scanline. Usually a measuring tape (eg of 30 m) is stretched out along a direction for which plunge and azimuth are recorded. It may be possible to generate quick scanline data from photographs, from laser surveys (eg using quarry face profilers) and also from borehole walls and cores.
- Detailed scanline. The orientation of each discontinuity plane is measured using a compass clinometer and noted together with the intersection of that plane (or its projection into space) along the scanline. Figure 3.51 shows a data entry sheet for such a survey. It is useful to code the degree to which discontinuities persist, for example less than 3 m may be assumed as the maximum trace length to indicate non-persistent (n) and all the rest as persistent (p). Many modern joint pattern analysis programs also require the discontinuity trace-length and truncation geometry to be recorded. Further discussion on discontinuity identification is given in Section 3.2.2.

**NOTE:** The purpose is to represent the IBSD of the 3D volume of the rock mass in its condition prior to detonation. Blast-induced fractures from backbreak of a previous blast round may significantly alter the pattern seen in a quarry face from that given by natural geological discontinuities alone. Blast-induced discontinuities will not generally extend far in from the surface and may be discounted from the discontinuity survey or have a low persistence attributed to them.

Using scanline data and simple methods developed in the rock mechanics field (see Box 3.24) it is possible to apply Wang's equation method for IBSD assessment.

### 3.9.2.2 *IBSD by Wang's equation method*

**Step 1**

The principal mean spacing *PMS* (m) for the three sets is determined as explained in Box 3.24. Alternatively, the Karzulovic and Goodman (1985) algorithm can be programmed to give *PMS* values from quick scanline data.

**Step 2**

Determine the three characteristic angles $\alpha$ (°), $\beta$ (°) and $\phi$ (°) that define how far these three sets diverge from the orthogonal condition. The angles between all three pairs of normals to sets A, B and C are equal to $90–\alpha$, $90–\beta$ and $90–\phi$. Therefore, $\alpha$, $\beta$ and $\phi$ can be easily found from an equal angle stereonet plot of the three poles using the standard method for finding angles between directions. Because of their interdependence, it is not important which pairs are assigned to each of $\alpha$, $\beta$ and $\phi$ .

**Step 3**

Plot the principal spacing data as histograms and assign the most appropriate principal spacing distribution.

**Step 4**

Apply Equation 3.68 using values from Table 3.25. This equation was calibrated originally by

1 2 3 4 5 6 7 8 9 10

Wang (see Wang *et al*, 1990) using statistical simulations, hence the so-called "equation method":

$$V_{i,p} = C_{i,p} \cdot \frac{PMS_A}{\cos\alpha} \cdot \frac{PMS_B}{\cos\beta} \cdot \frac{PMS_C}{\cos\phi} \tag{3.68}$$

where $p$ = 10, 20 … 100 (%); and $V_{i,p}$ is the volume of *in situ* blocks, denoted by the subscript $i$, at a particular percentage passing value given by the subscript $p$.

For example, the *in situ* block volume at 50 per cent passing, $V_{i50}$ (m³), will be given by Equation 3.68 using the coefficient $C_{i50}$ from Table 3.25, depending on the distributions of the spacings observed. If in doubt, either the exponential or lognormal choice for all three sets is considered to be a reasonable assumption. For certain sedimentary rock masses, a uniform distribution, where all spacings are equally common, may be appropriate for bedding spacings and used together with two exponential sets. Further discussion of the use of this equation method is given in Lu and Latham (1999).

To illustrate the use of Table 3.25, if all three discontinuity sets are taken to have an exponential spacing distribution and, for example, $PMS_A = PMS_B = PMS_C$ = 1.0 m and the mean set orientations are orthogonal, the 50 per cent and 80 per cent passing volumes for the IBSD are: $V_{i50}$ = 2.7 m³ and $V_{i80}$ = 8.9 m³.

When performing an IBSD analysis based on data where discontinuity persistence has been recorded (see Figure 3.51), it is often valuable to consider spacing data that:

- include both p- (persistent) and n-coded (non-persistent) discontinuities (see Box 3.24) to provide a lower bound for IBSD
- include only p-coded discontinuities to provide an upper bound to the estimated IBSD, see Box 3.27, Case History B.

In predicting IBSD for armourstone evaluation, when distributions are not known, the uniform distribution assumption and the inclusion of both p- and n- discontinuities gives a smaller and thus more conservative estimate of IBSD for the range of armourstone sizes of importance.

**Table 3.25** ***Coefficients, $C_{i,p}$ (-) for use with the equation method of IBSD assessment for a range of function types***

| $V_{i,p}$ (m³) | Exponential for three sets | Uniform for three sets | Exponential for two + Uniform for one | Lognormal for three sets |
|---|---|---|---|---|
| $V_{i10}$ | 0.332 | 0.375 | 0.420 | 0.469 |
| $V_{i20}$ | 0.710 | 0.700 | 0.825 | 0.949 |
| $V_{i30}$ | 1.207 | 1.052 | 1.282 | 1.511 |
| $V_{i40}$ | 1.852 | 1.460 | 1.824 | 2.225 |
| $V_{i50}$ | 2.708 | 1.939 | 2.487 | 3.094 |
| $V_{i60}$ | 3.980 | 2.548 | 3.325 | 4.283 |
| $V_{i70}$ | 5.867 | 3.343 | 4.439 | 5.949 |
| $V_{i80}$ | 8.948 | 4.495 | 6.151 | 8.498 |
| $V_{i90}$ | 15.332 | 6.623 | 9.144 | 13.376 |
| $V_{i100}$ | 38.922 | 17.772 | 24.905 | 38.207 |

**Box 3.24** *Scanline data and discontinuity spacing analysis*

This box presents the terminology and methods needed to generate an IBSD prediction using Wang's equation method.

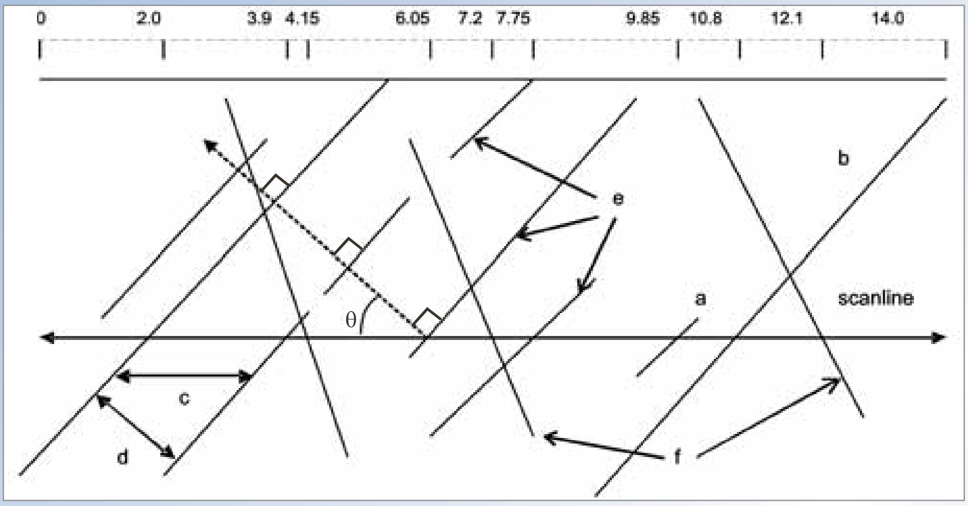
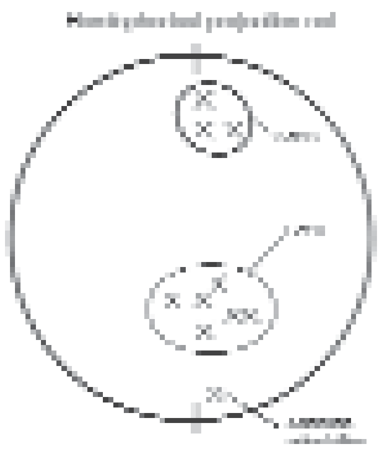



**Figure 3.50** *Scanline mapping showing spacing between discontinuity sets and example measurements. a: non-persistent discontinuity: length < 3 m; b: persistent discontinuity: length ≥ 3 m; c: spacing (DS); d: principal spacing (PS); e: Set A; f: Set B; θ is the angle between the scanline and a line normal to a discontinuity set.*

| Discontinuity data mapping sheet | | | | | | |
|---|---|---|---|---|---|---|
| General information | | | | | | |
| Job number 1 | | Quarry name: Scandanavian quarry | | Rock type: Granite gneiss | | |
| Number of tape: 1 | | Tape attitude: azimuth 176 | | Tape plunge angle: (+/-) 15 (down) | | |
| Sheet number: 1 of 5 | | | | | | |
| Discontinuity data | | | | | | |
| | | Intercept | Attitude | | | |
| No | Type | (m) | Dip direction | Dip | Persistence | Remarks |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0 | Start scanline | 0.00 | | | | |
| 1 | Joint set A | 2.00 | 358 | 48 | p | |
| 2 | Joint set A | 3.90 | 360 | 46 | p | |
| 4 | Joint set A | 6.05 | 348 | 50 | p | |
| 6 | Joint set A | 7.75 | 10 | 46 | p | |
| 7 | Joint set A | 9.85 | 340 | 45 | n 1.4 | |
| 8 | Joint set A | 10.80 | 358 | 42 | p | |
| | | | | | | |
| 3 | Joint set B | 4.15 | 190 | 73 | p | |
| 5 | Joint set B | 7.20 | 212 | 68 | p | |
| 9 | Joint set B | 12.10 | 175 | 65 | p | |



**Notes:** Tabulated data are shown after plotting on a stereonet has enabled sorting into sets and reordering. Calculation of mean spacing, *MS* (m), for each set then uses the classified intercept values, see Figure 3.50. Persistence: p – persistent discontinuity, n – non-persistent discontinuity with length given in (m). Rock engineers seek an unambiguous way of defining the orientation of a discontinuity plane. The best way is to refer to the **dip direction** (0° to 360°) measured clockwise from North, ie an azimuth direction. For the direction a ball would roll down an inclined plane where the **dip** or **dip angle** (0° to 90°) is the angle measued from horizontal of the ball's trajectory, ie its steepest path. Note that the strike direction of a plane is at right angles to the dip direction.

**Figure 3.51** *Illustration of data shown in Figure 3.50 presented on a modified scanline data entry sheet and representation of discontinuity sets as poles on equal angle stereonet.*

Discontinuity sets are systems of discontinuities that have approximately the same inclination and orientation. As a result of the processes involved in their formation, most discontinuities form in families that have preferred directions. In some cases these sets are clearly defined and easy to distinguish, while in others the structural pattern appears disordered. Rock engineers use stereonet software to assist with contouring poles and grouping sets. ***DS*** is the **discontinuity spacing,** defined as the distance between an adjacent pair of discontinuities measured along a straight line of a given orientation within or on the surface of a rock mass. ***MS*** is the **mean spacing** along a particular scanline calculated from the *DS* values.

**Box 3.24** *Scanline data and discontinuity spacing analysis (contd)*

If joints have been coded as falling into specific sets, various methods (eg Priest, 1993) make it possible to define the mean orientation for that set and thereby to refer spacings and mean spacings to the normal to the mean orientation of a given set. **Principal spacings, *PS***, refer to a given set of discontinuities and are distances between adjacent pairs from the same set – measured along an artificial scanline that runs normal to the mean orientation of that set. Using a stereonet, it is simple to determine $\theta$, the angle between the scanline orientation (recorded as the azimuth and plunge of the tape) and the normal to Set A (the centre of the cluster of poles for Set A, see Figure 3.51). The highly significant **principal mean spacing, *PMS*,** value for Set A can then be determined using the equation $PMS_A = MS_A \cos\theta$ . Given that there are typically three discontinuity sets, it will be possible to obtain $PMS_A$, $PMS_B$ and $PMS_C$. This may require more than one scanline. For more irregular patterns, an algorithm based on giving each joint a different set number, measuring the minimum angle between two individual sets and replacing the pair with a single weighted set can be implemented. Continuing this process until only three sets remain yields the three principal discontinuity sets with their mean orientation.

The **distribution of principal spacings** for any set may be plotted and their mean and standard deviation can be found easily. The frequency of occurrence in certain class intervals against spacing value for that class interval will produce a histogram of the discrete data and then an overall curve fit to the histogram can represent a continuous function. The spacing distributions are usually described well by negative exponential, lognormal or more rarely by a uniform function (Figure 3.52). Good fits to data have also been found for fractal, ie power law, functions (Lu and Latham, 1999). The function type that best fits the data should be determined. It can often be judged by eye. When combinations of different distribution types are encountered for each set, it should be noted that weighted interpolation between pure end members may not provide an accurate solution when assigning coefficients for use of the Equation Method; see column 3 in Table 3.25.

**NOTE:** Spacings associated with individual discontinuity sets can be derived from quick scanline data (only spacings are noted), provided there are sufficient numbers of scanlines and the mean orientations of each set have already been determined, eg by extensive sampling of the orientations of all the discontinuities in the domain of interest (see Karzulovic and Goodman, 1985).

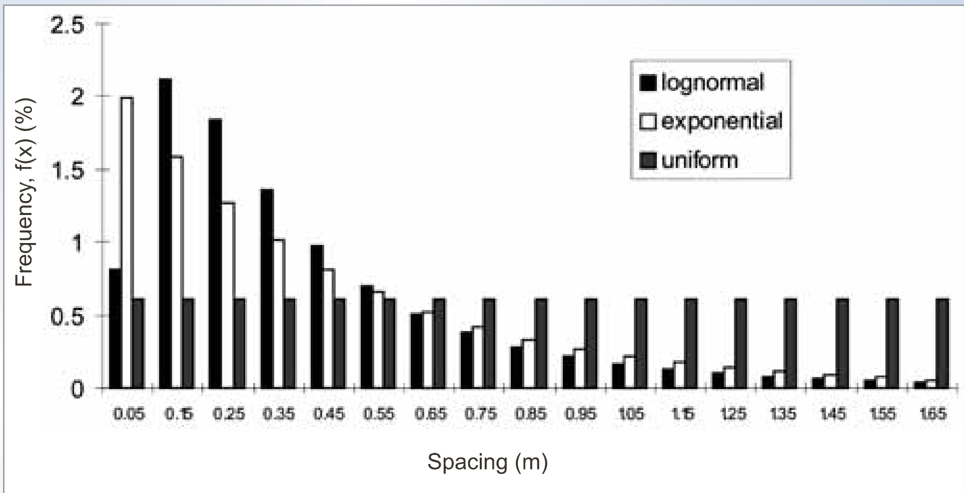



**Figure 3.52** *Illustration of three commonly found principal spacing distributions for discontinuity sets*

### 3.9.2.3 *IBSD by the dissection method*

The dissection method (Wang *et al*, 1991b) requires detailed scanline data, carried out in directions that intersect the main discontinuity sets and therefore adequately sample the rock mass structure. Computer programs (see Wang *et al*, 1992b) and internet searches for modern alternatives will be helpful. Such programs use the co-ordinates of planes of discontinuities obtained from full records of detailed scanline data (Figure 3.50) containing intercept and orientation of planar discontinuities, in order to determine the volumes enclosed between the planes.

The algorithm is generally organised as follows:

- dissect the boundary block into two blocks of varying shape by taking the first discontinuity from the data file

- dissect these two blocks with the next discontinuity in the file to give three or four blocks
- continue dissection to the last discontinuity, storing co-ordinates of all corners of all natural blocks
- derive block volumes (maximum length and nominal diameter of each block may also be given).

IBSD analysis using dissection programs will typically have the following steps:

**Step 1**

The user defines the BOUNDARY BLOCK enclosing the rock mass to be evaluated, choosing six discontinuity planes.

**Step 2**

The input file is read giving each successive discontinuity plane, for one or more scanline segments, and the dissection program is run.

**Step 3**

The output is analysed in the form of 3D views of the rock mass, histograms, distribution curves, stereoplots of discontinuity poles etc, as illustrated in Box 3.27 Case History B.

#### 3.9.2.4 IBSD by 3D stochastic network modelling

Another approach starts by characterising each joint set measured in the field using the best fit distributions for dip angle, dip direction, spacing and persistence (see Box 3.24 for explanation). A program is then used to randomly simulate the pattern created by intersecting discs or other geometries with the appropriate size distribution so that a stochastic network geometrically resembling the measured joint pattern is created. In relation to rock-blasting simulation, IBSD results were obtained this way; see Aler *et al* (1996). Other programs – see, eg, Dershowitz *et al* (1998) – can also generate an IBSD that will have a statistical matching of discontinuity geometries to the measured ones. It is usual to run a Monte Carlo simulation to obtain many realisations of the IBSD and adopt an average IBSD. Such approaches are often considered most appropriate where block patterns are very irregular. See also Thornton *et al* (2002) for a discussion of stochastic modelling of fragmentation.

#### 3.9.2.5 IBSD from drill core data

The *volumetric* joint count, $J_v$ (1/m), is a measure of the number of joints intersecting a volume of rock mass expressed as the average number of joints per cubic metre. $J_v$ is generally calculated from the sum of the reciprocals of each principal mean spacing (ie $J_v = 1/PMS_A + 1/PMS_B + 1/PMS_C$) and can also be calculated for random and irregular jointing. Palmström (2001) proposed a block shape factor, $\beta$ (-), typically set to a value of $\beta = 36$ when it is not known, which, when multiplied by $J_v^{-3}$ , gives the estimated average block volume, $V_{i50}$, assuming an orthogonally jointed rock mass. By considering the likely largest and smallest spacings typical of the various joint sets, upper-bound and lower-bound $J_v$ estimates can be generated, which similarly can provide an approximate maximum and minimum *in situ* block volume.

Palmström also suggested a simple method for obtaining the weighted joint density, $JD_w$ (1/m), which is similar to the volumetric joint count, $J_v$ ($JD_w \cong J_v$), given either 1D core recovered data or 2D data obtained from surfaces. The 1D weighted jointing measurements that can be made on drill cores to give $JD_w$ are obtained as follows:

1 2 3 4 5 6 7 8 9 10

- while core logging, measure the angle, $\alpha$ (°), between core axis and the dip (angle) of each discontinuity and assign weightings to each joint:
  - Joint weighting: $f = 1$ for $\alpha > 60°$
  - Joint weighting: $f = 1.5$ for $31° < \alpha < 60°$
  - Joint weighting: $f = 3.5$ for $16° < \alpha < 30°$
  - Joint weighting: $f = 6$ for $\alpha < 16°$
- count the number of joints ($n_1$, $n_2$, $n_3$, $n_4$) within a given core section length of interest, $L$ (m), having each of the four possible joint weightings $f$ =1, 1.5, 3.5 or 6 respectively, associated with the obliquity of the joint.
- calculate the weighted joint density, $JD_w$ (1/m³), using Equation 3.69:

$$JD_w = [(n_1 \times 1) + (n_2 \times 1.5) + (n_3 \times 3.5) + (n_4 \times 6)]/L \tag{3.69}$$

The value of $JD_w$ may be interpreted as having units of per metre cubed. It may then be used identically to $J_v$ as a means to assess typical *in situ* block volume, $V_{i50}$, representative of a sampled section length of core. An examination of, say, 5 m lengths of sampled core sections with the most intact lengths of recovered core might be used to estimate the maximum *in situ* block volume, $V_{i100}$, for the quarry area as a whole.

The potential drawback is that the interpretation is often based on vertical drill cores that, in spite of the weightings, may not be capable of representatively sampling the discontinuities that slice up the rock mass. Horizontal drilling and/or drilling perpendicular to major joint sets, to supplement vertical drilling, is recommended.

## 3.9.3 Blasting and blast design

This section first provides the reader with a brief introduction to those blasting factors that concern armourstone and aggregates production (Section 3.9.3.1). The fragmentation process is briefly described (Section 3.9.3.2). The basic differences between aggregates and armourstone blast design are presented (Section 3.9.3.3) and practical measures often found useful to maximise the yield of armourstone are discussed (Section 3.9.3.1).

### 3.9.3.1 *Factors affecting blasting for armourstone*

Certain aspects of armourstone production require attention to details that are not usually emphasised in the extensive literature on blasting, eg JKRMC (1996), Jimeno *et al* (1997), Persson *et al* (1993). The focus with armourstone production is on larger stones than for normal fragmentation blasting. The aim of any blast is to produce more stones of the size and form that will facilitate subsequent operations and lead to minimum overall costs. The blast design is a significant process in securing desired fragmentation but there are many difficulties to overcome, not least because there are many factors affecting fragmentation beyond the control of the blast engineer.

**Uncontrollable factors**

- discontinuity spacings and orientation (bedding, joints, faults, cohesion across planes)
- strength and elasticity (rock type, weathering characteristics)
- density, porosity, permeability
- presence of water in blastholes, fractures and joints
- spatial variations of geology and rock types in general.

**NOTE:** All of these factors are essentially geological characteristics of the rock mass or due to weathering. While uncontrollable, these factors may generally be measured and their effect taken into account in the blast design. *In situ* block size distributions can be assessed using the techniques described in Section 3.9.2.

**Controllable factors**

- the properties and detonation methods of the explosives used, including delay timings
- the blast design (configuration and drilling pattern).

Successful blasting engineers work to clearly defined objectives such as the required size distribution results, ease of blastpile digging and minimum disruption to the next blast. They apply theoretical understanding of the mass fragmentation process and rock mass characteristics, knowledge of the effects of using different explosives and detonation techniques, environmental constraints and, lastly, experience and expertise in combining these, which may include the assistance of blasting software. The most important fragmentation objectives for armourstone blasts are:

- blasting for improved yields of heavy stones in specially set-aside faces of aggregates quarries
- blasting for improved or reduced yields of stones blocks in dedicated quarries.

The economics of the second case are constrained by a need to produce, as far as is possible, only the material demanded by the design. This may require that secondary breakage is embraced fully as a means of production when setting the blasting objectives (See Box 3.28).

### 3.9.3.2 *Fragmentation processes*

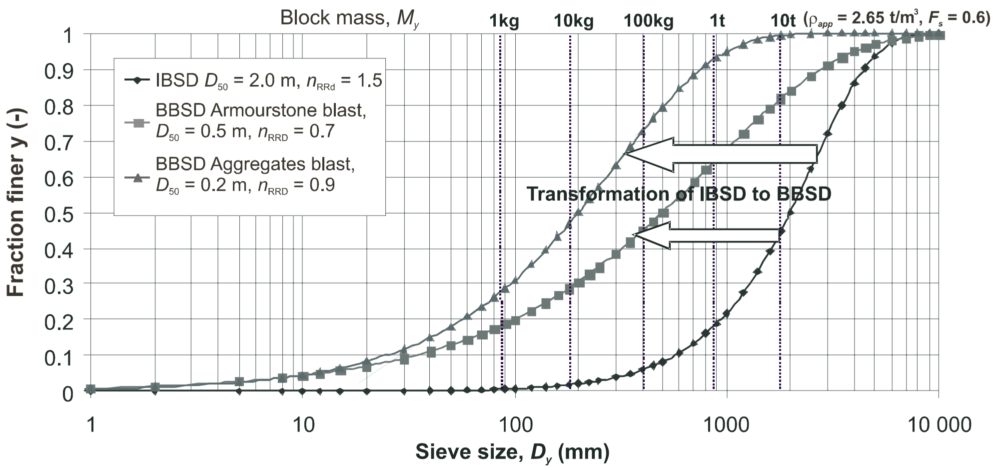
In Box 3.27, the manner in which the *in situ* bedding, jointing and other discontinuities slice up the natural rock mass into blocks of predefined shape distributions and size distributions before blasting is illustrated (see Figure 3.60). The concentrated release of energy from explosives detonated in confined blastholes transforms the IBSD to a BBSD of finer material (Figure 3.49). The sudden very high gas pressures in the blast causes shockwave transmission, compressive crushing near the hole, radial tensile fracturing and slabbing tensile cracking at free faces. Fracturing and fragmentation are accompanied by gas flow into cracks, extending them further. The explosive gas, assisted by gravity, heaves the blocks away from the face and into the blastpile. The ability to achieve a desired BBSD depends on knowledge of the IBSD, the strength and persistence of the natural geological flaws and:

- other uncontrollable factors such as strength, elasticity and density that contribute to the inherent ease of breakage or *blastability* of the rock
- blast energy mobilised through the blast design.

### 3.9.3.3 *Comparison of armourstone and aggregates blast design*

Design of an **aggregates blast** aims to minimise excess oversize (and expensive secondary breakage) keeping the average BBSD to < 10 per cent exceeding about 3 t while ensuring not too much rock is reduced to useless fines by excessive blast energy. Typically, a specific charge of 0.4–0.7 kg/m$^3$ of Anfo (kilogrammes of explosive per cubic metre of *in situ* rock) is used in a two- or three-row shot to achieve sufficient breakage.

Blasting engineers working on armourstone operations should be aware of fundamental differences in fragmentation results compared with aggregates blasts (see Figure 3.53) and in practical blast design, where Section 3.9.3.4 will be of assistance. For an **armourstone blast**, a specific charge as low as 0.2 kg/m$^3$ is often used.




**Notes**

$F_s$ is the shape factor, see Section 3.4.2

$n_{RRD}$ is the uniformly coefficient of the size distribution curve, Section 3.4.3.3

**Figure 3.53** *Illustration of theoretical scenarios for an aggregates blast and an armourstone blast applied to the same rock mass. IBSD and BBSD are represented by Rosin-Rammler curves*

### 3.9.3.4 *Suggestions for improving the yields of armourstone*

Generally, the proportion of armour stones in the blast increases with increasing tensile strength, increasing Young's Modulus and increasing discontinuity spacing. Normal blasting practice (eg for aggregates and ores) aims to achieve high-fragmentation blasts. By contrast, greater percentages of armour stones can be achieved by adjusting common practice through consideration of the following (see Figure 3.55 for definition of blasting terminology).

1 A low **specific charge**. Generally, a specific charge as low as 0.11–0.25 kg/m³ can be used. If possible, the explosive used should have lower velocity of detonation, *VOD* (m/s). For such low specific charges, maintaining high drilling accuracy is critical to avoid insufficient rock break-out.

2 The **spacing-to-burden ratio** should generally be less than or equal to 1, with burden larger than the discontinuity spacing in a jointed rock mass.

3 If the **bench** is either too high or too low, armourstone production will be poor. For an initial estimate, bench height could be selected as two to three times the burden. In planning bench levels, the rock mass from which most armourstones might be produced, such as thickly bedded layers, should be located nearly at the top of the bench alongside the stemming section of the holes.

4 A large **stemming length**, larger than the burden, is usually recommended.

5 A small **blasthole diameter**. A diameter of less than 100 mm is recommended.

6 One row of holes is found to be better than multiple rows. If permitted, holes should be fired instantaneously rather than using inter-hole delaying (this may cause high ground vibration).

7 A **bottom charge** of high energy concentration is needed for the bottom to break clean away.

8 A **decoupled column charge** of ANFO (ammonium nitrate/fuel oil) packed in plastic sausages is effective when a 300–3000 kg range is recommended – the explosives are evenly distributed, giving quite even fragmentation.

9 A **decked charge**, to break up the continuity of explosives, will be necessary in most situations when armourstone greater than 3 t is recommended. The material for decking can be either air or aggregates.

The most common objective of an armourstone bench blast is to achieve a BBSD with the maximum percentage of the largest stones possible. The aim of such a blast is to cause the minimum of new fractures while having sufficient energy concentration to loosen the *in situ* blocks fully and bring the rock face down cleanly. The best achievable BBSD curve will lie close to and just to the left of the upper part of the IBSD curve, spreading out considerably at lower sizes, eg see Box 3.27 Case History B (Figure 3.62). Where the mean discontinuity spacing gives vast *in situ* blocks, blast design must ensure sufficient breakage to limit the proportion of blocks above 20 t, which is about the limit for practical handling. A lower armourstone recovery can often be more economical, even though more rock is eventually excavated and therefore more is left behind as over-production. Excavation of the blastpile and keeping good faces and toes becomes more difficult the greater the yields of heavy armourstone and the lower the specific charge. The rate of output from excavators, loaders and selection plant is also reduced (Figure 3.54).

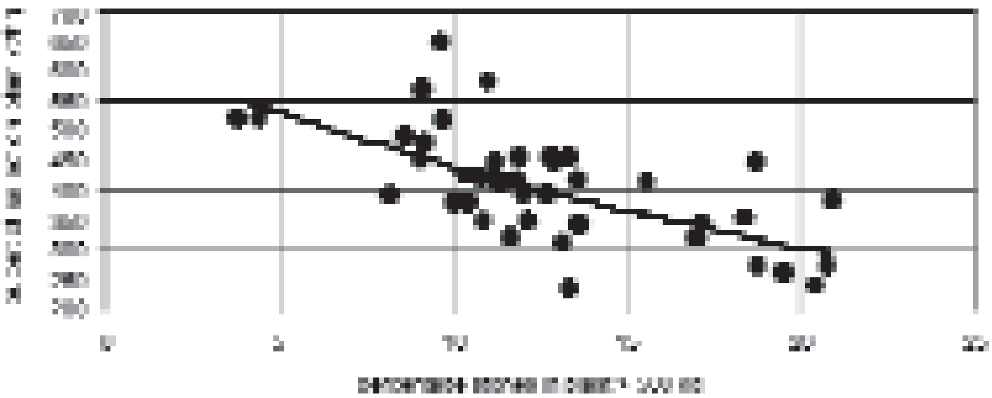


**Figure 3.54** *The influence of armourstone recovery on output of selection plant (courtesy J van Meulen)*

## 3.9.4 Prediction and assessment of yield curves

Several models that allow yield curves to be predicted are given here, together with additional references to new blastability models and a simplified look-up table for approximating yields (Table 3.26). Methods for assessment of sizes in a blastpile are identified and case histories incorporating use of both IBSD and BBSD for armourstone yield prediction are included.

**NOTE:** Blast terms are provided in Figure 3.55.

Prediction of blasted block size distributions, BBSDs (fragmentation curves, yield curves), is the subject of significant research effort as the possible error in prediction remains very high. Accuracy is limited because the geological conditions cannot easily be determined for every blast and the implementation of the blast design may suffer from practical constraints. For dedicated quarries, early prediction of quarry yield curves – whether by trial blasts or by scanline and borehole discontinuity surveys together with blast modelling – plays a vital part in breakwater design optimisation; see for example the discussions on berm breakwaters given in Section 6.1.6. Described below are several approaches to fragmentation prediction:

- **Kuz-Ram model**, Section 3.9.4.1: implemented in many software applications; may be useful if IBSD is poorly known; care is needed to check that $n_{RRD}$ is realistic
- **Bond-Ram models (BRM),** Section 3.9.4.2: make good use of IBSD assessments and are therefore favoured for armourstone; uncertainty in Bond Work Index limits reliability; has two different implementations
- **Kuznetsov-Cunningham-Ouchterlony (KCO) model**, Section 3.9.4.3: replaces Rosin-Rammler equation in a promising new approach; good for fines assessment; requires reasonably accurate maximum IBSD assessment if to be useful for predicting armourstone yields

- **simplified look-up table,** Section 3.9.4.4: provides an alternative to models; simplified guidance is read from a table given a minimum of discontinuity data for typical aggregate or armourstone blasts.

After a trial or production blast, it is essential to be able to assess the BBSD on the quarry floor. Methods to assess the yield curves that are outlined in this manual include:

- **image analysis**, Section 3.9.4.5: illustrates the basis of commercial software and how the photographic image can be converted to yield curves
- **photo-scanlines**, Section 3.9.4.6: provides a method for assessing size distributions from photographs; no specialised software tools required
- **direct screening and block measurement**, Section 3.9.4.7: illustrates practical methods for sizing the blasted materials, establishing various points on the yield curve.

**Summary guidance on selection of methods for predicting quarry yield curves**

Experience to date does not point to a single best prediction method. The best practice is somewhat clearer for prediction in higher fragmentation blasts for mines and aggregates quarries because there is a growing number of documented studies with the blastpile assessment accuracy needed (associated with sieving of a sample of the full-scale blast or well-controlled image analysis), together with detailed IBSD and rock mass analysis. It remains a relatively small database if all the blast design variables are to be investigated. Field data from low-energy blasts where the objective is often simply to liberate *in situ* blocks for use as armourstone are even scarcer. The case histories (Box 3.26 and Box 3.27) are illustrative of the ongoing search for successful armourstone blast prediction methodologies.

If site investigation data is minimal but is sufficient to provide *RQD* (rock quality designation, see Section 3.2.2) or *PMS* (principal mean spacing (m), see Box 3.24) values for the *in situ* rock mass, Table 3.26 can provide a starting-point prediction without the need to implement a blast model.

If a reasonably good estimate of the rock mass factor, $A$ (-), can be made (Box 3.25), but discontinuity spacing is poorly known, the Kuz-Ram model will provide a complete prediction curve, but with a value of uniformity coefficient, $n_{RRD}$ (-), that is most likely to be too high. For example, see the data in Table 3.29, which suggest that $n_{RRD}$ for armourstone blasts is typically 0.7–0.9. Typical armourstone blasts have lower uniformity coefficients than high-fragmentation blasts, so it is vital that the correction identified by Spathis (2004) is applied to all uses of the Kuznetsov equation (Equation 3.71) in BBSD models for armourstone production.

To take advantage of the known importance of the *in situ* discontinuities, it is invariably worth the effort to obtain data to estimate the maximum and typical *in situ* block volumes. The weighted joint density method (Section 3.9.2.5) using drill core data is suitable in poorly exposed greenfield sites when scanline surveys and photographic face mapping are impossible.

If a thorough site investigation can reveal the essential variations of the *in situ* rock mass properties, the IBSD curve giving 100, 80 and 50 per cent passing values will help the blast prediction considerably. The Bond-Ram models make good use of the whole IBSD and if the work index, $W_i$, is sufficiently well calibrated for the rock mass in question, they appear promising. An advantage is that they do not rely on an accurate maximum *in situ* size, and focus on the 80 per cent passing sizes that have greater significance for armourstone production.

The KCO model approach appears to be suitable for predicting the smaller sizes (below 50 mm) of any blast. It also appears that if IBSD analysis methods are used to constrain $D_{b100}$ ($\approx D_{i100}$) accurately it may work very well. At present, one must chose from two approaches offered for setting the curve undulation parameter, $b$ (-) (see Equations 3.78 and 3.79). Each one can give critically different proportions of large blocks between $D_{b100}$ and $D_{b50}$, where the subscript $b$ denotes after blasting. Any future results supporting the simpler empirical Equation 3.77 and the successful setting of rock mass factor, $A$ (-), and $D_{bmax}$ (m), will help consolidate the wider use of the KCO model in armourstone blast prediction.

If a breakwater design is to be finalised on the basis of a best prediction of average yield for the whole dedicated quarry, it is sometimes advisable for the yield curve prediction to be conservative and not overly optimistic about obtaining large percentages of the bigger block sizes. To settle for slightly smaller sizes in the prediction gives the blast engineer the option of using greater fragmentation if and when there is a tendency to over-produce very large blocks, and hence to keep production closely on track with the prediction. By contrast, refining the blast to produce more large blocks is only rarely feasible. Once the design has been finalised upon a predicted yield curve and a maximum quarry utilisation, every effort should be made by the quarry production team to produce to that curve.

Once the quarry has been opened, blast assessment is essential and weekly yield curves, indicators of IBSD and production blasting data should be actively analysed. It will often be possible to use one of the prediction models suggested above and to calibrate it further for the intrinsic properties of the rock mass (eg Bond Work Index $W_i$, rock mass factor $A$) and methods in question, so that, for example, the specific charge can be adjusted to accommodate regional variations of IBSD in the developing quarry.

#### 3.9.4.1 *Kuz-Ram Model*

Cunningham brought Kuznetsov's (1973) work up to date, introducing the Kuz-Ram Model in 1983. Later revisions to Kuz-Ram, Cunningham (1987), included improved estimation of the rock mass factor A based on Lilly's (1986) blastability index. There are three important equations that by simple substitution of parameters, give the BBSD curve. The use of the Kuz-Ram, or similar models, requires caution. Factors of recognised importance such as detonation delay timing are not included in Kuz-Ram, while the effect of rock mass structure and the burden-to-spacing ratio need careful consideration (Konya and Walter, 1990).

**(i) Rosin-Rammler equation**

This equation (Rosin and Rammler, 1933) provides the basic shape of the BBSD to be expected in terms of $D_{b50}$ and $n_{RRD}$, giving the fraction passing, $y$, corresponding to a certain sieve size $D_y$ (see also Section 3.4.3.3):

$$y = 1 - \exp\left\{\ln\left(\frac{1}{2}\right)\left(\frac{D_y}{D_{b50}}\right)^{n_{RRD}}\right\} \cong 1 - \exp\left\{-0.693\left(\frac{D_y}{D_{b50}}\right)^{n_{RRD}}\right\} \qquad (3.70)$$

After $D_{b50}$ and $n_{RRD}$ have been determined from Equations 3.71 and 3.72 below, substitution of $D_y$ values will return fraction passing values from which the complete BBSD curve can be deduced. For a BBSD prediction focused on armourstone sizes of say, 0.1 m to 1–2 m, the Rosin-Rammler equation is considered the most attractive simple choice. It should be noted that where data from sieved or photo-analysed blastpiles deviate surprisingly from the Ros-Ram fitting function near the maximum sizes, this could be attributable to the inherently poor sampling of the coarsest fraction, which can throw the measured results out from the average production in question. Furthermore, various shortcomings of the Ros-Ram equation were noted including:

- reported as sometimes giving a poor fit to blastpiles with high yields of armourstone sizes (Lizotte and Scoble, 1994)

1 2 3 4 5 6 7 8 9 10

- failure to give a clear maximum size because the function is asymptotic to the 100 per cent passing value
- commonly unable to describe with reasonable accuracy the fines content below sizes of about 50 mm in a blast. This is of particular concern for predicting the detailed nature of the quarry run and the resultant behaviour of core materials derived from the quarry.

**(ii) Kuznetsov equation**

The Kuznetsov equation gives the blasted block size at 50 per cent passing, $D_{b50}$ (in m not cm) as a function of ($A$, $V$, $Q$, $E$), which locates the position of the BBSD curve:

$$D_{b50} = 100A\left(\frac{V}{Q}\right)^{0.8} \cdot Q^{0.167} \cdot \left(\frac{E}{115}\right)^{0.633} \tag{3.71}$$

where:

| | | |
|---|---|---|
| $A$ | = | rock mass factor (-); $A$ =1 for extremely weak rock, $A$ = 7 for medium rock, $A$ = 10 for hard, highly fractured rock; $A$ = 13 for hard, weakly fractured rock. Several schemes now exist for improved estimation of $A$ eg using Lilly's original blastability algorithm, see Cunningham (1987), Widzyk-Capehart and Lilly (2002), the essential parts of which are given in Box 3.25 |
| $V$ | = | volume of rock broken per blasthole ($m^3$) |
| $Q$ | = | charge concentration per blasthole (kg) |
| $E$ | = | relative mass strength of explosive (-); for ANFO: $E$ = 100 and for TNT: $E$ =115) |
| $Q/V$ | = | **specific charge** ($kg/m^3$), a general measure of explosive power in the blast. |

Spathis (2004) pointed out an implicit assumption in Cunningham's Kuz-Ram application of Kuznetsov's original equation. The assumption is increasingly invalid for lower $n_{RRD}$ values typical of armourstone blasts because the mean size differs more significantly from the median size as $n_{RRD}$ decreases. Spathis plotted the correction needed as a function of $n_{RRD}$, which indicates that for $n_{RRD}$ as low as 0.8 the characteristic size, $D_{b50}$, would be 1.8 times too large if Equation 3.71 is used without the correction. This could in part explain why uncorrected applications of the Kuz-Ram model often give overly coarse predictions of armourstone blasts, as they typically have low uniformity indices, eg $n_{RRD}$ of 0.7–1.0.

**(iii) Cunningham's uniformity index algorithm**

This empirical formula (Equation 3.72) derived by Cunnigham (1987) determines the steepness of the BBSD curve, $n_{RRD}$ (-), as a function of blast design geometry (see Figure 3.55).

**NOTE:** There is no significant body of evidence from sieved distributions to support Equation 3.72. Still it remains widely used.

$$n_{RRD} = \left(2.2 - 14\frac{B}{d}\right) \cdot \left[0.5\left(1 + \frac{S}{B}\right)\right]^{0.5} \cdot \left(1 - \frac{W}{B}\right) \cdot \left[\mathrm{abs}\left(\frac{BCL - CCL}{L}\right) + 0.1\right]^{0.1} \cdot \frac{L}{H} \tag{3.72}$$

where:

| | | |
|---|---|---|
| $d$ | = | blasthole diameter (mm), typically minimum of 70 mm |
| $B$ | = | burden (m), see Figure 3.55 |
| $S$ | = | spacing between blastholes (m) |
| $BCL$ | = | bottom charge length (m) |
| abs (x) | = | absolute value of x |
| $CCL$ | = | column charge length (m) |
| $L$ | = | total charge length (m), $L = BCL + CCL$ |

$H$ = bench height or hole depth (m)

$W$ = standard deviation of drilling accuracy (m).

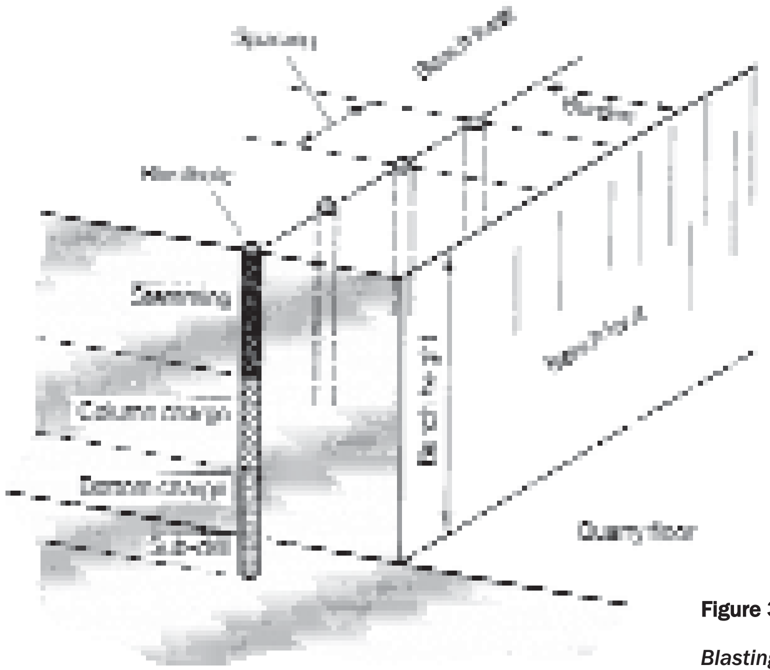



**Figure 3.55**

*Blasting geometry terminology*

**Box 3.25** *Guidance for the determination of the rock mass factor A used in blast prediction*

This box provides guidance for setting parameters of the rock mass from which the rock mass factor, $A$ (-), needed for the Kuz-Ram and KCO models, can be estimated. Only very rarely would a rock mass achieve $A$ values above 14. For a rock to be considered for armourstone, it is considered likely that $A$ would fall in the range 9–14.

$$A = 0.06\ (RMD+JF+RDI+HF) \tag{3.73}$$

where:

| | | |
|---|---|---|
| $RMD$ | = | rock mass description = 10 if powdery or friable, = JF if vertically jointed, = 50 if massive rock |
| $JF$ | = | joint factor = joint plane spacing term, $JPS$ + joint plane angle term, $JPA$ |
| $JPS$ | = | 10 if average PMS (eg cube root of the product of three principal mean spacings) < 0.1 m, 20 if average PMS is within range 0.1–1 m, 50 if average PMS > 1 m |
| $JPA$ | = | 20 if the main discontinuity set has a dip direction outwards from face, 30 if it has a dip direction roughly parallel to the face and 40 if the dip direction is inwards from the face of the rock mass (for explanation see Box 3.24) |
| $RDI$ | = | rock density influence = 0.025 $\rho_{rock}$ – 50 with $\rho_{rock}$ in (kg/m³) |
| $HF$ | = | hardness factor, depending on uniaxial compressive strength, $UCS$ (MPa), or Young's Modulus $E$ (GPa), HF = $E$/3 if $E$ <50, or $UCS$/5 if $E$ > 50 |

### 3.9.4.2 Bond-Ram Models

Da Gama (1983) applied Bond's Third Theory of Comminution to blasting using Bond's relation (Equation 3.74 below) to fix the 80 per cent passing size in the blast, $D_{b80}$ (m). Bond's relation was applied together with the Rosin-Rammler Equation 3.70, and Cunningham's uniformity coefficient in Equation 3.72, by Wang *et al* (1992b). They called this combined approach the Bond-Ram model. It is termed BRM(A) in this manual.

**BRM(A)**

**Bond equation:** based on Bond's Third Theory of Comminution, the reduction in the 80 per cent passing size during blasting is expressed in terms of the blast energy, $W$ (kWh/t), and a material property the Work Index, $W_i$ (kWh/t), as given in Equation 3.74:

$$W = 10 \cdot W_i \cdot \left\{ \left( \frac{1}{\sqrt{D_{b80}}} \right) - \left( \frac{1}{\sqrt{D_{i80}}} \right) \right\} \tag{3.74}$$

where $D_{b80}$ and $D_{i80}$ are the 80 per cent passing sieve sizes, after blasting and *in situ* respectively (in microns) and $W$ is the energy required for fragmentation and is a function of ($E$, $V$, $Q$, $\rho_{rock}$). The blast energy, $W$ (kWh/t), can be estimated using Equation 3.75:

$$W = \frac{0.00365 \cdot E \cdot \left( \frac{Q}{V} \right)}{\rho_{rock}} \tag{3.75}$$

where:

| | | |
|---|---|---|
| $E$ | = | weight strength of explosive (%) relative to ANFO |
| $\rho_{rock}$ | = | rock density (t/m³) |
| $V$ | = | volume of rock broken per blasthole (m³) |
| $Q$ | = | charge concentration per blasthole (kg) |
| $Q/V$ | = | **specific charge** (kg/m³), a general measure of explosive power in the blast. |

The Work Index $W_i$ (in kWh/t) is analogous to Bond's Work Index for grinding, but is here calibrated for blasting (Da Gama, 1983) as follows:

$$W_i = 15.42 + 27.35 \left( \frac{D_{i50}}{B} \right) \tag{3.76}$$

where $B$ is the burden (m), see Figure 3.55, and $D_{i50}$ is the 50 per cent passing *in situ* block size (m).

**NOTE:** In grinding, Bond's Work Index values are known from tables for grinding of different ores, or they are determined by grinding experiments. Such index values may be misleading if used directly in blast models without a correction factor.

**NOTE:** The empirical coefficients in Equations 3.74–3.76 have dimensions that take account of the indicated units, such that $W$ and $W_i$ have units of kWh/t.

To apply this BRM(A) model, $W$ and $W_i$ values together with $D_{i80}$ from IBSD information are substituted in Equation 3.74 and $D_{b80}$ is determined. Substituting $y = 0.8$ and $D_y = D_{b80}$, together with $n_{RRD}$ value as determined from Equation 3.72, in Equation 3.70, then gives $D_{b50}$, from which the complete BBSD curve of Rosin-Rammler form can be deduced.

**BRM(B)**

Chung and Katsabanis (2000) demonstrated that Equation 3.72 gave $n_{RRD}$ values that were consistently too high compared to results from sieved blastpiles. They suggested linking $D_{b50}$ determined from Kuznetsov's Equation 3.71 with $D_{b80}$ determined from Bond's theory, as a means to obtain $n_{RRD}$ in the Ros-Ram equation (Equation 3.12), thereby providing an alternative to Cunningham's Equation 3.72. In doing so, the value of $n_{RRD}$ (-) is given analytically by 0.842/(ln $D_{b80}$ – ln $D_{b50}$). This, together with $D_{b50}$ from Kuznetsov's equation (Equation 3.71), was found to provide better Ros-Ram coefficients in Equation 3.70 for generating final BBSD prediction curves that are closer to field data. This Bond-Ram approach presented by Chung and Katsabanis (2000) is a promising yield prediction approach for armourstone production and is termed **BRM(B)** in this manual.

**NOTE: $W_i$ values for bench blasting for armourstone**

To produce more accurate Bond-Ram predictions, further calibration of an appropriate value for $W_i$ is recommended for quarry bench blasting for armourstone. Da Gama (1983) suggested the use of Equation 3.76, a relationship derived from empirical studies on a small dataset of blasts in a basalt quarry. From a back analysis of case histories, results presented in Lu and Latham (1998) suggested a somewhat lower range of values, eg $W_i$ = 6.7 ± 1.1 kWh/t for one particular Carboniferous limestone quarry and $W_i$ = 10 ± 4 kWh/t for host rock from various ore mining blasts. Lower values of $W_i$ imply greater ease of blasting into small pieces. Blasting engineers wishing to adopt the Bond equation for blasting are advised to consult recent research, eg Kahriman *et al* (2001) to guide the choice from the values suggested by Da Gama for basalt (~25 kWh/t) and the significantly lower value of 10 kWh/t as suggested above and recently by Chung and Katsabanis (2000), or calibrate their own case-specific $W_i$. The range of possible values for $W_i$ for rock masses considered in the Bond-Ram model appears to extend from about 5 kWh/t to 40 kWh/t.

Approaches that see the blasting process in terms of the work done to overcome the inherent *blastability* of the rock mass during a dynamic comminution process are becoming more widely used.

### 3.9.4.3 KCO model

In recognition of the poorer fit in the fines region of the two-coefficient Ros-Ram and power law equations, more complex equations with four or five curve-fitting coefficients have been introduced. These curve shapes can overcome the underestimate of fines often found with Rosin-Rammler curves and are designed to account for more complex combinations of breakage mechanisms such as fine scale crushing near the borehole, fines development occuring along propagating branching cracks, and the coarser fragmentation by tensile cracking (Djordjevic, 1999; Kanchibotla *et al,* 1999). Ouchterlony (2005a) has proposed a three-parameter cumulative size distribution function, $f(y)$, with no reduction in curve fitting accuracy, given here as Equation 3.77:

$$y = \frac{1}{1 + \left[ \frac{\ln\left(\frac{D_{b\max}}{D_y}\right)}{\ln\left(\frac{D_{b\max}}{D_{b50}}\right)} \right]^b} \qquad (3.77)$$

where:

| | | |
|---|---|---|
| $D_{b50}$ | = | medium size of blasted stone (m). It is given by Equation 3.71 |
| $y$ | = | percentage passing finer (%) |
| $b$ | = | curve undulation parameter (see Equations 3.78 and 3.79) |
| $D_{bmax}$ | = | upper limit to the fragment size (m). It can be taken as equal to the largest *in situ* block size, $D_{i100}$ or either the burden or spacing if smaller than $D_{i100}$ . |

When introducing the correct parameters into Equation 3.77, the equation becomes a BBSD prediction model. A suitable name proposed for the model is the KCO (Kuznetsov-Cunningham-Ouchterlony) model.

Ouchterlony (2005a) has proposed two methods for predicting the value of the curve undulation paramater, $b$ (-).

1 The first is to adopt Cunningham's uniformity index, $n_{RRD}$ (-), from Equation 3.72 and to also introduce the relationship of $D_{b50}$ (m) and the size distribution's slope. A good approximation for $b$ (-) was found, given here as Equation 3.78:

$$b = n_{RRD} \cdot 2 \cdot \ln(2) \cdot \ln\left(\frac{D_{bmax}}{D_{b50}}\right) \qquad (3.78)$$

2 The second is to use an empirical formula (Equation 3.79), derived from sieved results from many full-scale blasts (Ouchterlony, 2005b):

$$b = 0.5(D_{b50})^{0.25} \cdot \ln\left(\frac{D_{bmax}}{D_{b50}}\right) \tag{3.79}$$

The function presented in Equation 3.77 fits BBSD sieving results from a wide range of rock types and blast conditions remarkably well and plugs into the Kuz-Ram model with ease, improving predictive capability in the fines range and the cut-off at the upper limit, especially if a good $D_{i100}$ estimate can be substituted for $D_{bmax}$ .

Its suitability for armourstone blasts also looks promising. It is suggested that the KCO model offers great potential in most bench blasting operations. For armourstone blast prediction, as with all prediction models, it should be applied with caution, especially as it has been developed for blasts with relatively higher specific charges and burden to spacing ratios than is common for armourstone blasts. It should also be noted that many unconventional blasting methods such as decoupling and simultaneous detonation are used for armourstone blasts. Accuracy of the KCO model and the function given by Equation 3.77 has not been examined as thoroughly in the 80–100 per cent passing size range where it is most critical for armourstone prediction, as for the medium and smaller sizes.

#### 3.9.4.4 Simplified guidance for BBSD prediction

To give a quick prediction of armourstone yields when the above methods cannot be applied, it may be instructive to make one quick characterisation of the joint spacing in the rock mass such as the average *PMS* value . An *RQD* summary value, if that is all that can be determined, may give an indication, but with poor reliability. One can then classify the potential quarry yields into three ranges, I, II and III, assuming the rock mass has three orthogonal sets, each with the same *PMS* and negative exponential spacing distribution and using concepts developed from Wang's Equation Method given above. Table 3.26 shows a range of *PMS* values: from 0.1 m to 1.2 m covering almost all characteristic *PMS* values likely to be encountered in natural rock masses. Column 2 of the table shows how the spacing may appear much smaller if a scanline runs obliquely and cuts all three sets; the figure given is for the minimum possible mean spacing. Traditionally, discontinuity spacings along a borehole or from core logging are described in terms of the *RQD* (rock quality designation value), defined as the proportion of scanline or borehole core that consists of intact lengths of 0.1 m or longer. The *RQD* is highly dependent on the direction of the borehole or scanline and columns 3 and 4 show the ranges of *RQD* for the different *PMS* values of this orthogonal system.

**NOTE:** A reduction in the 50 per cent passing size from 0.2 m *in situ* to 0.1 m blastpile is a size reduction factor of 2 and a volume reduction factor of 8. Similarly, a uniformity index such as $n_{RRD}$ given for a quarry material in terms of size is a factor of 3 higher than if given for volume or mass, ie $n_{RRD} = 3\ n_{RRM}$ .

**Table 3.26** *Rapid assessment of in situ and blasted block sizes ($V_{i80}$ and $V_{b80}$) relating to the principal mean spacings (PMS) (Wang et al, 1991a)*

| *PMS* (m) (*) | *MS* (m) | Max *RQD* (%) | Min *RQD* (%) | $V_{i80}$ *in situ* ($m^3$) | $V_{b80} = V_{i80}/6$ armourstone blast ($m^3$) | $V_{b80} = V_{i80}/20$ aggregates blast ($m^3$) | % $V_i$ >1.2 ($m^3$) | Range |
|---|---|---|---|---|---|---|---|---|
| 0.1 | 0.06 | 74 | 48 | - | - | - | - | I |
| 0.2 | 0.12 | 91 | 78 | 0.1 | - | - | - | |
| 0.3 | 0.17 | 96 | 89 | 0.2 | - | - | - | |
| 0.4 | 0.23 | 97 | 93 | 0.6 | 0.1 | - | 7 | II |
| 0.5 | 0.29 | 98 | 95 | 1.1 | 0.2 | 0.1 | 18 | |
| 0.6 | 0.35 | 99 | 97 | 1.9 | 0.3 | 0.1 | 30 | |
| 0.7 | 0.40 | 99 | 97 | 3.1 | 0.5 | 0.2 | 40 | |
| 0.8 | 0.46 | 99 | 98 | 4.6 | 0.8 | 0.2 | 52 | |
| 0.9 | 0.52 | 99 | 98 | 6.5 | 1.1 | 0.3 | 62 | III |
| 1.0 | 0.58 | 100 | 99 | 9.0 | 1.5 | 0.5 | 70 | |
| 1.1 | 0.64 | 100 | 99 | 11.9 | 2.0 | 0.6 | 75 | |
| 1.2 | 0.69 | 100 | 99 | 15.5 | 2.6 | 0.8 | > 80 | |

**Notes**

Based on Carboniferous limestone and a specific charge of ~0.2 and ~0.4 kg/$m^3$ for armourstone and aggregates blasting respectively.

* *PMS* in the table can be replaced by the cube root of the product of all three *PMS* values.

For $PMS = 1$ m, $V_{i80}$ in column 5 indicates the 80 per cent passing volume is 9 $m^3$. Table 3.26 gives the complete percentage passing values. From $V_{i80}$, the 80 per cent passing volume after blasting, $V_{b80}$ has been calibrated assuming a volume reduction factor (geared to the 80 per cent passing value) of 6 for armourstone blasting and 20 for high-fragmentation blasting. These factors are thought to be reasonably general although obtained from full-scale trial blasts in a limestone quarry; see Case History A, Box 3.26. Clearly, volume reduction factors must depend particularly on specific charge, rock type and burden spacing details. The application of a volume reduction factor for armourstone blasting to the case of *in situ* blocks of 1.2 $m^3$ will result in a block volume of 0.2 $m^3$ or block masses of just over 0.5 t for most rock types. The percentages given in column 8 and assigned for each *PMS* might therefore be taken as the maximum percentages of heavy armourstone blocks (ones larger than 0.2 $m^3$) assuming an effective armourstone blast has been used. Table 3.26 shows three ranges of *PMS* values with the following significance:

- Range I: $PMS < 0.4$ m, virtually impossible to produce more than 5 per cent blocks heavier than 0.5 t
- Range II: 0.4 m < $PMS$ < 0.9 m, necessary to maximise the percentage of large blocks heavier than 0.5 tonnes
- Range III: $PMS > 0.9$ m, a very high percentage of large blocks including *mammoth* blocks may result from a blast designed to maximise large blocks. These may be disruptive. An optimum blast designed to produce the maximum percentage of blocks in the range defined in the contract blocks should be sought.

#### 3.9.4.5 *Mass distribution assessment by image analysis*

Automated image analysis methods are becoming more widespread for determining blastpile size distributions in mining and quarrying operations. Digital photographs taken while piles are being loaded (so as to represent the full depth of the pile) and taken from above truck-loads provide input that readily available image analysis software will convert into size distributions using sophisticated correction algorithms. A blind trial of various commercial image analysis software packages (Latham *et al*, 2003) gives a snapshot of their performance. Figure 3.56 shows images with known size distributions of the type often used to calibrate image analysis software. Franklin and Katsabanis (1996) compiled a monograph of papers and references to such methods.

At least half a dozen commercial automated sizing systems are now in widespread use, not only for blast yield assessment, but also for production control of processed minerals. There is potential for wider use of such systems in quality control of gradings, eg barge deliveries of light gradings.

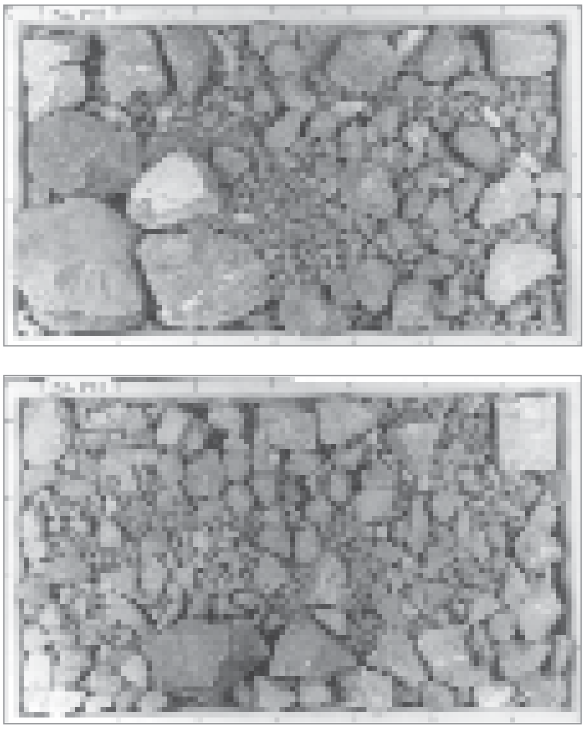


**Figure 3.56**

*Typical blastpile size distributions with similar appearance. Scale divisions = 1 m; P44: $n_{RRD}$ = 0.7, $D_{63.2}$ = 800 mm, $D_{50}$ ~ 460 mm; P41: $n_{RRD}$ = 0.9, $D_{63.2}$ = 350 mm, $D_{50}$~240 mm. The same distributions are shown in Figure 3.53. Note that Kuz-Ram often predicts $n_{RRD}$ > 1.0*

### 3.9.4.6 Photo-scanline methods

An alternative simple method for analysing photographic data (Lu and Latham, 1996) that can be undertaken without software is to superimpose scanlines directly on the scaled photographs. Many scanlines are drawn on each photograph with directions chosen to minimise bias. As with any image method, care is needed to correct for perspective distortion. A single length distribution from measurements of segment lengths defined by intersections between the particle edges is created from all the photographs making up a representative sample. It is invariably found that the cumulative form of this length distribution has a Rosin-Rammler form. The best fit photo-scanline Rosin-Rammler parameters $n_{RRDp}$ , $D_{63.2p}$ , for uniformity and characteristic length can be obtained from a linearised plot. To convert the Rosin-Rammler equation to a linear form, substitute the left-hand side of Equation 3.80 as the variable $Y$ and log $D_p$ as the variable $X$ and apply linear regression of $Y$ on $X$ to obtain the gradient and intercept, which give $n_{RRDp}$ and $D_{63.2p}$.

$$\log\left[\ln\left(\frac{1}{(1-y)}\right)\right] = n_{RRDp}\cdot\log D_p - n_{RRDp}\cdot\log D_{63.2\,p} \tag{3.80}$$



1
2
3
4
5
6
7
8
9
10

Equations 3.81 and 3.82 are the calibration equations to convert from segment length distribution coefficients (denoted with subscript $p$) to $n_{RRD}$ and $D_{63.2}$:

$$D_{63.2} = 1.119\ D_{63.2p} \tag{3.81}$$

$$n_{RRD} = 1.096\ n_{RRDp} - 0.175 \tag{3.82}$$

As for any assessment of blastpiles that sample only the surface-visible blocks, the results are likely to give coarser BBSD predictions than is representative of the entire pile. Taking many sample photographs during blastpile loading is preferable.

#### 3.9.4.7 *Direct screening and stone measurement methods*

It may sometimes be practical to count the number of stones $N$ in the entire potential armourstone *oversize* material in a blast, and to perform measurements of stone dimensions from a representative sample of, say, $N/5$ blocks. The sizes can be converted to masses using shape factors based on blockiness. Knowing the total rock mass in the blast and estimating the total mass in the oversize, the upper part of the BBSD can be plotted (see Box 3.27, Case History B Figure 3.62) and may be merged with photo-scanline or image analysis results.

In a production with no crushing, it is possible to assess the proportions in a blast if it is all processed. Yield curve data presented in Ouchterlony (2005a) is exclusively based on such a sieve analysis of blasts. The sorted material volumes are logged during production through the selection plant (eg trommel screen, see Section 3.9.7). Provided the coarsest proportion from the blast can be estimated, for example by counting stones in heavy grading classes or as described above, a curve based on assessment at three points can be drawn. In Figure 3.57, three important points on the yield curve were used to chart the change in BBSD while reducing specific charge.

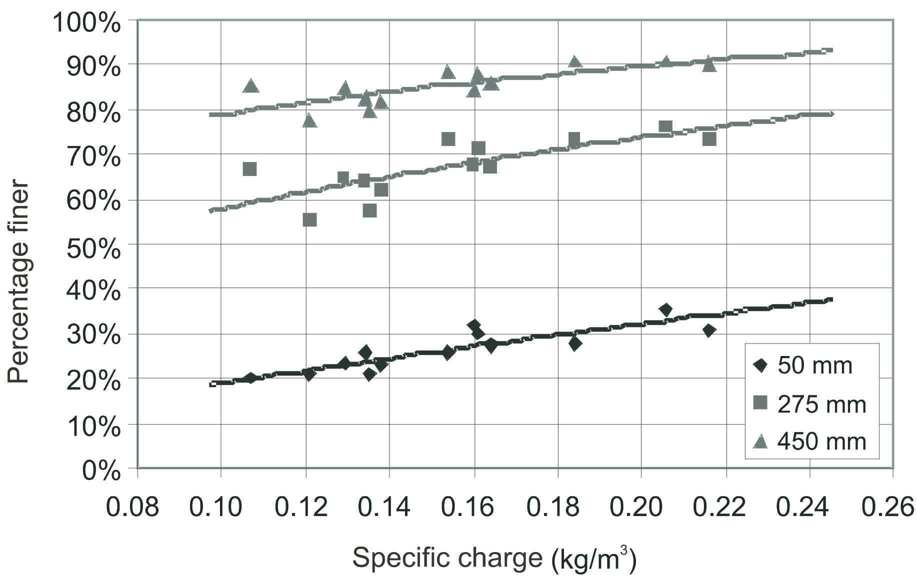



**Figure 3.57** *Use of a three-point method to characterise fragmentation and demonstrate the decrease in $D_{b50}$ with increasing specific charge of ANFO – data from one quarry (courtesy J van Meulen)*

**Box 3.26** *Case History A: improving armourstone yields in an aggregates quarry*

Full-scale trial blasts were conducted in an aggregate-producing quarry with the objective of improving armourstone yields. Results are summarised in Wang *et al* (1992b), which includes details of quality control for gradings, shape and integrity. The limestone quarry has a classical orthogonal pattern with sub-horizontal bedding (some healed with many stylolites) and two vertical joint sets seen in the two right-angled faces. Figure 3.58 shows vertical jointing and bedding in the east quarry face, revealing a closely spaced joint set that was not seen in the main north face of quarry, also partly shown in the far left of the figure. Data from 13 quick scanlines taken on two faces and the exposed surface of the rock mass at the top of the quarry were used to generate the statistics for the three sets of discontinuities summarised in Table 3.27. Wang's Equation Method was applied using lognormal distribution coefficients from Table 3.25 and the *PMS* values in Table 3.27. In Figure 3.59, the IBSD is plotted as a zone of possible distributions considered to represent the extreme possibilities ie by using both all n- and p-discontinuities and by using only the p-discontinuities. With a rock density of 2.66 t/m³, it may be estimated that about 50 per cent and 70 per cent of *in situ* blocks are over 2 t and 1 t respectively and that the biggest *in situ* blocks may be 15 m³.

**Figure 3.58** *Vertical jointing and bedding in the east quarry face of a limestone quarry. The man (in the centre) indicates the scale*

**Table 3.27** *Summary statistics of measured discontinuity orientation and spacings for each set*

| Set number | Mean orientation | | Principal mean spacing (*PMS*) and standard deviation (σ) | | | |
|---|---|---|---|---|---|---|
| | | | Persistent and non-persistent discontinuity data | | Persistent discontinuity data | |
| | Dip direction (degrees) | Dip (degrees) | *PMS* (m) | σ (m) | *PMS* (m) | σ (m) |
| Bedding | 261 | 12 | 0.598 | 0.392 | 0.598 | 0.392 |
| Joint Set I | 90 | 79 | 0.399 | 0.265 | 0.575 | 0.301 |
| Joint Set II | 185 | 83 | 0.659 | 0.594 | 1.259 | 0.969 |

**Note**

For definitions see Box 3.24.

**Box 3.26** *Case History A: improving armourstone yields in an aggregates quarry (contd)*

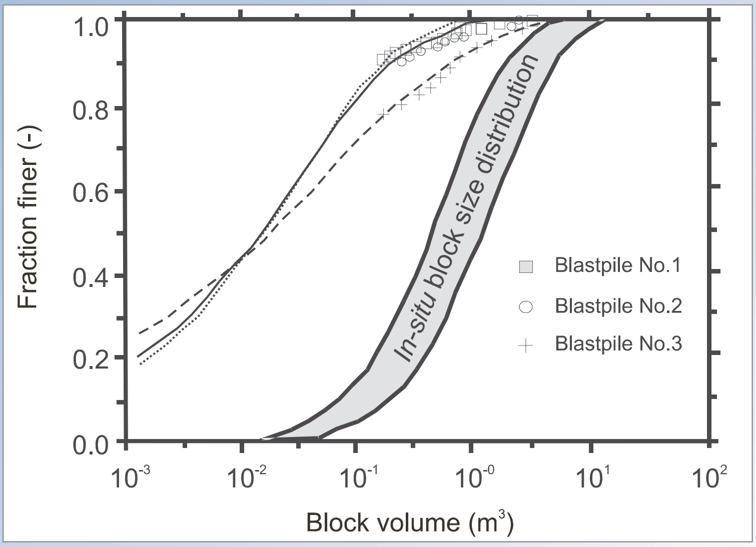



**Figure 3.59** *In situ and blastpile armourstone size distributions determined from photo-scanline and oversize stockpile measurements from three different blast designs in a limestone quarry. Lines based on linking oversize with photo-scanline determination of $D_{b63.2}$*

Details of three blasts are included in Table 3.28. The oversize stones from each blast were measured in detail and combined with photo-scanline assessments of $V_{b50}$ giving the line plots shown in Figure 3.59. Blast no 1 was a conventional high-fragmentation blast producing 8 per cent armourstone. The average volume of these stones was relatively small, with no stone over 10 t. By modifying the blast design with burden-to-spacing ratio of about 1.5 and a low specific charge of 0.2 kg/m³, a yield of 22 per cent armourstone was achieved. An important observation was that the directly measured largest stone sizes in blast no 3 were almost as large as those predicted by the IBSD analysis. Therefore, it was unlikely further significant improvement in yields of armourstone could be made by blast design. Important conclusions were: (i) determination of IBSD will help the blasting engineer know when an armourstone blast has been optimised; (ii) integrity and shape were not significantly changed by the variations in blast design during this study. Note some results presented above appear contradictory. $D_{b50}$ for blasts nos 1 and 3 appear similar, whereas the Kuznetsov equation (Equation 3.71) suggests the different specific charge should have increased it by some 43 per cent in blast no 3. Different spacing/burden ratio or locally different IBSDs provide the most likely explanations for this apparent inconsistency.

**Table 3.28** *Details of three blast designs*

| | | Blast round: | No 1 | No 2 | No 3 |
|---|---|---|---|---|---|
| Drilled geometry | Burden, *B* | (m) | 5.00 | 5.02 | 5.34 |
| | Spacing, *S* | (m) | 4.04 | 4.35 | 3.47 |
| | No of blastholes | (-) | 13 | 13 | 13 |
| Explosives | Total amount of explosive (ANFO equivalent) | (kg) | 2584 | 1767 | 1383 |
| | Specific charge, *Q*/*V* | (kg/m³) | 0.358 | 0.227 | 0.205 |
| Armourstone | Percentage of armourstone sized blocks > 0.18 m³ or 0.48 t | (%) | 8.5 | 11.3 | 22 |
| | Mean size of armourstone | (m³) | 0.474 | 0.449 | 0.563 |
| | Percentage of armourstone containing at least one flaw, *F* | (%) | 22.9 | 24.2 | 25.4 |
| | Mean value of *LT* (= *l*/*d*) | (-) | 2.3 | 2.31 | 2.37 |
| | Percentage of armourstone blocks with *LT* > 3 | (%) | 11.3 | 14 | 12.3 |
| | 50 per cent passing block volume in blastpile using photo-scanline methods, $V_{b50}$ | (m³) | 0.0175 | 0.0172 | 0.0191 |

**Box 3.27** *Case History B: Assessment of armourstone potential*

An aggregates quarry required an evaluation of the armourstone potential of the quarry. The investigation considered IBSD analysis of four zones in the quarry using the dissect method (Wang *et al*, 1991b); see Figures 3.60 and 3.61. The BBSD from an armourstone blast design was assessed with photo-scanlines across the blastpile surface and by direct block measurement of oversize (> 3 t) material. These blastpile assessments were compared with predicted yields from blast models (Figure 3.62). Using actual blast design parameters and IBSD information, the Bond-Ram model, BRM(A), was found to fit the oversized part given by measured blocks and to predict slightly smaller sizes than the photo-scanline assessment of the blastpile surface . It was considered unlikely that the blast design could be improved significantly since the upper part of the predicted BBSD curve and largest blocks assessed in the blastpile were of the same size as those predicted from the IBSD analysis (3–10 $m^3$). The blast model that produced yield curves in close agreement with measurements was then used to provide the quarry with suggested blast designs to maximise armourstone. Yield predictions were provided for various parts of the quarry. This example is based upon work by McKibbins (1995).

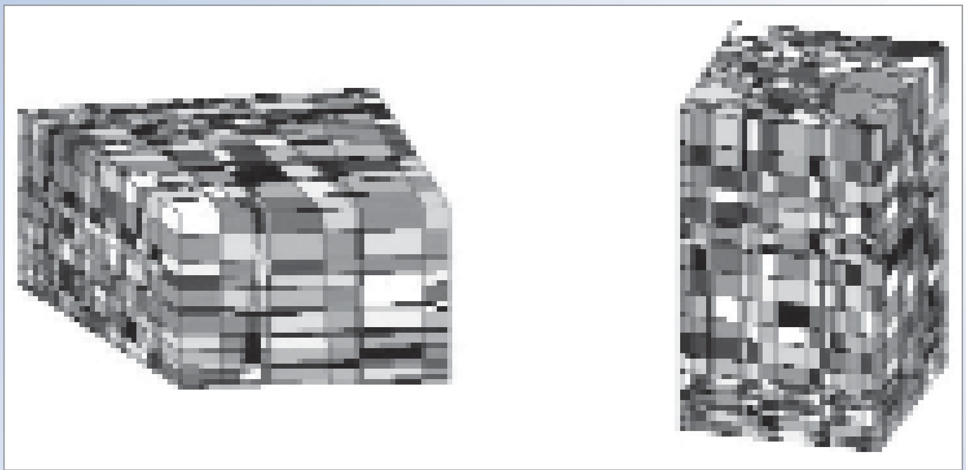


**Figure 3.60** *Computational dissection of rock masses – left: from Zone B (2100 $m^3$); right: Zone D (975 $m^3$) – using discontinuity location and orientation data from three perpendicular scanline segments*

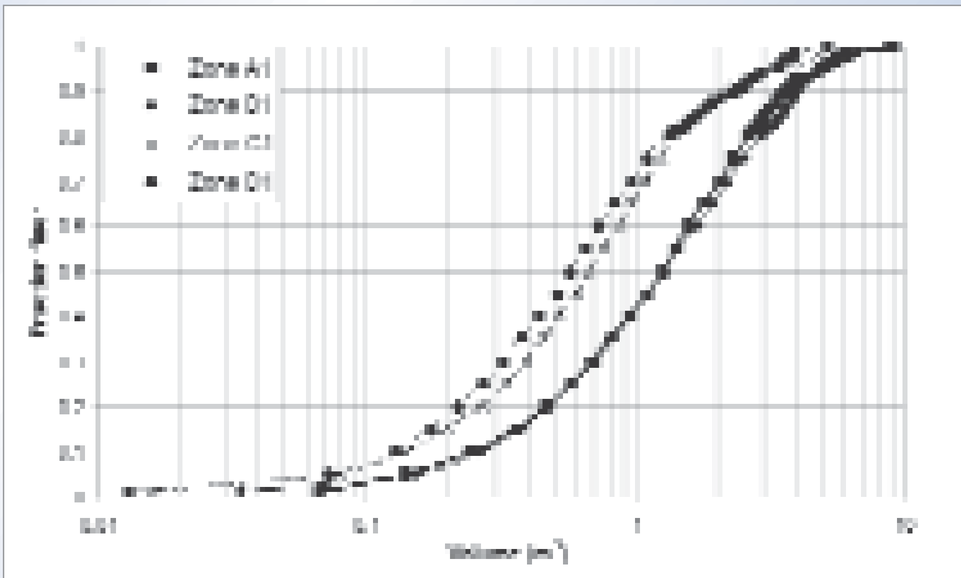


**Figure 3.61** *IBSD summary from dissect method yielding many thousands of individual block volumes. Zones A and B are highlighted as being better suited to armourstone production than Zones C and D*

**Box 3.27** *Case History B: Assessment of armourstone potential (contd)*

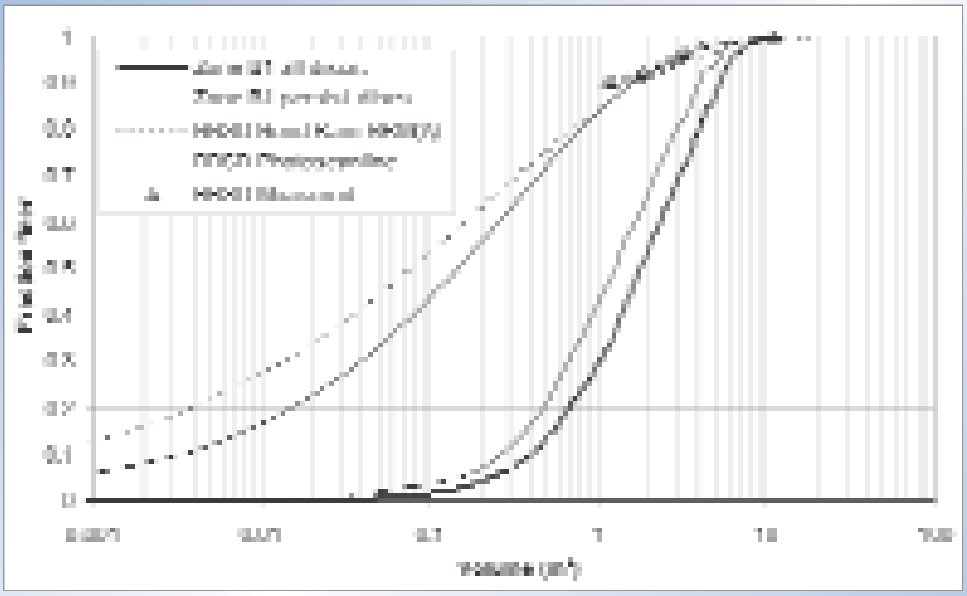


**Figure 3.62** *Example of blasting analysis result. IBSD curves, produced by considering only persistent discontinuities (coarser IBSD) and all discontinuities, define an envelope for IBSD in Zone B. The BRM(A) Bond-Ram model for BBSD provides the best prediction of yields for this blast design based on comparison with assessment of the blastpile using the photo-scanline method and by direct oversize block measurements. The photo-scanline survey sampled only the surface blocks in the blastpile*

## 3.9.5 Matching yield curves and demand

The procedure for matching a quarry yield curve with the demand for different tonnages of the various armourstone gradings is useful for any quarry but is particularly useful in dedicated quarries to:

- plan production
- consider the potential benefits of secondary breakage
- calculate the amount of quarried but wasted material
- optimise the design of berm and conventional breakwaters with regard to maximum use of quarried materials.

Given any predicted average BBSD yield curve for the production in a quarry, an approximation may be defined by Rosin-Rammler coefficients such as $M_{50}$ and $n_{RRM}$. It is then instructive to present, on the same plot, the proportions required for different armourstone gradings. For example, berm and conventional breakwater designs may require very different proportions of the larger stone sizes, which can lead to significant differences in the utilisation of quarried materials. Judicious use of secondary breakage may sometimes help to avoid leaving behind vast amounts of material.

Having obtained the predicted BBSD yield curve that will form the basis of the quarry production assumption, the yield fraction curve is transformed by differentiating the BBSD curve. Finally, these values are divided by $M_{50}$ given in tonnes, to make the area under the new curve equal to 1.

The *yield fraction per tonne* plot can be obtained from the Rosin-Rammler coefficients as follows:

$$y_{pt} = \frac{1}{M_{50}} 0.693 n_{RRM} \left( \frac{M_y}{M_{50}} \right)^{n_{RRM}-1} \exp\left\{ -0.693 \left( \frac{M_y}{M_{50}} \right)^{n_{RRM}} \right\} \quad (3.83)$$

For a given mass $M_y$ in tonnes, the $y_{pt}$ value gives an approximation for the fraction of the blast that lies within the range $M_y \pm 0.5$ t. So that complex grading requirements can be converted, demand and yields are considered within 1 t bands. If, for example, there is a large order for breakwater armourstone, including 20 per cent of material of 3–6 t, this design requirement, ie demanded volumes, would be represented by a bar that occupies 0.2 of the area under the curve or is 0.2/3 units high between mass values of 3–6 t. This can then be compared directly with the area under the $y_{pt}$ curve between 3 t and 6 t that represents the proportion of quarry yield falling within this range. A good match means the 3–6 t requirement is compatible with the rest of the order, but other ranges must also match well if quarry utilisation is to approach 100 per cent.

The methods of matching yields and demands are illustrated in Box 3.28 and explained further in Vrijling and Nooy van der Kolff (1990) in the context of comparing utilisation of quarried material given alternative breakwater designs, and in Latham and Wang (1992) for consideration of armourstone supply rates. Note the *yield fraction per metre* curves may also be formulated using the derivative of any cumulative yield curve function or an equation equivalent to Equation 3.83 but presented in terms of sizes. Examples of average production yield curves are given in terms of the best-fit Rosin-Rammler parameters in Table 3.29, together with supplementary blast design data. These average figures were obtained from back analysis of materials supplied to breakwater projects over extended production periods targeting different armourstone size requirements.

**Table 3.29** *Examples of yield curves in dedicated quarries, after Vrijling and Nooy van der Kolff (1990) (courtesy J van Meulen)*

| Rock type | $I_s$ MPa | Density t/m³ | $M_{50}$ kg | $M_{80}$ t | Sieve $D_{50}$ m | $n_{RRM} = n_{RRD}/3$ | Q/V kg/m³ | Target kg |
|---|---|---|---|---|---|---|---|---|
| Diorite | - | 2.70 | 39.19 | 0.435 | 0.289 | 0.35 | - | - |
| Greywacke sandstone | - | 2.67 | 5.13 | 0.042 | 0.147 | 0.40 | - | - |
| Granite | - | 2.67 | 347.63 | 8.192 | 0.601 | 0.267 | - | - |
| Granite | - | 2.67 | 295.58 | 6.965 | 0.569 | 0.267 | - | - |
| Basalt | - | 2.80 | 210.45 | 2.85 | 0.50 | 0.323 | - | - |
| Lapilli tuff | - | 2.71 | 5.32 | 0.088 | 0.148 | 0.30 | 0.175 | 30-150 |
| Granite | 9.7 | 2.64 | 4.88 | 0.115 | 0.145 | 0.267 | 0.325 | 500-2000 |
| Granite | 9.7 | 2.63 | 29.91 | 1.107 | 0.267 | 0.233 | 0.225 | 2000-5000 |
| Andesite | 7.4 | 2.76 | 14.12 | 0.523 | 0.204 | 0.233 | 0.216 | 60-300 |
| Shelly limestone | 1.0 | 1.89 | 15.8 | 0.279 | 0.241 | 0.293 | 0.431 | 500-2000 |
| Limestone | 5.8 | 2.66 | 9.89 | 0.366 | 0.184 | 0.233 | 0.265 | 1000-3000 |
| Dolomitic limestone | 4.7 | 2.70 | 95.62 | 1.586 | 0.389 | 0.30 | 0.133 | 4000-8000 |
| Granite | - | 2.65 | 23.98 | 0.887 | 0.247 | 0.233 | - | - |

**Notes**

$I_s$ = point load strength index (MPa)

$Q/V$ = specific charge (kg/m³)

Target = blast design target, ie armourstone mass range to be produced in largest proportions. To convert from mass to sieve size, express mass in tonnes, divide by density (t/m³), take the cube root to obtain nominal diameter, $D_n$ (m), then divide by 0.84 to obtain sieve diameter, $D$ (m).

**Box 3.28** *Matching quarry yield and rock volumes demanded by any given design*

A worked example of how production can be planned to reduce costs by maximising utilisation of a quarry is illustrated using the yield fraction per tonne, $y_{pt}$, diagram (Figure 3.63) and an example spreadsheet (Figure 3.64).

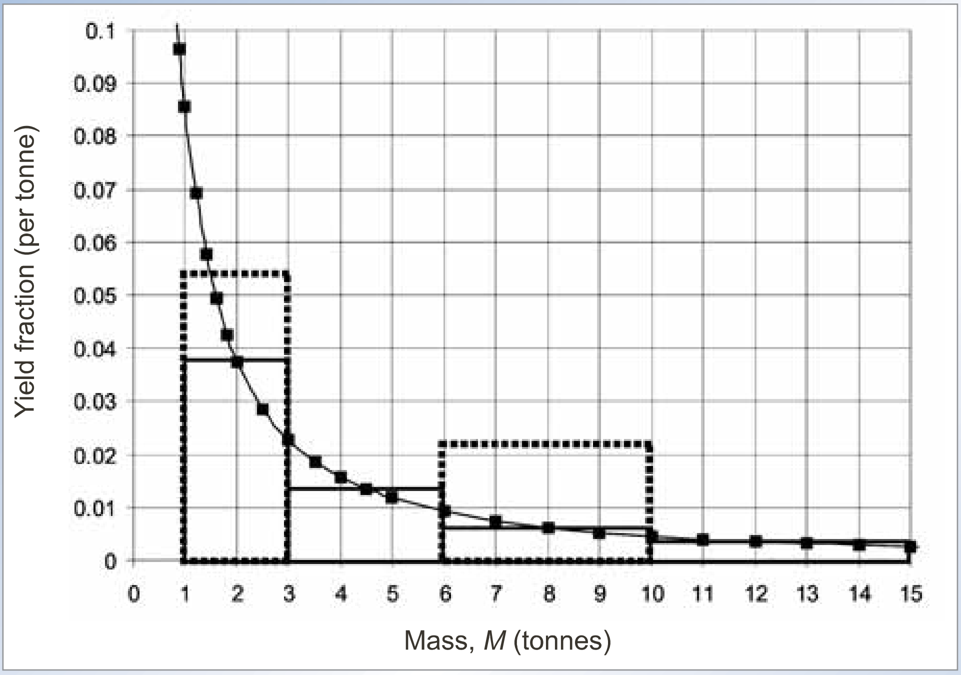



**Figure 3.63** *Example of matching quarry yield with armourstone requirements in a contract*

Areas within dotted rectangular bars represent requirements for 1–3 t and 6–10 t armourstone as a fraction of the total breakwater materials demanded. Similar plots with different scales can be used to examine the 0–1 t materials. Areas within solid rectangular bars represent ideal fractions for total quarry utilisation. These rectangles are drawn after obtaining the $y_{pt}$ curve, where in this case BBSD is described by $M_{50}$ = 24 kg, uniformity index, $n_{RRM}$ = 0.233 (equivalent to 63.2 per cent passing nominal diameter of 350 mm, and $n_{RRD}$ of 0.70, as given in the spreadsheet presented in Figure 3.64). It is apparent that the largest shortfall factor of about four times exists for the 6–10 t grading. The detailed armourstone requirements total 197 500 t and this would require about 800 000 t of material to be quarried, a 25 per cent quarry utilisation.

Analysis of the $y_{pt}$ diagram illustrates the potential for secondary breakage of > 10 t to make up the shortfall of 6–10 t and for the unrequired 3–6 t to match almost perfectly the extra 1–3 t needed, assuming a certain efficiency loss during secondary breakage. The spreadsheet further illustrates the detailed implementation of the production plan that achieves a much better 61.8 per cent use of quarried rock.

**NOTE:** This example shows clearly that blasting for large armour stones is required, here 6–10 t, although an examination of 60–300 kg and 300–1000 kg is also of interest. If the requirement for 6–10 t had been much lower, obtaining the smaller gradings would have been critical. Blasting could then have been directed towards a more favourable BBSD for such an order, ie it would have focused on producing slightly greater fragmentation to generate smaller product.

From a simple estimate suggesting that the unit rate for both routine quarrying and for secondary breakage was €1.5 per tonne, and with totals from production plus secondary breakage of 352 322 t, the price per tonne of ordered rock would be 352 322/197 500 × €1.5 = €2.68/t.

**Box 3.28** *Matching quarry yield and rock volumes demanded by any given design (contd)*

| Quarry production demands | | | | Quarry yield prediction and matching | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Assumptions: BBSD by Rosin Rammler curve with nominal block size at 63.2% passing, $D_{n63.2}$ = 350 mm, $n_{RRD}$ = 0.7 , $\rho_{rock}$ = 2.65 t/m³ | | | | | |
| Classes of material | Total demand eg for breakwater contract | Mass (NLL value) | Production | Production from BBSD prediction | Balance | Secondary breaking of >10 t (65% efficiency) | Balance | Secondary breaking of 1-10 t (90% efficiency) | Balance excess |
| | (t) | (kg) | (%) | (t) | (t) | (t) | (t) | (t) | (t) |
| > 10 t | | | | 18 628 | 18 628 | -18 628 | 0 | | 0 |
| | | 10 000 | 94.2 | | | | | | |
| 6–10 t | 17 500 | | | 7008 | -10 492 | 12 108 | 1616 | -1616 | 0 |
| | | 6000 | 92.0 | | | | | | |
| 3–6 t | 0 | | | 11 728 | 11 728 | | 11 728 | -11 728 | 0 |
| | | 3000 | 88.3 | | | | | | |
| 1–3 t | 22 500 | | | 23 336 | 836 | | 836 | -836 | 0 |
| | | 1000 | 81.0 | | | | | | |
| 300–1000 kg | 39 375 | | | 30 466 | -8909 | 3260 | -5650 | 5650 | 0 |
| | | 300 | 71.5 | | | | | | |
| 60–300 kg | 55 625 | | | 43 836 | -11 789 | 3260 | -8529 | 8529 | 0 |
| | | 60 | 57.7 | | | | | | |
| 1–60 kg | 62 500 | | | 94 375 | 31 875 | | 31 875 | | 31 875 |
| | | 1.0 | 20.2 | | | | | | |
| fines | | | | 90 139 | 90 139 | | 90 139 | | 90 139 |
| | 197 500 | | | 319 514 | | 0 | 122 014 | 0 | 122 014 |
| *Quarry utilisation = 61.8%* | | | | | *Total secondary breaking = 32 808 tonnes* | | | | |

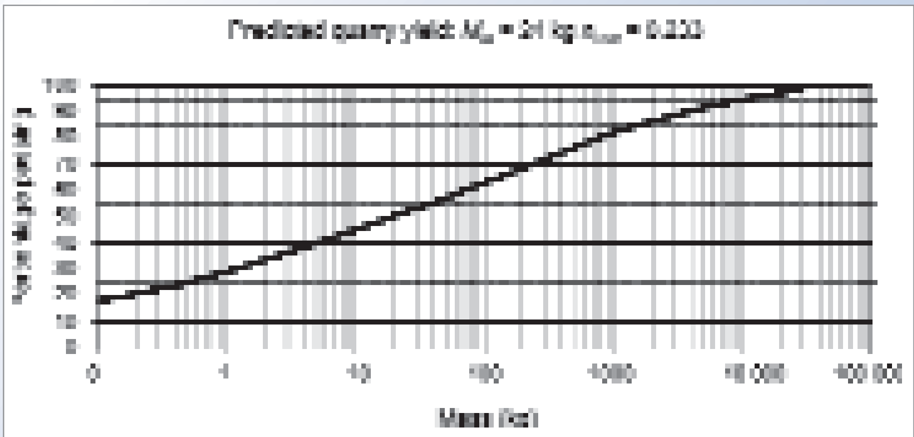



**Figure 3.64** *Spreadsheet analysis together with predicted BBSD yield curve for planning the matching of quarry yield with demand (courtesy J van Meulen)*

## 3.9.6 Quarry layout

The production of armourstone will influence the organisation and possibly the layout of the quarry. The purpose of the present section is not to present the details of quarry organisation but rather to highlight key issues that should be considered by producers of armourstone or clients when visiting a quarry that may produce armourstone. The impact of armourstone production on the quarry organisation will in fact depend on the quantity, the grading and the type of production of armourstone.

### *3.9.6.1 Extraction face*

Extraction of armourstone may not be possible from all extraction faces. The selection of the appropriate quarry face is heavily controlled by the geotechnical properties of the rock mass, especially the discontinuity spacing and the natural block sizes for heavy armourstone. This may limit the number of faces or benches available in the quarry to zones least affected by discontinuities if heavy armourstone is to be produced (for further discussion see Sections 3.2.3, 3.9.1 and 3.9.2).

### *3.9.6.2 Sorting and selection*

Specific methods for sorting and selection of armourstone are presented in detail in Section 3.9.7. They are generally divided into two categories: fixed heavy equipment and mobile or semi-mobile equipment. The costs associated with the purchase of heavy equipment are significant. Moving fixed heavy equipment, such as heavy trommel screens or grizzlies, around the quarry will incur substantial costs, so it is important to determine their optimum position. The travel distance of dump trucks from the face to the primary crusher should also be minimised. For example, a trommel screen close to the primary crusher will enable both facilities to be fed at their maximum capacity and will reduce the distance that dump trucks need to travel. Lighter equipment, such as static grizzlies, may be built in-house at lower cost.

### *3.9.6.3 Secondary breakage*

Secondary breakage is an essential technique to adjust the quarry yield to the actual contract requirement. In other words, the excess of oversized materials can be reduced by breaking them into smaller required gradings without affecting the total armourstone blasting. Although, total production of a given grading by secondary breakage is not cost-effective, when considered in the context of the whole production of the quarry and other required gradings, it is often the most cost-effective solution (see Box 3.28).

Secondary blasting may be hazardous and should be performed only when no other technique is possible. Use of black powder may be very efficient. A sufficient area should be dedicated to ensure safe and productive working conditions for secondary breakage. The material should be spread out so that the hydraulic excavator equipped with hydraulic hammer (sometimes called *pecker*) or other means can reach all the stones easily. It may be organised in lines between which the breaking, sorting and transport means (from muckpile to breaking area and from breaking area to the stockpiles) can work without significant interference. As space management is paramount in armourstone operations, a layout scheme such as that shown in Figure 3.65 should be adopted for safer working.

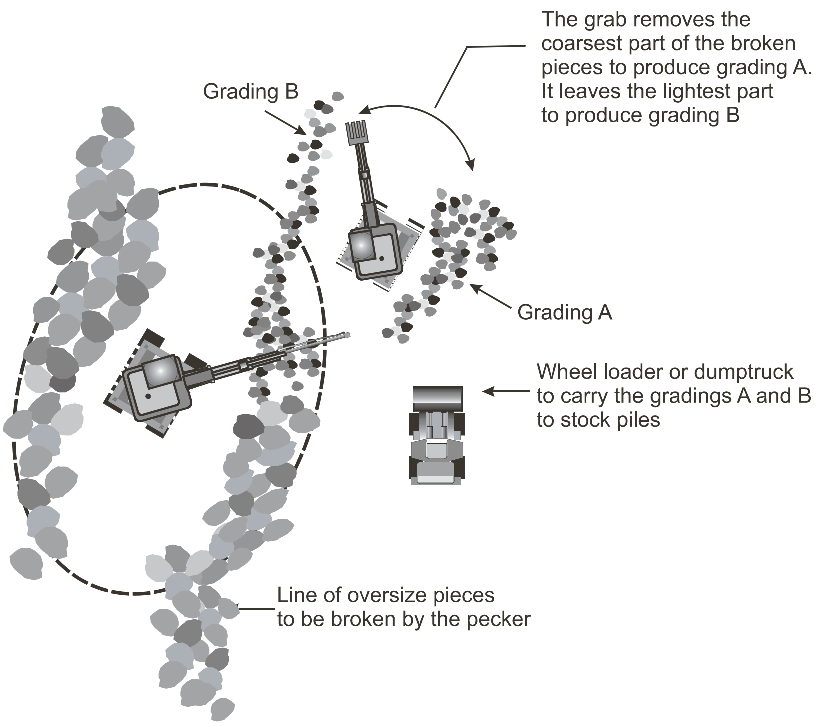



**Figure 3.65** *Organisation of the working area for secondary breakage*

### 3.9.6.4 *Stockpiling*

For the organisation of stockpiles, the key principles to follow are to:

- reduce the travel distance of machines transporting quarried rock from the faces
- facilitate movement of machines while stocking or loading
- limit the height of the stock to reduce breakage and spalling if this is of concern (but note that wide areas will be required).

Consequently, stock may be located at different places in the quarry such as:

- close to the **bottom of the extraction face**. This may be effective in separating the armourstone activity from the aggregate activities. It will also limit the number of handling events and so reduce breakage caused by handling. If the gradient of access slopes is gentle (say below 5–7 per cent), delivery trucks may even have access for loading
- **temporary stocks** may be laid out in an unused area adapted for secondary breakage or reselection to take place. Temporary stocks may also be required for the loading of trains
- when space is available, organising stocks in a **dedicated zone** of the quarry is a convenient solution to separate the quarrying activity from the loading activity.

Stockpiles are organised to separate the different gradings physically, as shown in Figure 3.66. The organisation of the stockpiling areas should enable machines to circulate easily and minimise multiple handling when building or when emptying the stockpiles. The area should have an appropriate floor to avoid the armourstone becoming contaminated with fines and to enable traffic in all weather conditions. Stockpiles of heavy armourstone may have a limited number of layers (two or three) if there is concern about breakage. Typical stockpile capacity may be 100 t in one layer of $HM_{3000-6000}$ on a 10 m × 15 m area (see Figure 3.67) or 200 t in two layers. Light or coarse armourstone may be piled to 3 m high and approximately 1500 t may be stocked on a 10 m × 40 m area. Alternatively, the stockpiling capacity may be as high as 1.5 t/m² for 6–10 t armourstone, 2.0 t/m² for 3–6 t armourstone and 2.5 t/m² for 1–3 t armourstone.

**Figure 3.66** *Armourstone organised in several standard grading stockpiles*

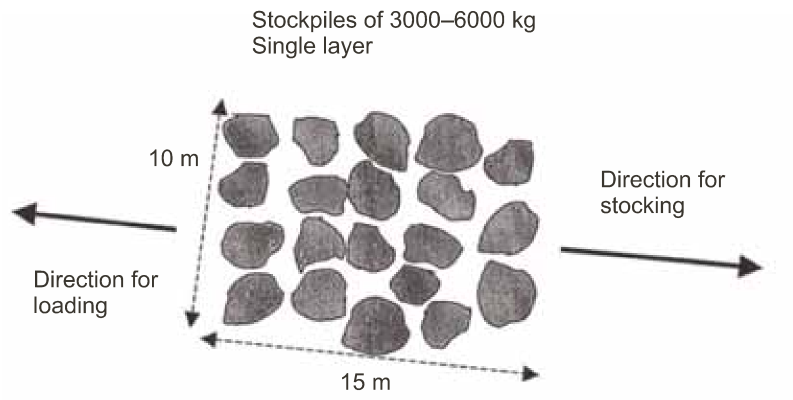



**Figure 3.67** *Stockpiling of armourstone in layer of 3–6 t armourstone. One layer represents approximately 100 t of stone*

### 3.9.6.5 *Loading areas*

Loading by the client generally takes place from the quarry stockpile to minimise handling costs. Therefore, the quality of the track as well as the slope at the stockpiles should be appropriate for this type of traffic whatever the weather. Specific attention should be paid to the simultaneous traffic of on-road and off-road types of truck and the security issues that this brings. When using reselection for grading control, it should be performed at the time of loading.

## 3.9.7 Selection, sorting and processing

This section deals with the production of armourstone and proposes different approaches to controlling the mass distribution. Aspects related to selection with respect to shape and integrity are discussed in Section 3.10. When choosing the most appropriate means to select, sort or process armourstone, the following items should be considered:

- grading to be produced
- need for secondary breakage and reselection if light or coarse armourstone are to be produced
- quantity to be produced

- time available before delivery
- production rate
- target cost/price.

The system generally adopted just after blasting consists of directing suitable excavators to extract the blocks of heavy armourstone. A wheel loader can then load out the smaller materials. The purpose is to free the face as rapidly as possible and to avoid having too many machines congesting the face area. The material should be sent to stations that are best suited to separate the fractions, eg heavy armourstone to stockpile areas for reselection, light armourstone to a selection plant (trommel, barsizer, grizzly screen, static grizzly), material destined to become coarse gradings to a crushing plant.

The most appropriate tools should be chosen, from the following three types:

- **fixed heavy equipment** – has a high investment and running cost and needs significant civil work for installation. It can rarely be moved around the quarry once installed. Examples are high-capacity trommel screen, grizzly sizers or static bars and fixed aggregate processing plants
- **light equipment** – can be moved around the quarry and can sometimes be built in-house, such as static grizzlies and barsizers
- **non-dedicated equipment** may also be used to process armourstone. This can simply be plant used for aggregate production or other types of machinery that are available at the quarry for other activities, such as excavators or grabs.

Detailed guidance on machine capacity may be found in any technical documentation of the manufacturer (see Section 9.3.1 where links to equipment manufacturers' websites are given).

#### 3.9.7.1 *Production technique for heavy armourstone*

For **heavy armourstone**, visual estimation of the mass with marked-up calibrated reference stones may be sufficient if performed by a trained or experienced operator. The quality of the operator's visual estimation should be checked against actual weighing. Specialised weighing devices are recommended for the largest heavy gradings (greater than ~ 6 t). For heavy armourstone and the larger light gradings, there are two options:

- for individually handled stones in heavy gradings, armourstone may be selected at the blastpile and transported directly to the appropriate stockpile
- all oversize stones may be transported to a temporary stockpile that is then reselected. This may result in higher output rates (see Box 3.29). This is an appropriate way to ensure quality control of the material during grading preparation.

It is advisable to be aware of grading requirements and whether mass distribution testing will use the reference method or alternative methods; see Section 3.8.3.2.

**Box 3.29** *Reselection of armourstone*

Reselection of larger stones can sometimes be at higher outputs than selection at the face because the material is much more single-sized. It should be spread out for machinery to access stones easily. The principle of reselection is that a loader fitted with a weighing device and forks instead of a bucket weighs the stones and transports them to stockpiles of standard gradings. If there is doubt about whether the stock complies with requirements, sub-class stockpiles may be used and the stones placed into 1–2 t, 2–3 t, 3–4 t, 4–5 t, 6–8 t, 8–10 t, 10–12 t stocks etc. An excavator may also be used, but specific attention should be paid to the organisation of the stocks to minimise the travelling distances. Table 3.31 provides the appropriate size of machine and experience of outputs.

**Table 3.31** *Relationship between the appropriate machine capacity (t) and size of stone to be reselected*

| Equipment capacity | > 10 t | 6–10 t | 3–6 t | 1–3 t | 0.3–1 t | 60–300 kg |
|---|---|---|---|---|---|---|
| Front-end wheel loader with fork (bucket not appropriate) (t) | 45.0 | 30.0 | 22.5 | Not recommended | | |
| Excavator (t) | 60.0 | 50.0 | 37.5 | 27.5 | 17.5 | 10.0 |
| Powerfork (t) (to be fitted to excavator) | 3.65 | 3.05 | 2.30 | 1.70 | 1.10 | 0.60 |
| Average selection rate (t/h) | 250 | 215 | 160 | 95 | 43 | 15 |

**NOTE:** The average output of a front-end wheel loader is difficult to determine since it depends on many parameters, eg the travel distance.

The final grading is produced by recomposition during loading at the quarry and not at the delivery stage. Consequently, the final grading may either be a standard or non-standard grading. The proportion of stones required from each sub-class to create a good fit to the average target grading curve is determined. Mixing at the construction site will ensure that the proper grading is available for construction.

Table 3.32 gives an example of how to prepare a quality control guide table for a 6–10 t grading with $M_{50}$ between 8.5 t and 7.5 t. The last two columns can be used as a grading plan for 1000 t used by the machine driver when loading the trains, barges or trucks. The operator keeps a record of the number of pieces loaded from each sub-class and once or twice a day a grading curve is plotted. If sizes are drifting off target grading curves, future loads can be adjusted.

**Table 3.32** *Heavy grading quality control plan*

| Sub-class | Cumulative % in sub-class | Percentage in sub-class | Tonnage in sub-class | Average stone mass (t) | Number of stones |
|---|---|---|---|---|---|
| < 4.0 t | 0.0 | 0.0 | 0 | | |
| 4.0–5.0 t | 2.5 | 2.5 | 25 | 4.5 | 6 |
| 5.0–6.0 t | 5.0 | 2.5 | 25 | 5.5 | 5 |
| 6.0–7.0 t | 27.5 | 22.5 | 225 | 6.5 | 35 |
| 7.0–8.0 t | 50.0 | 22.5 | 225 | 7.5 | 30 |
| 8.0–9.0 t | 67.5 | 17.5 | 175 | 8.5 | 21 |
| 9.0–10.0 t | 85.0 | 17.5 | 175 | 9.5 | 18 |
| 10.0–12.0 t | 91.0 | 6.0 | 60 | 11.0 | 5 |
| 12.0–14.0 t | 97.0 | 6.0 | 60 | 13.0 | 5 |
| 14.0–16.0 t | 100.0 | 3.0 | 30 | 15.0 | 2 |
| Total: | | | **1000 t** | | **126** |

**NOTE:** Although permitted according to the standard, at this stage there should not be any piece smaller than the 4 t. This allows for the fragments to be produced during the handling of the materials during transport and placing.

1
2
3
4
5
6
7
8
9
10

### 3.9.7.2 *Production technique for coarse armourstone and lighter gradings of light armourstone*

It is generally not economical to select large quantities of the smaller grades (smaller than 300 kg) using picking with excavators and grabs because of low production rates. The following methods are preferable:

- typical aggregate quarry processing plant such as a crusher with customised settings (see Box 3.30)
- vibrating screen and grizzly
- selection hill (see Box 3.31)
- trommel screen (Box 3.32)
- bars or static grizzly (see Box 3.33)
- barsizer (see Box 3.34)
- sidekick (see Box 3.35).

For all such equipment, the following relationship between the opening dimension and the mass of the (armour) stone may be used:

$$D_{sp} = f \cdot \left(\frac{M}{\rho_{app}}\right)^{1/3} \tag{3.84}$$

where:

$D_{sp}$ = upper or lower opening dimension (m)

$M$ = upper or lower selection mass required, ie $M_{70}$ or $M_{10}$ (kg)

$\rho_{app}$ = the rock density (kg/m$^3$)

$f$ = shape factor, used here as a guide to equipment settings, depending on the type of system used for selection, (-).

From experience, values of shape factor, $f$, to give appropriate settings for a range of methods are as follows:

- visual selection: 0.60
- vibrating screening unit: 0.60 × (length of square holes)
- vibrating grizzly unit: 0.55 × (opening at the end)
- barsizer: 0.45 × (opening at the tips)
- static grizzly: 0.40 × (average opening)
- trommel screen: 0.35 × (square root of the screen hole area).

**NOTE:** These values of shape factor, $f$, have been determined based on data from a number of quarries and should be considered as rules of thumb for size determination. Where a precise prediction is required, specific measurement of the produced size should be undertaken to confirm that the settings are appropriate.

### 3.9.7.3 *Production technique for core material directly from muckpile*

The selection technique to produce core material directly from the pile of blasted stone (*muckpile*) essentially depends on (i) the quality expected and achievable, (ii) the quantity needed in the contract, (iii) the equipment available at the quarry or the cost of getting it.

As identified in Section 3.4.4, there are two types of core material and these have different means of production.

**Quarry run**. This category includes everything from the finest material of the quarry yield up to a maximum size in the blastpile and is best described as 0–*M* kg. Consequently, the production simply consists of removing the oversize. This can easily be done with a wheel loader or an excavator. When using a wheel loader, the large size of the bucket and the limited visibility of the driver will make it practically impossible to produce a lighter core material than 0–1000 kg. Using an excavator with a smaller bucket and digging towards the cabin could produce a 0–500 kg material. Note that the grading of the *muckpile* gets finer when digging deeper into it.

**Processed core materials**. This material is produced by removing both the oversized and fines, generally by means of a robust static grizzly (see Box 3.33). Due regard should be given to the lower cut-off value since it significantly affects the amount of by-product for which an alternative use should be found. Changing the lower limit from 1 kg to 5 kg may effectively lead to rejection of an extra 10 per cent of quarry yield (see also Section 3.4.4).

### 3.9.7.4 *Technologies for the different selection or processing methods*

This section presents different techniques or tools suitable for armourstone production, illustrated in Boxes 3.30–3.35 as follows:

- crusher (Box 3.30)
- selection hill (Box 3.31)
- trommel screen (Box 3.32)
- bars or static grizzly (Box 3.33)
- barsizer unit (Box 3.34)
- sidekick (Box 3.35).

Vibrating screens and grizzlies may be used for production of coarse grading armourstone provided they are sturdier than traditional aggregates screens. They can be located after the primary crusher with possible adjustment of its characteristics to produced gradings with nominal upper limit up to 100 kg or 200 kg (see Box 3.30). This may be appropriate for production of gabion stone, for instance. The vibrating screen decks will need to be adapted to handle the larger stones. Constraining the maximum feed size and the smallest mesh or hole opening will generally prevent damage. Typical limitations are given in Table 3.30.

**Table 3.30** *Limitation of screening device to limit damages*

| | Maximum feed size | Minimum passing size |
|---|---|---|
| Grizzly | ~ 120 kg | ~ 100 mm (1.7 kg) |
| Holed steel plate | ~ 200 mm (13.0 kg) | 150 mm (5.6 kg) |
| Woven wire mesh | ~ 125 mm (3.2 kg) | 75 mm (0.7 kg) |

**NOTE:** It is easier to make round holes in a steel plate in a workshop than to make square ones. The diameter should be increased by 1.23 times the width of a square hole needed for a similar screening result. However, a steel plate with round holes has a lower screening capacity. Bigger screening areas and decks are therefore required for similar production rates.

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The **use of sidekicks** (Box 3.35) may be an alternative to grizzly screens, which are generally expensive to use. In practice, to process crusher output with a grizzly screen, an appropriate barsizer is hung at the end of the conveyor belt. The top size of the grading is thus controlled by the crusher setting, the bottom size by the setting on the barsizer.

When using traditional aggregate facilities to produce armourstone, special attention should be given to the **capacity of the conveyor belt** underneath the crusher outlet. The strength, width, number of idlers and travel speed of the belt will normally be suitable for larger stones than usual. A rule of thumb is that the width of the belt should be at least three times the length of the biggest stone (see Section 3.4.3). The travel speed should generally not be more than 1.0–1.5 m/s, which may necessitate a reduction in crushing rates.

**Box 3.30** *Production of coarse armourstone with a crusher*

When large quantities of gradings lighter than 60 kg are required, processing the quarry run through grizzlies and bar spacers may not be the most efficient since (i) the size of the feed material may damage the smaller screens, (ii) the percentage of product in the feed might not be high enough for this method to be efficient (say 15 per cent minimum for efficiency). Alternatively, 10–60 kg may be produced with a standard size jaw crusher such as would be available in an aggregate quarry. However, the crusher is generally part of the whole quarry process and using it for armourstone production may be significantly disruptive.

Considering a jaw crusher with characteristic dimensions of width, $W$ (mm), between the fixed and the moving plate and $L$ the length of the crusher opening, (mm), the maximum mass, $M$ (t), for the crusher feed without risk of blockage/damage is approximately:

$$M = 2.3\,(L/1000 \times W/1000)^{0.17} \tag{3.85}$$

The product size is controlled by the **closed side setting of the crusher**, *CSS* (mm), that can be adjusted according to the percentage of product required. Wear of the crusher plates should be taken into account and the range of adjustment is approximately 50 mm. Table 3.33 gives typical values of settings of single-toggle crushers for production of 5–40 kg to 40–200 kg armourstone.

**Table 3.33** *Setting of single-toggle jaw crushers*

| Size $W \times L$ (mm) | Size $W \times L$ (inch) | Min CSS (mm) | Max CSS (mm) | Max grading | Power (kW) |
|---|---|---|---|---|---|
| 360 × 500 | 14 × 20 | 40 | 75 | coarse grading | 20 |
| 500 × 760 | 20 × 30 | 50 | 115 | coarse grading | 55 |
| 760 × 1067 | 30 × 42 | 100 | 175 | 5–40 kg | 110 |
| 1067 × 1220 | 42 × 48 | 140 | 210 | 5–40 kg | 160 |
| 1220 × 1500 | 48 × 59 | 165 | 250 | 10–60 kg | 215 |
| 1500 × 1800 | 59 × 71 | 175 | 300 | 40–200 kg | 300 |

The output of a crusher in t/h is about $0.0016 \times L \times CSS$, where $L$ (mm) is the length of the crusher opening and *CSS* is the closed side setting of the crusher (mm).

**Box 3.31** *Production of coarse armourstone using a selection hill*

To produce core material in which fines are not acceptable, a selection hill may be used where segregation of the material will take place by tipping the quarry run along the hill. For best results, it should be at least 10 m high. Typical core of 5–500 kg may be achieved (see Figure 3.68).

Safety procedures should be strictly applied. The safest way to proceed is by having the dump truck tipping on the top of the selection hill and then having a bulldozer push the material over the side of the hill. Alternatively, a banksman can guide the driver of the dump truck to the edge of the selection hill. In addition, no activity should take place at the bottom of the selection hill while tipping is taking place, especially when the quarry run contains large stones that may roll down.

The bottom of the selection hill where the larger stones sit is selectively excavated. The larger stones are excavated and stocked. The upper size of the grading is controlled by excavating at the face and the lower size of the grading is controlled by excavating at the bottom of the selection hill. As the slope becomes steeper, slides will occur that bring finer material down that should then be discarded.

The grading quality of the material achieved is highly controlled by the training and the experience of the operator.

*WARNING: safe procedure is to dump first and then doze over the side, not direct tipping as is shown.*

**Figure 3.68** *Schematic view of a selection hill in action. Left: dumping of quarry run by dump truck under guidance from banksman (not shown) and sorting of larger stones by natural segregation at the bottom. Right: removal of fines after excavation of the coarser stones (courtesy J van Meulen)*

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**Box 3.32** *Production of light armourstone with trommel screen*

Trommel screens are an appropriate means of producing light and coarse armourstone. The facility should be placed where use of loader and trucks can be optimised (see Section 3.9.6). A trommel screen consists of a hopper, a reciprocating feeder and a trommel constructed out of rings and spacer bars (see Figure 3.69). The material moves forward by gradient and rotation over and through grids of increasing sizes to the end of the trommel.

Separation should be sufficient to avoid the different gradings becoming mixed after screening. When a limited number of gradings are required, the production rate may be increased by placing two identical barrels together in the trommel at the same dropping zone. Should there be concern about the fines content of the feed material, the first screening section can be doubled, to reduce the input rate from the feeder to the trommel at the trommel's normal rotation speed.

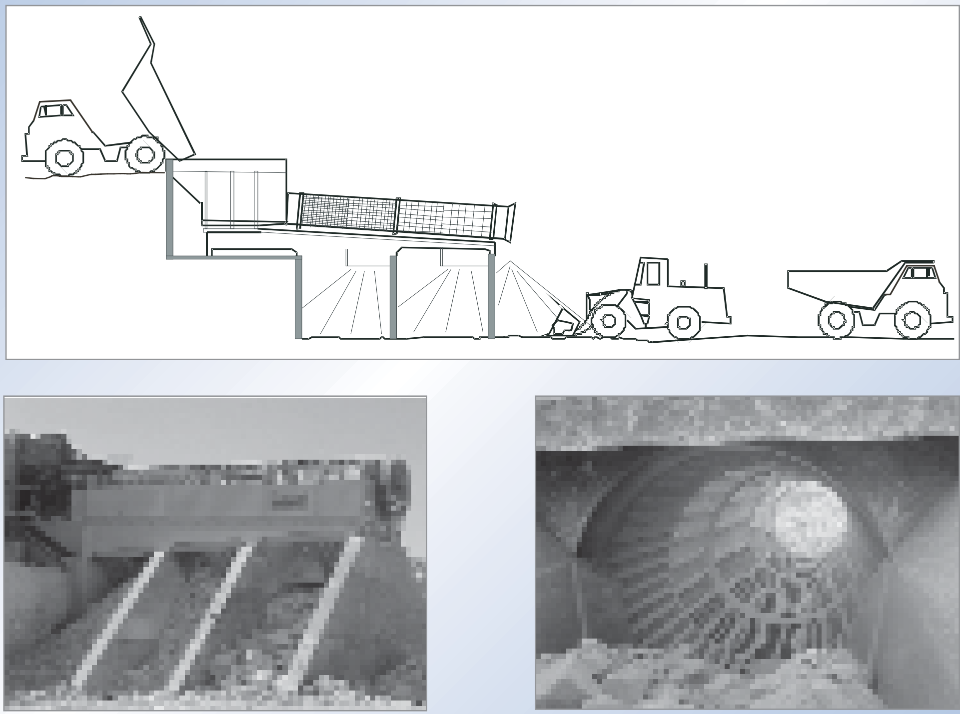


**Figure 3.69** *Trommel screen. Top: cross-section of a trommel in action, showing the hopper being fed by a dump truck and sorted material removed by a front wheel loader; bottom left: side view, showing the wide separation walls; bottom right: trommel screen viewed from the hopper (courtesy J van Meulen)*

**Box 3.33** *The use of bars or static grizzly*

The static grizzly (set of bars) is a versatile type of selection equipment (see Figure 3.70). It can be used to remove fines from production of core material as well as to produce coarse or fine material. It may be built, and the spacing of bars adapted, in-house. Attention should be paid to the length necessary to ensure effective screening and the angle needed to prevent material becoming stuck on the screen. An appropriate physical separation should always be made to avoid the separated products being remixed.

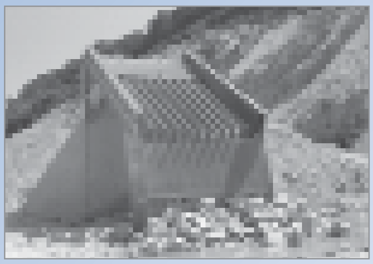


**Figure 3.70**

*Left: Static grizzly for processing of core materials by fines removal (courtesy A Moiset) and right: Static barsizer for processing of coarse and light armourstone (courtesy J van Meulen)*

A static grizzly system is relatively simply made from H- or I-beams and, when properly constructed, can be quite effective. Screening for only one size is possible, for example taking out the material smaller than 5 kg from quarry run to produce core material 5–500 kg. If the structure is built strongly enough it can perform well when exposed to routine tough loadings.

It is important to achieve the right balance between the speed the material slides over the bars and the rate at which material falls through the opening between the bars. If the slope is too shallow, the material will not slide and blockages may occur. On too steep a slope, the material may slide too fast to fall through the openings.

The sliding speed of the material depends on:

- the type of equipment used to feed the bars: truck, wheel loader, feeder dumping or trickling
- the moisture content of the material: wet material tends to be slower
- the shape of the material: round particles tend to be faster
- the percentage of fines: material with more fines tends to be slower.

Adjusting the angle of the bars is a difficult and time-consuming operation. Alternatively, the speed of the material can also be controlled by chains placed over the material flux. These chains may be lifted or lowered or alternatively their mass can be increased or decreased by adding or removing weights on the chains. The latter option is generally easier.

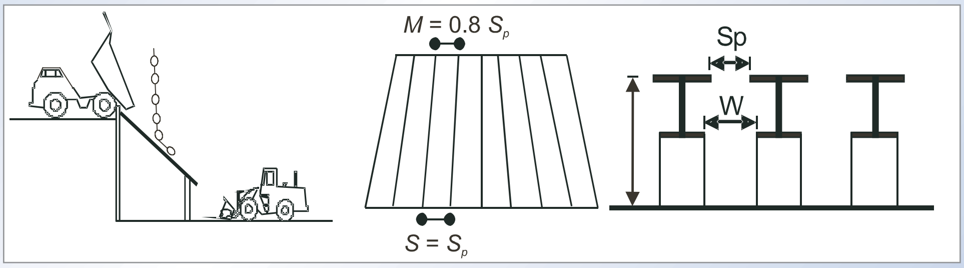



**Figure 3.71** *Static grizzly. Left: side view; centre: top view; right: side view of the grizzly bars from the end (courtesy J van Meulen)*

Components and settings recommended for construction of a static screen are as follows:

- bars should slope at approximately 26–28 degrees
- the chain curtain may be made of old anchor chain or old bulldozer tracks
- the opening between the bars should diverge from $M = 0.8 \times S_p$ (at the top) to $S_p$ (at the bottom), where $S_p$ is the opening between the bars at the end to ensure that a stone will not get blocked (Figure 3.71)
- the flanges of the beam at the underside should be smaller than the flanges on the topside, to ensure that a stone will not get stuck when falling through (see Figure 3.71 right)
- to avoid any blockage caused by the support connection between the beams, the support spacing should be at least $2.5 \times S_p$ .

The stones falling in between the bars near the end of the bars will hit against the end wall. This wall should be structurally strong enough to resist repeated impact of stones. If made of concrete, it should be protected by a steel plate when the falling stones are larger than 1 kg.

If several gradings are produced by static bars, the width between the separation walls should be more than the width of the bucket of the wheel loader, ie generally larger than 4 m.

The greater the length of static grizzly, the more efficient it is. A reasonable balance may be found if 6 m bars – a commonly available commercial length – are used, as they allow a machine to pass underneath the grizzly, promoting a good recovery rate.

**Box 3.34** *The use of a barsizer unit*

A barsizer unit is composed of round bars of axle steel, fixed at one end while the other end can oscillate freely when hit by stones. Simultaneous emptying and feeding of the barsizer should be avoided to limit impact to the wheel loader working at the bottom of the barsizer.

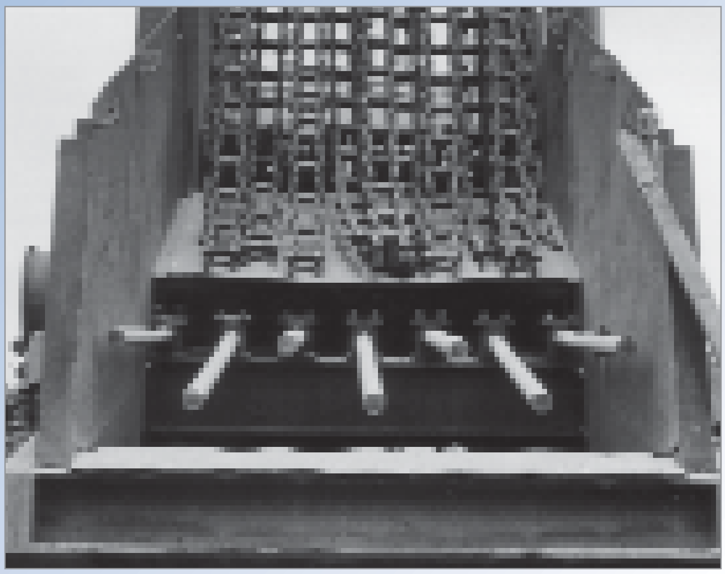


**Figure 3.72**

*View of a barsizer from the end. Note the free oscillating bars and chains to control the material flux (courtesy J van Meulen)*

The bar diameter is generally 100 mm for stones up to 1.5 t and 115 mm for stones up to 3.0 t. For lighter gradings, say NUL of 8 kg or 85 kg, bars of 70 mm or 85 mm may be sufficient. The angle for the top bar varies between 23–26 degrees and for the bottom bar between 28 and 30 degrees depending on the shape and the moisture content of the stones. The bar length is 2800–3000 mm. The connecting brackets that fix the bars to a main beam are the main weakness. Possible loosening and movement of the brackets under repeated use may affect the bar openings at the free end. The equipment thus requires frequent monitoring and adjustment.

As with the static grizzly, the quality of the product is regulated by the speed at which the material moves across the bars. The angle of the bars is critical, therefore, and the chains should reduce the speed. The speed with which the material is loaded on to the bars is also of the utmost importance. A trickle gives a better clarified product but lower production rates.

When sufficient height is available, several barsizers may be mounted one after the other. A wall or block face may be used for this purpose – see Figure 3.73. Robust separation walls should be built to separate the different gradings and to resist the impacts. Experience shows that a reinforced concrete wall with 8–10 mm steel plates can be sufficient for stones of up to 500 kg.

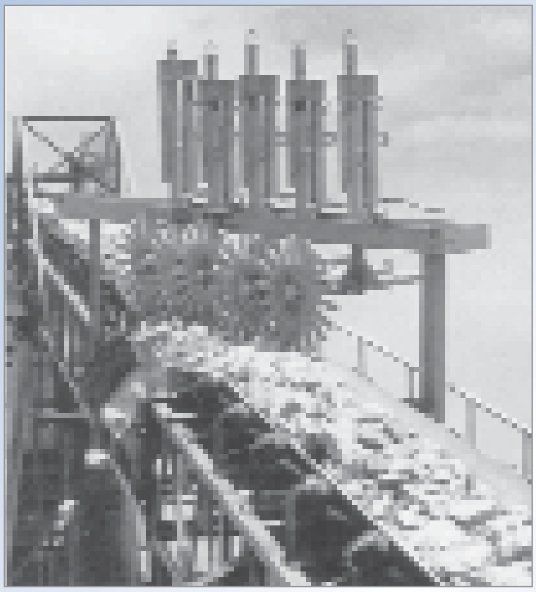
The collection bays should have sufficient capacity, notably the bay that receives the most material, ie the smallest size of material separated. If not, the selection plant may have to stop when material is collected from the bays. Since material falls into the bays from height, they may be kept partly full to reduce secondary breaking due to falling.

**Figure 3.73**

*View of a set of two barsizers to produce gradings. Gradings being sorted are 0–10 kg, 10–60 kg and over 60 kg (courtesy J van Meulen)*

**Box 3.35** *The use of sidekick for grading selection*

The sidekick, which is generally used to discard balls of clay at the quarry, is an ideal machine for the production of 5–40 kg and 10–60 kg gradings – see Figure 3.74. The sidekick is installed on the conveyor taking the material from the primary crusher. The wheels, which turn by the material hitting against the spokes, push the material over the edge of the conveyor belt to a temporary stockpile. The size of the stones is controlled by the height of the spokes above the conveyor belt. It is a cheap and simple but quite effective method and, if available, can avoid the need to modify the plant set-up to accommodate other equipment. The productivity depends on the crusher setting and output.



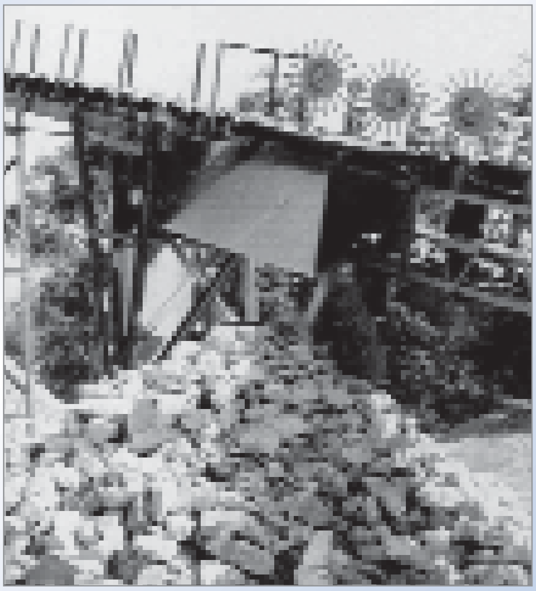


**Figure 3.74**

*Examples of sidekicks in operation (courtesy J van Meulen)*

### 3.9.7.5 Secondary breakage of oversized stones

Secondary breakage may be needed to resize oversized stones or stones in excess of an armourstone grading class. It can also be used for stones that are wrongly shaped. Secondary breakage may be a significant part of the activity of a dimension stone quarry if armourstone is to be produced.

Secondary breakage can be performed using:

- secondary blasting, see Box 3.36
- drop ball attached to a crawler crane, see Box 3.37

- hydraulic hammer attached to an excavator, see Box 3.38
- drop ball used by a face shovel, see Box 3.39
- drop hammer attached to a wheel loader or excavator, see Box 3.40.

**Box 3.36** *Secondary blasting*

In addition to reshaping or size reduction, secondary blasting may be used on extremely oversized stones. This method is a known fly-rock hazard and so should be performed with great care and avoided where possible. Stone to be secondary-blasted should be carried, if possible, to a safe location out of the way of the daily operations. Splitting oversized stones with carefully positioned drill holes charged with black powder is less dangerous and more efficient.

Before drilling, the stone should be examined for any signs of weakness that may affect the blast. Small holes of 33–51 mm are drilled into the stone in a row, triangle or square pattern, depending on the result expected. In dimension stone quarries, the machines used for production may be used to prepare the blasting and generally drill 33 mm holes at the rate of 1.4 m per hour. The depth of the drilled holes is just over half the thickness of the stone. The specific charge is generally about one-third of the normal blasting ratio, and black powder, high explosives or detonating cord may be used. The stemming should be carried out with care to avoid fly-rock. Stemming with water in the drill hole is very effective for high explosives. The control on the result is poor and the pieces produced may not be useable.

**Box 3.37** *Drop ball and crawler crane*

A drop ball attached to a crawler crane (Figure 3.75) is a low-productivity method to break oversize blocks. Personnel should keep at a safe distance because of flying stones. An old crawler crane is normally dedicated to this activity.

The ball is made of manganese steel with a mass of generally 3.5 t to 5.0 t. It is lifted and dropped on to the stone. The ball may not hit its target every time and the control of the fragmentation size is poor. The fragments produced may not be useable because of inappropriate shape or size.

**Figure 3.75** *Crawler crane with 3.5 t manganese drop ball (courtesy J van Meulen)*

**Box 3.38** *Hydraulic hammer for secondary breakage*

A hydraulic hammer attached to a hydraulic excavator (sometimes termed a *pecker*) is readily available and therefore frequently used for size reduction and correction of shape (see Figure 3.76). For this technique to perform well, the appropriate size of hammer and excavator needs to be selected – a small hammer will only produce chipping.

Based on experience, Table 3.34 gives the relationship between the appropriate sizes of hammer, excavator and the stone to be broken. The grading to be produced is one class of stone smaller than that indicated in the table.

**Figure 3.76** *Hydraulic excavator with 3.5 t hydraulic hammer (courtesy J van Meulen)*

**Table 3.34** *Relationship between the appropriate sizes of hammer, excavator and stone to be broken*

| | Initial grading | | | | | |
|---|---|---|---|---|---|---|
| Parameter | > 10 t | 6–10 t | 3–6 t | 1–3 t | 0.3–1 t | 60–300 kg |
| Excavator size (t) | 60.0 | 50.0 | 42.5 | 32.5 | 22.5 | 15.0 |
| Hammer size (t) | 4.25 | 3.50 | 3.00 | 2.25 | 1.50 | 1.00 |
| Production rate (t/h) | 275 | 225 | 170 | 115 | 65 | 35 |

**NOTE:** When the material is spread out and easily reached by the hammer, higher outputs are possible.

**Box 3.39** *Secondary breakage using face loader shovel and drop ball*

A face shovel with a bottom dump bucket can both pick up a manganese drop ball itself and drop it on to a stone to break. This breaking can be quite effective but the control over the resulting sizes is poor. The use of this type of machine is optimum since the drop-balling can be done by the face shovel while waiting for trucks to load. Reselection of the results is generally required. That is best done by individually selecting the graded stones required using an excavator with an appropriate grab. The wheel loader can then clean up the smaller unsuitable stones and fragments. A skilled operator may be able to produce smaller sizes of stones such as 60–300 kg with no further reselection required other than removing the fines. The results of secondary breakage can then be collected and loaded by wheel loader immediately.

**Box 3.40** *Drop hammer for secondary breakage*

The drop hammer system (Figure 3.77) is not very commonly available, but it is an appropriate tool for breaking large stones into only slightly smaller stones. Inside a tube, a heavy impactor is dropped on to the pin at the bottom so that the impact energy for each blow is approximately 5.5 times as high as for a hydraulic hammer with the same weight of hammer. The high impact energy makes it possible to break the stones in two while the hydraulic hammer has a much more progressive breakage action.

The hammer can be mounted on an excavator of a smaller size or on a wheel loader. When mounted on a wheel loader, positioning the hammer into the vertical optimum position is more difficult, but the production rate for big stones is similar to the rate with a hydraulic hammer.


**Figure 3.77**

*Example of drop hammer mounted on wheel loader*

## 3.9.8 Handling and transport at the quarry

This section provides a brief overview of the types of equipment used to handle and transport armourstone at the quarry. The handling is generally part of the selection process. Wheel loaders or excavators working at the plant or the pile of blasted material (the *muckpile*) are generally used to separate the oversize stones, feed to and empty from static bars or trommels etc. Thus the machines used may be equipped with appropriate weighing devices such as load cells in the hydraulics system or in the structure itself.

### *3.9.8.1 Choosing loaders and trucks*

The key considerations in choosing the equipment are:

- whether the machine is typically to be used for selection only or for loading
- whether the target grading implies that bulk or individual handling will be necessary and also the capacity required
- the travel distance in the stocks or between the stocks and the working area
- the availability of reinforced transport vessel bodies, which will permit rougher handling, assuming that breakage is not a concern
- protection against contamination with fines.

Table 3.35 summarises the types of handling equipment generally used, while Table 3.36 summarises the standard forms of transport.

**Table 3.35** *Characteristics of handling equipment*

| Equipment | Typical grading size | Comment |
|---|---|---|
| Wheel loader with bucket | Any, depending on the capacity | • Not suitable for selection of heavy stones.<br>• Care needed to avoid fines (gridded buckets rarely prevent fines).<br>• Excellent short-distance loading of bulk materials and individual stones on to barge or train from stock.<br>• Can apply sufficient pressure to engage stockpile for loading several blocks at a time. |
| Wheel loader with forks (see Figure 3.79) | Any, depending on the capacity | • Good for individual stones larger than 3 t. |
| Excavator with bucket (see Figure 3.78) | Any, depending on the capacity | • Excellent for loading bulk materials at the quarry face.<br>• Can pick out oversize and perform some selection. |
| Excavator with grid bucket (see Figure 3.78) | Any, depending on the capacity | • Can select smaller-sized stones below 300 kg.<br>• Requires shaking of bucket to let fines fall through. |
| Excavator with grid bucket | Smaller than 1000 kg | • Appropriate for loading but may take fines.<br>• Not appropriate for selection. |
| Excavator with orange peel grab | More than 60 kg | • Not so good for selection of smaller stones, but suitable for loading selected smaller gradings, eg up to 1000 kg (several stones at a time) into dump trucks without damage.<br>• Appropriate for selection of light gradings.<br>• Can apply sufficient pressure to engage stockpile for loading several blocks at a time. |
| Excavator with finger grab (three tynes) | More than 60 kg | • Good for selection of individual stones, but grabs are expensive for stones heavier than 5 t.<br>• Can apply sufficient pressure to engage stockpile for loading several blocks at a time.<br>• May be expensive to maintain. |
| Excavator with power fork (three to five tynes) (see Figure 3.78) | 300 kg to 30 t | • Very good visual selection of individual heavy stones.<br>• Appropriate for loading of train or flatbed wagon since it easily permits repositioning of the stone. |
| Crawler crane with finger grab | More than 60 kg | • Outdated; good selection tool but slow. |

**Note**

The size of the machine and the type of handling bit should be selected with reference to the grading.

**Table 3.36** *Characteristics of trucks used in quarries*

| Truck type | Grading | Comment |
|---|---|---|
| Off-highway dump-truck | Any depending on the capacity | • Rigid axle or articulated.<br>• For stones heavier than 3 t, loading by excavator is preferred.<br>• Excavators can place the stone in the bucket of the truck whereas wheel loaders always dump the stones and as a consequence cause more damage to the stone and the truck.<br>• Care needed to limit fines. |
| Road truck and trailer with aluminium or steel body | < 40 kg | • Very appropriate for coarse grading.<br>• Careful loading is required to avoid damage to the trailer. |
| Road truck and wagon with steel body | < 2000 kg | • Very appropriate for coarse grading.<br>• For heavy armourstone say 300 kg to 2 t, the wagon should have a reinforced steel body.<br>• Careful loading is required to avoid damage to the truck body |
| Road truck and flatbed trailer | > 1000 kg | • Appropriate for any heavy armourstone.<br>• Careful loading is required to limit damage to the trailer.<br>• Locking individual stones with chains on to the flatbed may be time-consuming. |

For armourstone production, an excavator may perform several roles at the quarry such as selection and loading trucks for deliveries. Wheel-mounted excavators may therefore be preferred to the track-mounted excavators, which are more appropriate for clearing the blastpile. The cost of re-equipping an excavator with alternative grabs is around 10 per cent of the excavator cost. This should be considered when preparing the business plan for armourstone production.

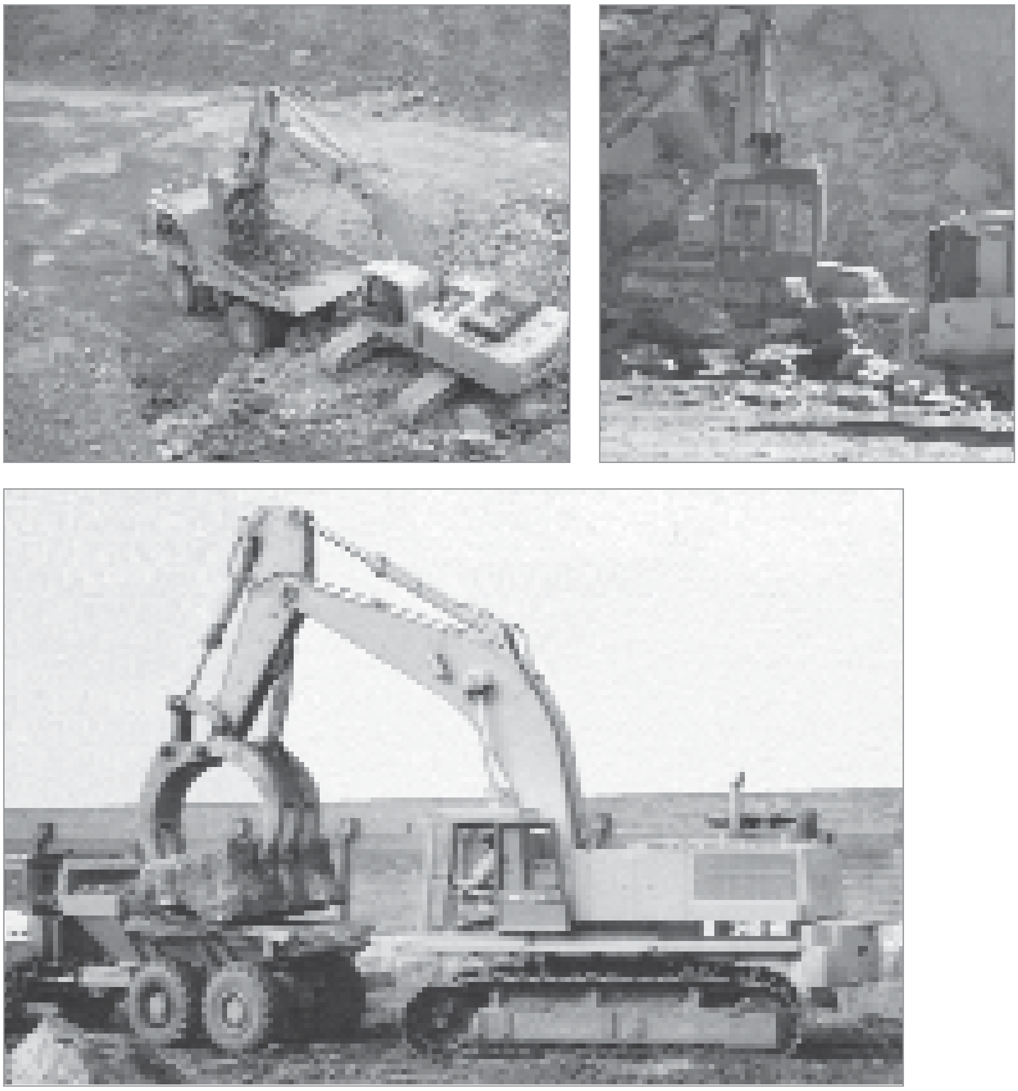


**Figure 3.78** *Use of excavator for handling. Top left: mounted on tracks clearing muckpile and sorting oversize (courtesy S Dupray); top right: mounted on track with grid bucket selecting stones after secondary breakage with hydraulic hammer (or pecker) (courtesy S Dupray); bottom: with high-capacity five-tine power fork at the quarry for individual handling of heavy stones (courtesy J van Meulen)*

Figure 3.79 *Wheel loader mounted with a fork used to handle heavy grading armourstone (courtesy J van Meulen)*

### *3.9.8.2 Placing wire loops in stones*

The contractor should liaise with the quarry production for those cases where the blocks of armourstone need lifting aids to be attached. For example, the site crane may have to place some stones that are just beyond its lifting capacity if the grab remains on, but when the grab is taken off, the stone placement work is done only with a crane and hook. A wire loop or eye bolt should then be placed in the stone, by drilling, inserting the loop or bolt and grouting in place, so as to be able to lift the stone with the hook. Eye bolts are not considered good practice if the rock is to be moved around since it may bend and not be accessible to the hook after some handling.

Personnel placing the stones should indicate where in the stone the loop is required, taking into account the shape of the stones and the thickness of the layer in which the stones are to be placed. In the quarry, the stones are generally placed on their flat side (which is easiest and natural). However, two of these flat stones placed on top of each other will most probably be less than the required thickness of the layer, which means that the loops should be placed in the stones in such a way that when lifted and placed on top of each other two stones make the approximate layer thickness required.

Because the driller has to stand on top of the stone with a handheld hammer, the stones should be laid out in a stable position. Smaller stones are more difficult to drill because of their smaller sizes. Using a drill crawler is often not possible because of the small drill-hole size required. Consequently the labour costs are high. To ensure satisfactory grouting, the wire should be completely degreased, so either new wire without grease or degreased old wire should be used. Suitable resins are available on the market. The holes should be clean of water and dust before pouring the resin into the holes. The hole has to be filled with resin to approx three-quarters of the depth before the wire is pushed in. The resin has to cure for a minimum of three days before the stone is lifted. Characteristics of wire loops are presented in Table 3.37.

Eventually the wires will rust away. The long-term effect of the wires rusting on the stone is not known. There is also the visual impact of the wires to consider, especially for those stones placed above low water and in the outer layer.

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**Table 3.37** *Characteristics of wire loops as a function of the arnourstone grading*

| Wire loop characteristics | unit | < 5 t | 5–10 t | 10–18 t |
|---|---|---|---|---|
| Diameter drill hole | mm | 32 | 42 | 42 |
| Depth of drill hole | mm | 200 | 200 | 350 |
| Distance between the two holes | mm | 500 | 500 | 600 |
| Diameter steel wire | mm | 24 | 32 | 32 |
| Length of steel wire | mm | 1250 | 1250 | 1500 |
| Daily output driller (10 h) | number | 45 | 50 | 40 |
| Stones per 8 kg resin pack | number | 24 | 17 | 11 |

### 3.9.9 Loading trucks or trains at the quarry

Truck operatives in the quarry should be aware of the safety regulations that are applicable and of any specific on-site procedures and restrictions. In particular, they should be aware of blasting times and of the approved routes to follow. Table 3.38 summarises recommended equipment for loading of trucks as a function of the grading concerned. Figure 3.80 shows typical loading of a train and chaining of armourstone on to trucks at the quarry.

**Table 3.38** *Types of loading equipment for trucks at the quarry as a function of grading size*

| Grading | Type of loading machine |
|---|---|
| < 40 kg | Wheel loader |
| < 300 kg | Wheel loader, excavator with bucket, excavator with closed-tyne grab |
| < 2000 kg | Excavator with closed-tyne grab, excavator with powerfork |
| > 1000 kg | Wheel loader with forks, excavator with large closed-tyne grab, excavator with powerfork |

Care is required to prevent damage to truck bodies or railway wagons, and to the armourstone, induced by:

- wheel loader dropping the stones
- excavator with bucket – loading over the back is least likely to damage the body, whereas loading over the side gives a smaller target and hence a higher chance of causing damage
- excavator with grab – care should be taken when swinging the grab not to catch the sides of the body
- excavator with grab/powerfork – with large stones care is required to ensure stones cannot drop out of the grab/fork and on to the truck
- movement of armourstone during transit – individual stones may be chained down to prevent movement.

**Figure 3.80**

*Loading of armourstone on to truck and train (courtesy A Moiset). Left: armourstone being chained to truck*

## 3.10 QUALITY CONTROL OF ARMOURSTONE

The purpose of this section is to provide the reader with practical information on the objectives and methods available for performing controls during production and purchase of armourstone. The reader may also refer to ISO 9000:2000 for information on quality control or to EN 13383-1:2002 for information on factory production control as defined in Europe. Practical information on quality control is given in Laan (1995) and Read (1988).

Quality control consists of the procedures used to monitor and maintain properties of armourstone. It should be seen not as an incidental extra serving only to increase costs but as an integral part of production and use of armourstone that will invariably save costs in the long run. It should be performed with reference to a set of requirements to be achieved as demanded by the design, eg grading, or with reference to results of initial type tests, eg mass density or integrity.

Quality control of armourstone focuses mainly on maintaining grading requirements but also addresses all aspects of rock quality and durability requirements. Quality control is necessary at different stages of armourstone life and is carried out by different bodies with different aims (see Table 3.39):

- quality control should take place during **armourstone production** and should routinely be performed by the producer, sometimes assisted by a laboratory (see Section 3.10.1)
- **at tender stage**, a client should evaluate the quality control processes of potential armourstone suppliers and also assess their ability to produce armourstone (see Section 3.10.2)
- **during supply**, the client may subject the material to quality control before it has left the quarry or at delivery (see Section 3.10.3). Assistance from a third party may sometimes be called upon.

Table 3.39 *Type of quality control*

| Stage | Producer | Contractor | Client | Third party |
|---|---|---|---|---|
| Production (see 3.10.1) | *** | * | * | * |
| Bid stage (see 3.10.2) | ** | ** | *** | ** |
| During supply (see 3.10.3) | ** | *** | * | ** |

**Note**

* may be involved under certain conditions; ** involved or may be responsible; *** very involved or responsible.

### 3.10.1 Production quality control

The quarry is responsible for performing sufficient quality control to ensure consistency of the production with expected properties. In Europe, the concept of *Factory Production Control* (FPC) has been extended to armourstone products. It mainly consists of measurement and feedback adjustment procedures designed to maintain production of aggregates of certified quality. **Annex D of EN 13383** presents guidance on quality control in the quarry during production (such as testing frequency). It is clearly the producer's responsibility to obtain proper documentation of the procedures and results if product certification and client satisfaction are to be achieved.

Quality control focuses on **intrinsic properties** and **production-induced** properties, especially gradings. A good knowledge of the rock source through evaluation of its ability to produce armourstone (see Sections 3.2.3 and 3.9.1) is necessary to determine the initial values of these properties and the optimum quality control of the production. Part of the quality control consists of ensuring that armourstone is coming from the areas designated in the extraction plan as suitable for armourstone. Significant variation within the rock source should be detected by quality control that focuses on petrography, density, porosity and discontinuity content. For armourstone produced in quarry zones known to have significant geological variability, the schedule of monitoring both intrinsic and production-induced properties should be increased accordingly. The production method should also be considered to determine the optimum quality control, eg quality control of gradings should be more frequent for eye-selected than for mechanically produced armourstone.

The operator performing the quality control should be trained in the characteristics of armourstone and the methods used to perform and report the controls. A major effort is required at the beginning of consignment preparation to establish the best procedures to adopt. Specific training and equipment may be needed to carry out the following.

- **Mass distribution control:** a weighing device or load cell on the grab arm is needed to carry out measurement and control. Their accuracy and precision should be regularly monitored, eg by repeated weighing of a set of stones or concrete blocks of known mass corresponding approximately to the mean mass or the nominal limits of the gradings in question. Before every weighing session, the calibration of the device should be validated. The controller should be trained to assess visually the mass of blocks of different gradings, eg by comparing their prediction to actual results of weighings, and to carry out sampling and grading measurement (see Figure 3.81). During eye-selection production of gradings, the machine operator should be able to see "visual comparison stones" for evaluation of the nominal lower and upper limits. Additional visual comparison stones of average mass generally improve the control of the average mass and, for steeper gradings, stricter controls may need to be in force. Dedicating one trained operator to the task of selection helps to control the grading. For mechanical production, part of the quality control is covered by fine-tuning the choice of bar spacing, active length and feed rate on to the device, to obtain the desired mass or size distribution of the produced material. If significant change of the input material occurs, variation in the fines content or shape of particles usually occurs. Wear and damage to grizzlies and screens is a potential source of drift in product properties and must be checked frequently.

- **Integrity control:** for heavy gradings, the control is generally carried out on each stone by visual inspection. The controller should be trained by an engineering geologist. For borderline stones, sonic velocity equipment maybe required (see Section 3.8.5) and it may be necessary to use an external laboratory to determine the appropriate value to choose for good integrity stones and to carry out the measurement and determine the acceptance criteria. Routine dropping of the stones in the quarry may be appropriate when limited to reasonable drop height such as from the machine.
- **Shape control:** the control is generally performed during visual selection. For mechanical production, shape is a characteristic of the product. Quality control then consists of ensuring that there is no deviation from the target shape, which would imply a change in the rock mass. A calliper (see Figure 3.82) is required and the controller should be experienced with measurement of shape. Witness stones are useful for the controller to verify borderline shapes. If needed, detailed measurements should be made for borderline stones of $LT \cong 3$, especially for heavy and light gradings.
- **Fines removal and coarse grading:** for core material where control of the fines is required, a bar or static grizzly (see Figures 3.83 and Figure 3.84) are simple means of mechanically removing fines and are preferable to using a gridded bucket. When producing coarse and light gradings with mechanical systems, attention should be paid to the control of cross-contamination and appropriate dividing walls should be installed as necessary (see Figures 3.69 and 3.73).

**Figure 3.81** *Control testing of mass distributions of a 300–1000 kg standard grading during production using weighbeams (courtesy A Moiset). This set-up enabled 140 stones to be weighed per hour*

**Figure 3.82**

*Use of a calliper for LT testing and quality control of blocks for the determination of strategically positioned "visual comparison blocks" used for control of shape (courtesy A Moiset)*

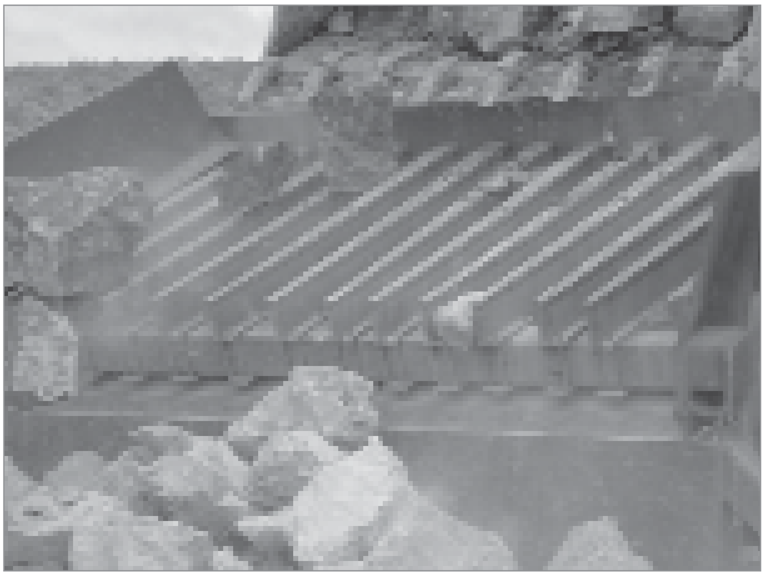

**Figure 3.83**

*Short-length static bar grizzly for fines control loaded with a front loader (courtesy A Moiset). Care is needed to avoid damage and blockage*

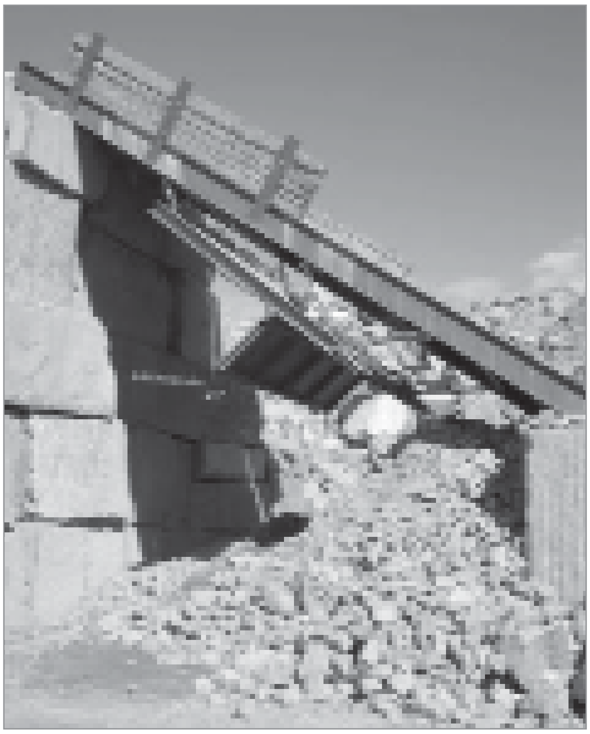

**Figure 3.84**

*Large static bar for production of different grading sizes (courtesy S Dupray)*

## 3.10.2 Quarry inspection

For many projects, the client and designer may have identified potential rock sources and need more information about the source and the quarries' operational capabilities before concluding the design or the choice of a quarry. On behalf of the designer, there may be a need for a quarry inspection that includes a visit to the quarry and some *Initial Type Testing* (ITT) to obtain detailed information that the producer does not have to hand such as shape parameters, eg mean *LT* and *BLc*, or integrity parameters, eg sonic velocity, drop test or full-scale splitting test (FSST). These tests will normally have been performed well before the quality control inspection described in this section. For cases where the structure is designed to match the quarry properties derived from extensive quarry evaluation (see Sections 3.9.1 and 3.6.3), the data described below will already be available.

Before the signing of a contract, the client should organise a visit to the production and transport facilities, ie quarry and any loading terminals, to assess its ability to provide the required material in accordance with the specification and to identify at an early stage any critical issues that may become a risk for the project. In particular, the inspection aims to ensure that the quantity and quality of materials, the lead-time for production, the organisation and the facilities of the quarry are in accordance with the needs to complete the deliveries in an acceptable condition. If there are no stockpiles, control is not possible and thus the client will normally insist that stockpiles are available. The client should be aware that the risk of non-compliance with the specification is much higher if the control is done during the production. Clients often require at least three days of stock production to be available on site to perform the control.

Suggestions of guidance for the inspection are given below and a typical *aide-mémoire* data sheet (Table 3.40) is provided and can be used as *pro-forma*. Although intended for the inspector to complete on the visit to obtain a thorough and consistent appraisal of relevant aspects of the quarry and its facilities, the producer may wish to keep such records. Attention should be paid to signs in the rock faces that indicate the rock mass and its quality are likely to change during the period of supply. The main focus of the quality inspection is to establish integrity and water absorption, which, if unacceptable, may indicate further information gathering is not necessary. Photographs of the stocks, extraction faces and production facilities are generally useful later in the project.

Inspection of the stocks aims to ensure that the quantity and the quality of the armourstone available, notably with regard to the mass distribution and integrity, are in accordance with the specifications. Assistance of a third-party laboratory may be needed to determine mass distributions of material available and to carry out relevant laboratory or *in situ* tests. In addition, an evaluation of the stockpile volumes and organisation, independent of the producer, will provide reassurance that estimates of the lead-time for the quarry to deliver are realistic. In practice, an armourstone provider without existing stocks of identified gradings needs longer to prepare the required grading. Planning the visual selection and stock handling, and, if necessary, secondary breakage or even the opening of additional extraction faces can add considerable time before the necessary supply rate or delivery date can be established. The accessibility and means of transporting stock should be studied with regard to the additional handling that may be required to reach the main transport facility.

The extraction process should be inspected to identify blasting characteristics such as specific charge, drilling and firing pattern, type of explosive and charge in the column. If any details on quarry yield in relation to the blasting method are available, eg amount of oversize, quantity of fines and characteristic sizes, then it is useful to integrate these with any determination of the quarry yield.

Inspection of the extraction face(s) in the quarry aims to identify and assess the quality of the production faces and their ability to produce the required quantity of stones. The quarry faces from where the armourstone is due to be produced should be located on a map (1:25 000 scale is preferable) and their characteristic geotechnical properties noted. These zones should be inspected and close attention paid to the lithological units exposed and their respective thicknesses, weathering grade, discontinuity content and variations. Simple indicators such as colour or grain size should be identified since they are generally useful to help match the origin of the material in the stockpiles that are being inspected during quality control of the production. Viewing other parts of the quarry may provide information on alternative faces for possible extraction. Assistance of an engineering geologist may be required during inspection or for further investigations that may be needed. Samples from the rock mass may be taken for further characterisation of the mineral fabric in the laboratory. The conclusion of this face inspection may be to limit extraction of armourstone to certain faces.

Inspection of the production facilities aims to ensure that the methods and equipment, eg capacity of machines or characteristics of mechanical sorting devices, are adequate to ensure the required quality and that they can be used in a reasonable manner. It also aims to determine the lead-time of production. The inspection should be performed during a production period to ensure a realistic insight into quarry procedures. The focus of the inspection depends on the grading concerned and the volumes produced, as both of these influence the techniques and tools involved. For mechanical production, equipment such as the primary crusher, grizzly, trommel screen and static bars, their active length and the bar spacing may be checked; the accuracy of weighing devices such as weighbridges and load cells on grabs may be controlled; while for visual selection, the accuracy of the mass classification by operators in the quarry may be checked by weighing some stones. It may be necessary to sample material and perform mass distribution determination on materials produced during the visit to ensure that the production techniques are suitable or, alternatively, to determine the actions to take for the requirements to be fulfilled. The breakage displayed by armourstone during mechanical sorting may be informative of the material integrity.

A list of the machine types and capacities available for, or involved in, armourstone production should be made. Critical situations where there may be a conflict on the use of a machine should be identified and clarified. For example, during simultaneous visual selection production of heavy grading and loading, the time periods for the machine with the grab to be on armourstone work should be carefully split throughout the day or additional, even dedicated, machines may be required to increase the production. Working areas where visual sorting or loading is planned should be identified and visited to ensure the floor quality is suitable so that unwanted fines are not likely to be loaded with the armourstone during handling, stockpiling or reselection at the quarry.

The loading terminal, ie road, train, fluvial or marine harbour, should be inspected and information gathered on the sizes and capacities of the machinery, eg to ensure that the capacity of the grab on the quayside is in accordance with the grading handled. Also, the period of work can be critical. For example, weather conditions may restrict riverborne vessels from reaching the terminal in winter or seaborne vessels having access at low tide or trucks being loaded at night in urban areas. When required, measures to mitigate damage to the terminal should be identified early, eg placing all-in on a quay to limit damage.

**Table 3.40** *Quarry inspection sheet for quality control by the client*

## General

Name: ______________________ Company: ______________________

Contact person: ______________________ Function: ______________________

Address: ______________________ City: ______________________

Tel: ______________________ Fax: ______________________

Date of the authorisation: ____________ Duration of the authorisation: ____________

Other: ______________________________________________

**Principal use of the quarry:** Aggregate quarry [_] Dedicated quarry [_] Dimension stone quarry [_]

## Rock source

Geological summary (ages and facies of the source, weathering grade etc): ______________

______________________________________________

Geometry (thickness used for armourstone production, orientation of layers etc): ______________

______________________________________________

Discontinuities (tectonics and main faults, other geological discontinuities etc): ______________

______________________________________________

Geotechnical properties (characteristic values, where available):

| | | | | |
|---|---|---|---|---|
| Water absorption: | [________] % | EN 13383 | Category $W_A$ | [________] |
| Compressive strength: | [________] MPa | EN 13383 | Category *CS* | [________] |
| Micro-Deval: | [________] % | EN 13383 | Category $M_{DE}$ | [________] |
| *LT* ratio | [________] | EN 13383 | Category *LT* | [________] |
| Durability: Category *FT* | [________] Category *MS* [________]; | | Category *SB* | [________] |
| Mass density: | [________] t/m³ | | | |
| Integrity: | $B_n$ [________] % | Sonic velocity: | [________]; m/s (on blocks) | |

Others such as sodium sulfate – methylene blue – point load – Los Angeles ______________

______________________________________________

## Equipment and facilities

Stocking zone: Area _______ ha; capacity _________ tonnes; accessibility for delivery trucks [_]

Handling machinery: excavator [_]; orange peel grab [_]; dedicated grab [_]; wheel loader [_]
others: ______________________________

| | | | | |
|---|---|---|---|---|
| Transport: main road | at [______] km | – name [______________] | | |
| fluvial terminal | at [______] km | – name [______________] | – capacity [______] t/h | |
| coastal harbour | at [______] km | – name [______________] | – capacity [______] t/h | |
| train terminal | at [______] km | – name [______________] | – capacity [______] t/h | |

Restriction on the use of terminals: ______________________________

Other information: ______________________________

______________________________________________

## Blast geometry

Blast [___] tonne; hole diameter [___] mm; burden [___] mm; spacing [___] m; face height [___] m;

Type of explosive [______]; specific charge [_____] kg/m³; delays [____] ms

**Table 3.40** *Quarry inspection sheet for quality control by the client (contd)*

## Production of the quarry

Average global production of the quarry [________] thousand t per year

Is grading pre-selection performed? [ Y/N ]

| **Standard coarse gradings (kg)** | $CP_{45/125}$ | $CP_{63/80}$ | $CP_{90/250}$ | $CP_{45/180}$ | $CP_{90/180}$ |
|---|---|---|---|---|---|
| Ratio of the production (%) | | | | | |
| Available in stock (thousand t) | | | | | |
| **Standard light gradings (kg)** | $LM_{5-40}$ | $LM_{10-60}$ | $LM_{40-200}$ | $LM_{60-300}$ | $LM_{15-300}$ |
| Average mass controlled [Y/N] | | | | | |
| Quarry yield (%) | | | | | |
| Available in stock (thousand t) | | | | | |
| **Standard heavy gradings (tonne)** | $HM_{0.3-1}$ | $HM_{1-3}$ | $HM_{3-6}$ | $HM_{6-10}$ | $HM_{10-15}$ |
| Average mass controlled [Y/N] | | | | | |
| Quarry yield (%) | | | | | |
| Available in stock (thousand t) | | | | | |

**Other gradings** ________________________________________

________________________________________

**Production control**

visual [_] bulk weighing on weighbridge [_] individual weighing [_] mechanical sorting [_]

other: ________________________________________

## Quality of the production in the stocks

Integrity Good [_] Acceptable [_] Marginal [_] [___] % (by number) of blocks with major breakage

Resistance to minor breakage: Good [_] Acceptable [_] Marginal [_]

Shape: Equant [_] Tabular [_] Elongated [_] [___] % (by number) of blocks out of spec

Durability: weathering [Y/N] Signs of freeze-thaw damage: [Y/N] Signs of Sonnenbrand: [Y/N]

Other: ________________________________________

## Identification

Date: [_______]

Inspectors: Name [________________________] Function: [________________________]

Name [________________________] Function: [________________________]

Quarry rep: Name [________________________] Function: [________________________]

Name [________________________] Function: [________________________]

### 3.10.3 Quality control during deliveries and construction

This section focuses on the quality control of the material that should be undertaken during construction and especially during deliveries. It is stressed here that most of the control should be performed at the quarry to minimise transportation of unsuitable materials. An *aide-mémoire* sheet for the client's controller is given for use either at the quarry or on site (see Table 3.42). The quality control during execution, ie of the armourstone as constructed, such as to check construction tolerances for layer thickness, is covered in Section 9.8 and Appendix A1.

This quality control aims at verifying that the material is in accordance with the specifications. It is necessary to account for the variation of armourstone properties caused by the natural variability at the rock source as well as the production technique, ie mechanical or visual. It should take place, whenever possible, before the delivery has left the producer's facilities to limit expenses if a delivery is to be refused. Alternatively, it may take place at a temporary stockpile or at an appropriate stage of transport. It is recommended to carry out a detailed control on 10 per cent of the deliveries or at least every 5000 t. This frequency should be adapted to account for the variability of the extraction or the production, eg increased for rock sources with high variability, decreased for mechanical production (see Table 3.41).

The frequency of testing should be selected to be representative of homogeneous batches of production. It should be selected by considering the potential range of variability of the property. It should also be related to the unit of production, eg weekly production or delivery schedule. Similarly if the material is taken out by barges, trains or trucks, the frequency should then be related to the size of these unit loads or sub-units of load. For example, if the total consignment is composed of two barges, the total load may be controlled using the bucket of a front wheel loader as sub-unit, so the control may consist of the grading measurement of a bucket every one-tenth of the loading period.

When temporary stockpiles are used in the project, these should be inspected with regard to the items listed below. The contractor is generally responsible for this control, but some clients may mandate a third-party control to be involved. The quality control focuses on the following items.

- the **origin of material** is controlled to ensure that the agreed rock source and, if relevant, the faces selected during the initial visit at the armourstone provider are used. Indicators such as petrography, colour and grain size are useful for this purpose
- the **mass distribution** is controlled. The fulfilment of nominal limits may be controlled visually by a trained inspector. Guidance is given on quantitative methods in the armourstone standard EN 13383 in Sections 5 and 6 (Part 2) and requirements are given in Section 4 (Part 1). Detailed explanations are given in Section 3.8.4. For heavy gradings, the average mass from each bulk weighing should be calculated, while for transport by train or road it may be convenient to note the number of stones in each transport unit. Detailed mass distribution may be determined on the first deliveries and checks may be made less frequently once mass distribution of deliveries has proved to be in accordance with the mass distribution of the material at the quarry. This is particularly important if there is a concern about stone breakage or contamination with fines. Control of mass distribution is illustrated in Figure 3.85. Specific attention should be paid to contamination from mixing with other gradings or soils during transport and temporary stockpiling (see Figure 3.86)
- **visual control of the shape** is generally sufficient (see Figure 3.85). Quantitative determination of shape with reference to EN 13383-2:2002 Paragraph 4.3 should only be carried by a third-party laboratory in cases of disagreement between the producer and the client. An example of a stockpile with inappropriately shaped armourstone is given in Figure 3.87

- **controls of integrity and microcracks** should be performed and reinforced where integrity is a concern. For large heavy gradings, eg above 10 t, borderline stones may be set aside for further inspection or control of integrity. A continuous inspection may be carried out by a trained inspector during loading, focusing on the various indicators such as discontinuity type and extent. This has proved to decrease significantly the quantity of major breakage where integrity was a concern. Sonic velocity is used in France monitoring integrity of armourstone during deliveries. The sonic velocity value determined during initial type testing (see Figure 3.88 for device) and calibrated against the drop-test is used to ensure no significant decrease of integrity occurs
- **mechanical sorting devices**, once the settings or openings through which stones are sorted are fixed, will provide a well-controlled production if the input fragmentation or grading is constant enough. These may be inspected at the beginning of the contract (see Section 3.10.2) and further inspections performed with corrective actions reinforced, if non-conformity is observed during deliveries or if the input of fines changes significantly. In this case, attention may be paid to the wear or loosening of equipment parts that are mobile or exposed to flow of armourstone. As a consequence of wear or to compensate for variation at the source, adjustment of setting may be required.

**Figure 3.85** *Control of grading at the quarry prior to deliveries. Top left: control of coarse armourstone, overseen by purchaser and producer representatives (courtesy J van Meulen); top right: control of light armourstone using a portable grab (courtesy J Perrier); bottom left: control of light armourstone using a portable grab net (courtesy J Perrier); bottom right: control of heavy armourstone using portable scale (courtesy A Moiset)*

**Figure 3.86** *View of a temporary stockpile of 800–2000 kg where contamination by fine material and soil is visible (courtesy S Dupray). The board in the front clearly indicates the grading, which allows drivers to deliver to the appropriate stockpile*

**Figure 3.87** *View of a temporary stockpile of 1000–3000 kg with inappropriate quality control (courtesy S Dupray). Stones with unsuitable shape and mass are in the deliveries. The different gradings are hardly separated and distinguished on site*

**Table 3.41** *Guidance on frequency of testing armourstone properties during deliveries*

| Property considered | Frequency for mechanically sorted armourstone | Frequency for individually selected armourstone |
|---|---|---|
| Size – coarse gradings | every 3000–5000 t | N/A |
| Mass – light gradings | every 3000–5000 t | N/A |
| Mass – heavy gradings | every 3000–5000 t | every 1500 – 2500 tonnes |
| Core material – mass | every 10 000–25 000 t | N/A |
| Shape – coarse and light gradings | As for size/mass grading testing (see above), but take into account the type of use, ie armour or underlayer | |
| Shape – heavy gradings | Visual inspection of 50 per cent of the stones | |
| Integrity | Visual inspection of all stones for heavy gradings; further quality control may be required for borderline blocks or poor integrity | |
| Rock density, water absorption, durability, strength (using point load at the quarry) | Adapt based on known variability of the source and the risk of further weathering: at least every 20 000 t | |

Note: N/A = not applicable

The procedures to follow in the event of non-fulfilment of specification requirements during quality control of armourstone during construction should be agreed between the purchaser and the producer, as early as possible to avoid any delay and discussion while trying to resolve quality issues. The responsibility for the cost associated with corrective actions should be agreed beforehand to avoid potential disputes and delays. There are generally three types of action that may be appropriate depending upon the seriousness of the non-fulfilment. However, every situation is specific and it is usually possible to avoid stopping deliveries by quick responsive action between the client and the supplier, the aim being to avoid reaching a deadlock. In nearly all cases the following applies.

- **for conformity and non-conformity of minor concern**, corrections may be achieved by removing individual stones with problematic mass, shape and integrity. Additional material of precise mass may from time to time be required to correct consignments with borderline mass distribution. When a tested sample from a stockpile just fails on mass or shape, then a second sample is made. If the two samples (treated as if a single sample) still fail to meet the criteria then the stockpile part that the two samples represented is disqualified. The producer is responsible for the cost of reselecting the whole stockpile. If supplier and client agree beforehand to a **tolerance approach**, this repetition of the test may be avoided by defining ranges of tolerance within which the material fulfils its requirement. The width of the tolerance should be selected with reference to the sensitivity of the structure to this parameter and to the precision with which it may be determined
- **for significant non-conformity**, which may be defined in the contract, a delivery may be refused by the client. The client inspection frequency is then generally reinforced and might even lead to a systematic overseeing of operations until fulfilment has been reached
- **for major non-conformity**, deliveries may have to be interrupted if production has to be halted. The extraction technique, the production technique and the production quality control may then be adapted; and the contractor and the producer, and perhaps even the client, may agree to select new faces in the quarry. In some cases, the contractor and/or the client may decide to source the material from another provider. The responsibility for the financial costs should be defined and agreed as early as possible.

In some cases, the client, the contractor or the provider may mandate a third-party laboratory to carry out the relevant testing, measuring and quality control documentation, in order to evaluate the importance of non-conformity and to propose actions to correct the deviation and to prevent further occurrences.



1 2 3 4 5 6 7 8 9 10

**Table 3.42** *Information sheet for inspection by the client of deliveries to site*

### Control during construction and deliveries

Contract: [______________________________]

Armourstone controlled: Grading: [___________] Provider [______________________________]

Place of quality control: Stockpiles [_]; Loading area [_]; Transport [_]; Construction site [_]

Size of the sample: [__________] kg

**Armourstone origin**

conform [_]; significant non-conformity [_]; major non-conformity [_]

If not conforming, nature of the deviation and correction proposed ____________________________________

______________________________________________________________________________

**Mass distribution**

conform [_]; significant non-conformity [_]; major non-conformity [_]

If not, nature of the deviation and correction proposed ______________________________________________

______________________________________________________________________________

**Shape**

conform [_]; significant non-conformity [_]; major non-conformity [_]

If not, Fraction (by number) of pieces out of spec [__] %

Correction proposed ____________________________________________________________

______________________________________________________________________________

**Integrity**

conform [_]; significant non-conformity [_]; major non-conformity [_]

Drop test was carried out [Y/N]

Sonic velocity measurement was carried out [Y/N]

If not, Fraction (by number) of pieces out of spec [__] percentage observed during full-scale test or [__] percentage during handling

Correction proposed ____________________________________________________________

______________________________________________________________________________

**Identification** Date: [_______]

| | | |
|---|---|---|
| Controller: | Name [__________________________] | Function: [__________________________] |
| | Name [__________________________] | Function: [__________________________] |
| Quarry rep: | Name [__________________________] | Function: [__________________________] |
| | Name [__________________________] | Function: [__________________________] |

## 3.10.4 Third-party quality control

Producer, contractor or client may seek assistance from an external laboratory or materials consultancy, to assist during the controls by providing some specific knowledge such as engineering geology, or equipment such as weighing devices, sonic velocity equipment (see Figure 3.88) or testing facilities. External laboratories may also be required during the training of quality control personnel for armourstone operations in the quarry.

In some cases, impartial third-party laboratory expertise is required to sort out discussions between provider and purchaser. In this case, the role of the third-party laboratory should be clearly stated. The standards or procedures in question also need to be clearly identified, as well as the acceptance criteria and associated tolerances. The laboratory should be able to sample the material freely, in general with the assistance of the quarry, which should provide handling equipment for heavy gradings. The laboratory should be able to inspect the facilities and the quarry faces as extensively as required for it to carry out its mission in good conditions. The third party reports to its commissioning client.

**Figure 3.88** *Testing of integrity of heavy armourstone using a sonic velocity concrete tester (courtesy T Wojnowski). Note the different stockpiles in the background*

## 3.11 ARMOURSTONE COSTS

Costing armourstone material is a difficult task since it depends on many factors related to the quarry but also to the contract itself. Ultimately, armourstone cost covers the costs of extraction, production and selection and handling of both acceptable and rejected materials, together with the subsequent disposal of the latter if required. On average, 75 per cent of the armourstone cost is attributable to machine costs and manpower.

The costs can be divided into fixed and variable elements.

- The importance of **fixed costs** will be relative to the type of quarry considered. For example, armourstone from a dimension stone quarry (see Section 3.9) is waste material and may contribute very limited fixed-cost elements to the armourstone production. By contrast, dedicated or aggregate quarries opening up production faces and special plant for armourstone contracts will need to recoup all the costs associated with evaluation, extraction and production. In detail, fixed costs are associated with quarry evaluation and site investigation (see Section 3.9), overburden removal, adjustment of blasts, establishing a production face, construction of access roads and possible remediation and environmental measures such as reshaping the area after extraction is finished. The investment cost in equipment for an average quarry can be in the range of €3–5 million. The time required for the preparatory activities for such a quarry is in the order of three months from the time appropriate plant is on site. Should the site have to be bought, approval from the different bodies involved may take considerably longer.
- **Running costs** are proportional to the volume of material produced and are associated with extraction and processing operations such as blasting, mobilisation of equipment for selection, transport and stockpiling. They are closely related to the grading produced. Total production costs are generally in the range of €5–8/t. The costs may also have to be increased to cover royalties and taxes.

Total production costs vary considerably with the type of stone quarried and the annual output. If specialist equipment is required, the producer may wish to stipulate a minimum throughput per day for a contract in order to minimise per tonne costs. Stocking and rehandling of pieces of armourstone is considered to have a high cost. It is generally accepted that almost two-thirds of the costs are associated with machine mobilisation, which may be divided as follows:

- 20–30 per cent for drilling and blasting and overburden removal
- 30–40 per cent for loading and selecting at the face
- 20 per cent for transport to the stockpile
- 10 per cent for screening or separation
- 10 per cent for loading at the stockpile before transport.

The key factors that may change this breakdown and thereby alter the final cost of the material may be summarised as follows (Everist, 1991).

- **primary cost factors**: an adequate match between the quarry yield and the uses made of it, ie use of all the sizes produced in a dedicated quarry, or a good match between oversize demanded for armourstone contracts and material suitable for aggregate production in an aggregates quarry. Any significant variation of the quarry yield may affect the cost
- **secondary cost factors**: an adequate match between the timing of the project and the armourstone production; tonnage of pre- or post-production that may be absorbed to limit left over material; placing schedule to limit rehandling and stocking at the quarry; anticipated weather; allowable time for production. If insufficient time is allowed, extra staff and equipment may be required, which may be costly or disruptive to the general quarry activity and the quarry may be advised to subcontract some of this specific armourstone activity.

A good match between the quarry yield and the armourstone production (Section 3.9.4) is an essential factor that reduces the need for secondary breakage and reselection. Consequently, contracts with designs that demand a series of gradings with significant gaps in sizes between them create extra production costs associated with handling, disposing or stocking costs. The unwanted sizes can be reprocessed by secondary breaking and crushing, which may be costly.

For dedicated quarries, costs may be increased significantly if excess material is generated, ie if some gradings produced are not accounted for at the design stage, or if large amounts of fines are removed but not used as aggregates, eg to make concrete armour units. Materials not used in the project will remain stockpiled in the quarry as waste, a figure of 60–70 per cent quarry utilisation usually being considered a success. A common pitfall is to underestimate the volumes of unwanted fines.

For heavy gradings that are essentially produced by hand-picking, the grading itself and the size of machine affects the picking and placing cost per tonne. Assuming that the materials to be selected are easily reachable and individually handled, the cost for sorting armourstone heavier than, say, 3 t is approximately €0.25/t (excluding loading the selected and the excess/waste materials). For smaller gradings, the cost per tonne increases rapidly because of the increased number of handling operations (see Figure 3.89).

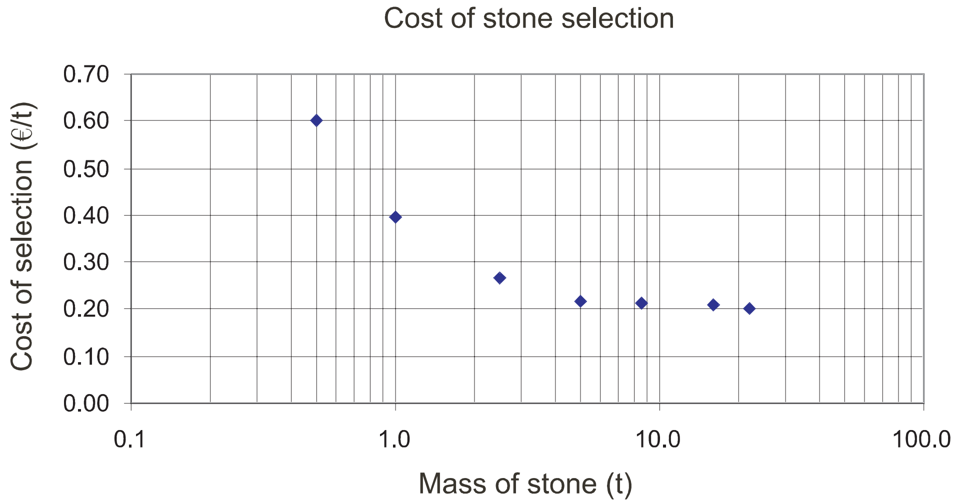


**Figure 3.89** *Estimation of the cost associated with selecting different armourstone sizes. Costs in euros. The differences result after combining the increased cost of the greater hydraulic excavator capacity needed and the speed of working expressed in terms of total tonnes selected per hour (courtesy J van Meulen)*

Where an aggregates quarry is to be modified to produce heavy armourstone, there will be costs associated with modifying quarry layout and operations. A breakdown of costs for such a project is given in Box 3.41.

**Box 3.41** *Costing the supply of heavy gradings from aggregates quarries*

Costing armourstone production is particularly important for aggregates quarries where this activity may cause significant disruption to traditional quarrying practices. This requires a detailed study of armourstone markets generally. Also to be included in the cost are extra wear and damage to the equipment and machinery, which is more severe for armourstone production than for aggregates production and proportionally higher for higher strength and abrasive rock types. An example costing is set out below.

A large aggregates quarry producing several million tonnes of aggregates per year accepted an opportunity to supply 20 000 t of a 5–7 t armourstone grading. The production process was hand-picking with orange-peel grab of oversized and some secondary breakage. The cost may be divided as follows:

- costs of layout modifications to the aggregate quarry, including costs associated with the aggregate activity (around 25 per cent)
- drilling and blasting (around 11 per cent)
- selection at the muckpile (around 12 per cent); secondary breakage (around 12 per cent)
- further selection and sorting (around 13 per cent)
- quality control and individual weighing (around 11 per cent)
- loading of the client's transport facilities (around 15 per cent).

The armourstone cost could have been reduced to the optimum if the contract requirements were known sufficiently in advance to allow stockpiling of appropriate oversize.

For coarse or light gradings, the use of mechanical sorting devices (see Section 3.9.7) should be evaluated carefully since it may greatly improve the cost-effectiveness of armourstone production. The unit costs are for putting the material on to the selection plant, ie direct tipping by truck is not greater for armourstone than for other materials. The depreciation of the plant and machinery through wear and tear has a considerable influence on the cost and should be carefully assessed. Table 3.43 gives an overview of the costs (2005 values) associated with various selection methods. These data are based on feedback from experience and should be adapted for individual situations.

**Table 3.43** *Typical costs associated with selection methods for coarse and light gradings including some core materials (cost level: 2005)*

| | Purchase cost (€) | Installation cost (€) | Procurement (wks) | Selection (steps) | Input life (t) | Product quality (see note) | Output (t/hr) | Unit cost (€/t input) |
|---|---|---|---|---|---|---|---|---|
| Selection hill | 0 | 0–2500 | 0 | 1 | N/A | 6 | 250 | 0.40 |
| Static grizzly | 15 000 | 10 000 | 3 + 1 | 1 | 250 000 | 5 | 250 | 0.30 |
| Mobile grizzly | 75 000 | 5 000 | 13 + 1 | 1 | 1 000 000 | 3 | 150 | 0.80 |
| Barsizer excl feeder | 50 000 | 15 000 | 8 + 4 | 2 | 1 000 000 | 2 | 150 | 0.90 |
| Barsizer incl feeder | 175 000 | 125 000 | 13 + 4 | 3 | 4 000 000 | 2 | 300 | 0.50 |
| Trommel screen small | 300 000 | 75 000 | 13 + 2 | 4 | 6 000 000 | 1 | 300 | 0.60 |
| Trommel screen large | 375 000 | 75 000 | 13 + 2 | 6 | 6 000 000 | 1 | 600 | 0.50 |
| Sidekick | 35 000 | 5 000 | 13 + 1 | 1 | 1 000 000 | 4 | 50 | 0.70 |

**Note**

Product quality levels: 1 = best; 6 = worst.

## 3.12 CONCRETE ARMOUR UNITS

When identifying rock sources and procurement options for cover layer materials, the required armourstone may not be found or may not be the most cost-effective option. As an alternative to the use of quarried rock in the marine environment, concrete armour units (prefabricated concrete elements) can be a competitive option, especially when heavy armouring is required. A wide variety of types of unit are available – examples are listed and illustrated later in this section.

Use of concrete armour units can help maximise utilisation of material resources. The most suitable type of armouring should be selected on the basis of:

- structural and hydraulic stability, including the risk of progressive damage (see Section 5.2)
- hydraulic performance – overtopping and reflection reduction (see Section 5.1.1)
- availability of rock of sufficient quality, size and quantity (see Section 3.9)
- fabrication, storage, handling and placement of armour units
- maintenance and repair of armour layers
- appearance.

Many types of unit are available on the market. Key considerations for selection are:

- the **hydraulic stability** of the unit under a given range of packing densities (Equation 3.91)
- the **structural strength** of the unit, in particular impact and fatigue stresses and other potential damage risks. In general, larger concrete armour units are more sensitive to breakage caused by the larger forces associated with block movements, while the tensile strength of concrete remains constant
- the **practicality of economic construction** of the unit under local conditions
- the **range of application** of the unit (including possible limitations based on field experience and testing).

This information can be gathered from surveys of field performance, laboratory testing or from unit developers.

1 2 3 4 5 6 7 8 9 10

In this section, design information for several types of concrete armour unit is summarised. Section 3.12.1 deals with the properties of concrete armour units and presents a classification of units, Section 3.12.2 summarises some of the units that are more widely used and their characteristics and Section 3.12.3 discusses the production of concrete armour units.

Many armour units are licensed under patent and the licensees have developed standards of practice and knowledge bases that allow them to provide support in design and construction monitoring. More up-to-date or comprehensive guidance may therefore be available from the licensees.

Design methods for calculating the hydraulic stability of concrete armour units are presented in Section 5.2.2.3.

## 3.12.1 Properties

### *3.12.1.1 Historical development of concrete armour units*

The first artificial armour units were simple parallelepiped concrete blocks. Further development of artificial armour units led to two basic armouring concepts:

- randomly orientated interlocking armour units
- uniformly placed friction-type armouring.

This section mainly focuses on randomly oriented armour units, for which the governing factors influencing stability are mass and interlocking of adjacent units. Some details of close-placed regular pattern units are also discussed.

In the 1950's the tetrapod unit was introduced, as casting of concrete allowed armour units to be shaped in ways that increased stability through better interlocking. The economic advantages of using tetrapods instead of massive units promoted their use in a large number of breakwaters around the world. Despite wear and breakage of the top-layer units they continue to be used today, for example in Japan.

The development of concrete armour units continued (see Table 3.44) in the form of highly interlocking units of more complex shape such as the Dolos, units that improved on the plain cube such as the Antifer grooved cube, and a generation of uniformly placed hollow or multi-hole units, such as the Shed.

**Table 3.44 History of concrete armour unit development**

| Armour unit | Country | Year | Armour unit | Country | Year |
|---|---|---|---|---|---|
| Cube | – | – | Antifer Cube | France | 1973 |
| Tetrapod | France | 1950 | Seabee | Australia | 1978 |
| Tribar | USA | 1958 | Accropode | France | 1980 |
| Modified cube | USA | 1959 | Shed | UK | 1982 |
| Stabit | UK | 1961 | Haro | Belgium | 1984 |
| Akmon | NL | 1962 | Diode | UK | 1984 |
| Tripod | NL | 1962 | Hollow Cube | Germany | 1991 |
| Dolos | RSA | 1963 | Core-loc | USA | 1996 |
| Cob | UK | 1969 | Xbloc | NL | 2003 |

Safety concepts for armour units were reconsidered after the failure of breakwaters in the late 1970s and early 1980s in Sines, Arzew, Tripoli and Diablo Canyon. The failure of these breakwaters was mainly caused by the structural failure of slender elements. Thereafter the trend was towards the use of more robust, bulky units of increased structural strength, placed in one layer with high safety margins for the hydraulic design. Armour units had previously been placed in two layers to cover the uncertainties with respect to hydraulic stability and structural integrity. The Stabit was the first randomly placed single-layer armour unit, introduced in 1961. The Accropode was developed in 1980, followed by the Core-loc and the Xbloc.

The most commonly used types of concrete armour units are:

- cubic-type blocks used in a double layer
- interlocking-type units used in a double layer
- interlocking-type units used in a single layer
- regularly placed friction restraint units used in a single layer.

PIANC (2005) has given a descriptive inventory of frequently used units. Several of the more widely used types will be further described in this section. It should be noted that there are probably in excess of 100 varieties of armour unit, many of which were developed for a single use, notably in Japan or Korea, and have not been used more widely. Some of the currently used units are identified in Figure 3.90.

**Figure 3.90**

*Commonly used concrete armour units*

New artificial units are coming on to the market every year and the reader should regularly update his technical database with the most recent information from technical publications.

### 3.12.1.2 *Classification and structural strength of concrete armour units*

Several classifications can be found for concrete armour units, see for example CEM (USACE, 2003) and PIANC (2005). A descriptive classification can be based on placement pattern (orientation), layer characteristics, shape and stability factor (see Table 3.45, also discussed in Section 5.2.2.3). The structural integrity of concrete armour units is mainly controlled by the shape of the unit.

**Table 3.45** *Classification of armour units by shape, placement and stability factor*

<table>
<tr><th rowspan="2">Placement pattern</th><th rowspan="2">Number of layers</th><th rowspan="2">Shape</th><th colspan="3">Stability factor (main contribution)</th></tr>
<tr><th>Own weight</th><th>Interlocking</th><th>Friction</th></tr>
<tr><td rowspan="5">Random</td><td rowspan="3">Double layer</td><td rowspan="2">Simple</td><td>Cube, Antifer Cube, Modified Cube</td><td></td><td></td></tr>
<tr><td colspan="2">Tetrapod, Akmon, Tripod</td><td></td></tr>
<tr><td>Complex</td><td></td><td>Stabit, Dolos</td><td></td></tr>
<tr><td rowspan="2">Single layer</td><td>Simple</td><td>Cube</td><td></td><td>Cube</td></tr>
<tr><td>Complex</td><td></td><td>Stabit, Accropode, Core-loc, Xbloc</td><td></td></tr>
<tr><td rowspan="2">Uniform</td><td rowspan="2">Single layer</td><td>Simple</td><td>Haro</td><td></td><td>Seabee, Haro</td></tr>
<tr><td>Complex</td><td></td><td></td><td>Cob, Shed, Tribar, Diode</td></tr>
</table>

**Note**

The Haro is also placed in double layers.

The majority of concrete armour units are cast using unreinforced concrete. A few units have used reinforcement steel, stainless steel, chopped wire or plastic. Reinforcement is seldom used, mainly because of fears of corrosion. Reinforcement has generally been found to be less cost-effective and if steel reinforcement corrodes the adverse effect on durability can outweigh any advantages in using it.

Concrete armour units are subjected to various load conditions. Possible reasons for breakage of armour units are static failure and construction-related breakages. Wave-induced movements of the units (rocking) are more likely to induce such breakages, however. The structural integrity of concrete armour units needs to be ensured, as the units' hydraulic stability deteriorates when they fracture or disintegrate, causing a reduction of the stabilising gravitational force and possible interlocking effects. Moreover, if wave action throws broken armour unit pieces back on to the structure, an increased rate of breakage may occur. Useful information on the structural integrity of units can be gained from past experience, finite element stress (FEM) modelling and full-scale integrity (drop) tests (see Section 3.8.5).

The use of fillets is recommended where high-tensile stresses are likely to develop in units with a complex shape. Such changes have been used on Stabit and Dolos units, and Melby and Turk (1997) have used FEM analysis on the Core-loc block to show that a 20 per cent reduction in maximum tensile stress may be obtained with a fillet equal to 10 per cent of the height of the armour unit.

Particular attention should be paid to known performance of armour units in service. Storms are generally infrequent events, so it may be necessary to wait for several years before a structure is exposed to an event close to the design conditions. Information on structural integrity of concrete armour units and the known range of application (eg maximum size) is also important, as the intrinsic strength of units decreases with increasing size. If the unit is used outside its range of application, breakage may occur before hydraulic failure of the structure is reached. More information on structural integrity of concrete armour units is presented in CEM (USACE, 2003).

### 3.12.1.3 Description of concrete armour units

A given unit can be defined by the following parameters:

- **name of the unit** and **variant**
- **volume of the unit**, $V$ ($m^3$) – the volume of solid concrete (see Table 3.46)
- **specific dimensions** – some artificial units have a complex shape, their specific dimensions have to be described precisely
- **class of concrete and type of reinforcement** – the minimum class of concrete should be indicated in accordance with EN 206-1:2000
- **licence** – this indicates if the unit is available through a licence agreement or is free of any patent or trademark.

**Layer systems of concrete armour units**

Armourstone is almost always used in a double layer system. Concrete armour units can be used in single- and double-layer systems depending on the type of armour unit.

The use of specific placement and orientation requirements for concrete armour units was introduced for particular types of units together with specific placement methods. Examples are known where the appropriate placement method was not carried out, leading to failure of the structure within a few years of completion. Most units have a specific placement method, which is either published or made available through a training programme.

The placement may be random, where there is neither control on the unit position nor on its orientation. There should, however, always be a target or minimum placement density. Alternatively, placement may be orderly, where the unit is placed at a given position with control on the orientation. There is no random placement with an orderly orientation method.

The geometry of the armour layer, which depends on the type of concrete armour unit used, is given by the following parameters:

- **armour layer thickness**, $t_a$ (m), defined as the distance normal to the underlayer surface, measured from this surface up to the average of the protruding points. This may differ from the overall thickness, which is defined as the distance from the underlayer to the most protruding points
- **placement grid** – most units are placed according to a predefined placement grid that defines the location of each individual unit in relation to the other units. In addition, specific orientation of the units on the horizontal plane may be required. An example is given in Figure 9.62 in Section 9.7.2.6, where the placement of concrete armour units is discussed
- **layer porosity**, $n_v$ (-), defined as the ratio between the void volume and the layer volume
- **packing density coefficient**, $\phi$ (-), defined as the number of placed units per square nominal diameter. This should be compared to the maximum packing density that is geometrically obtainable and the minimum density below which the hydraulic stability is not guaranteed
- **number of units per square metre of protected slope**, $N$ ($1/m^2$), calculated using the packing density coefficient, $\phi$. The consumption of concrete per square metre of protected slope, $V_c$ ($m^3/m^2$), can be estimated using the number of units, $N$.

Table 3.46 summarises the basic geometric design formulae and parameters for randomly placed concrete armour units. Characteristic values for widely used units are presented in Table 3.47 in Section 3.12.2.5.

**Table 3.46** *Basic geometric design formulae and parameters for randomly placed armour units*

| Parameter | Equation | Eq. No |
|---|---|---|
| Armour unit volume, nominal diameter and characteristic length | $V = \left(\frac{M}{\rho_c}\right) = D_n^3 = k_s D^3$ | (3.86) |
| Centre to centre distance between armour units | $\Delta x = X_c\ D = X\ D_n\ ;\ X = X_c / k_s^{1/3}$ <br> $\Delta y = Y_c\ D = Y\ D_n\ ;\ Y = Y_c / k_s^{1/3}$ | (3.87) |
| Area covered by one armour unit | $A_a = \Delta x\ \Delta y = X_c\ Y_c\ D^2 = X\ Y\ D_n^{\ 2} = \frac{n}{N}$ | (3.88) |
| Armour layer thickness | $t_a = n\ k_t D_n = n\ k_c\ D; k_c = k_t\ k_s^{1/3}$ | (3.89) |
| Armour layer porosity | $n_v = 1 - \frac{n\ V}{A\ t_a} = 1 - \frac{k_s^{2/3}}{X_c\ Y_c\ k_t} = 1 - \frac{1}{X\ Y\ k_t}$ | (3.90) |
| Packing density coefficient | $\phi = n\ k_t (1 - n_v)$ | (3.91) |
| Number of units per unit area | $N = \phi / D_n^{\ 2} = \phi / V^{2/3}$ | (3.92) |
| Concrete volume | $V_c = NV = t_a (1 - n_v)$ | (3.93) |

| where: | | |
|---|---|---|
| | $A$ | total surface area (m²) of armour layer panel parallel to slope |
| | $A_a$ | area covered by one armour unit (m²), equal to: $nA/N_a$ |
| | $D$ | characteristic armour unit length (m) |
| | $D_n$ | nominal armour unit diameter (m), the equivalent cube size |
| | $k_c$ | modified layer coefficient (-) |
| | $k_s$ | shape coefficient (-) |
| | $k_t$ | layer coefficient (-) |
| | $N$ | number of armour units per unit area (1/m²) |
| | $N_a$ | total number of armour units placed on surface area (-) |
| | $n$ | number of layers (-) |
| | $n_v$ | armour layer porosity (-) |
| | $t_a$ | armour layer thickness (m) |
| | $V$ | armour unit volume (m³) |
| | $V_c$ | concrete volume per unit area (m³/m²) |
| | $M$ | armour unit mass (kg) |
| | $X, X_c$ | dimensionless horizontal distance (-) |
| | $Y, Y_c$ | dimensionless upslope distance (-) |
| | $\Delta x, \Delta y$ | horizontal and upslope centre to centre distance between units (m) |
| | $\phi$ | packing density coefficient (-) |
| | $\rho_c$ | density of concrete (kg/m³) |

**Note**

The layer thickness, $t_a$ (m), is given here (see Equation 3.89) for completeness and because it is used in other equations in this table. It is, however, normally not used in design and specifications for construction. A specific type of unit is then prescribed, together with the lines and levels of the underlayer.

### 3.12.1.4 *Intrinsic properties*

**Density of concrete**

For most concrete artificial armour units, the density of concrete used for fabrication should be not less than the one used in the hydraulic stability calculations and tested in the laboratory. Usual values are 2350–2400 kg/m³, but some units (chiefly cubic blocks) have been used with a much higher density, eg 3000 kg/m³. Using high-density concrete armour units results in a lower volume of each unit and in a reduced layer thickness (see also Section 5.2.2.3). The benefits of high-density concrete may be offset to some extent by additional costs for heavy aggregates and for the placement of a larger number of smaller individual units. Attention should also be paid to the methods of obtaining dense concrete in relation to durability.

**Other properties of concrete**

Artificial armour units are usually made of plain concrete of a standard grade. Concrete is defined according to the European standard EN 206-1:2000. Key parameters to be defined in accordance with this standard are given below:

- **exposure class**: XS3 – tidal, splash and spray zones
- maximum **diameter of aggregates**, $D_{max}$, which generally varies from 20 mm up to 40 mm
- **workability** of concrete – slump class S2 (ie 50–90 mm); the workability can be increased by the use of plasticisers to keep the water/cement ratio, W/C (-), not greater than 0.45
- characteristic **compressive strength** and possibly the characteristic tensile strength (N/mm$^2$) for slender units (EN 206-1:2000 table 7 and 8). This data is to be made available by the unit developer according to their feedback from experience. Usual ranges of compressive strength are in the range of C20/25, C25/30 and C30/37, where the first number is the minimum characteristic strength of a 150 mm diameter by 300 mm cylinder, and the second is the minimum characteristic cube strength. For slender unreinforced units the tensile strength is more relevant, and tensile strength should be indicated by the developer (EN 12390-6:2002). The moulds are generally stripped as soon as practicable. A minimum strength for stripping should be indicated and the use of maturity tests is recommended to confirm strength. Water/cement ratio should be minimised to avoid porosity and further durability concerns. A recommended value is 0.45
- **density of concrete** (see above)
- **aggregates** – common aggregates are generally used and should be selected in accordance with national standards such as European standard EN 12620:2002. Aggregates are generally easy to obtain if no durability problem is encountered since they can be considered as quarry leftovers. Use of lightweight aggregates is not recommended as stability formulae show that very large units are required. Use of high density aggregates is recommended for hydraulic stability but the concrete durability must be carefully assessed
- **cement** – for works in the marine environment cement should be according to the standard EN 206-1:2000, which defines a cement content of 350 kg/m$^3$ for a 20 mm aggregate concrete. Common French practice is to recommend a cement content, $C$ (kg/m$^3$), for marine works of $C = 700/(D_{max})^{1/5}$, where $D_{max}$ is the maximum size of the aggregate (mm). Information on how to choose the cement depending on the aggressiveness of the environment can be found in the French standard P 18-011.

The reader is referred to EN 206-1:2000 for further details. A useful guidance on concrete in the marine environment is also given in Allen (1998).

**Durability of concrete**

Durable concrete should maintain not only its mechanical strength but also its good appearance and should not develop cracks or change surface texture.

Durability of concrete depends primarily on good fabrication processes, but the cement's chemical composition is also of great importance. It is recommended to use ASTM type II or III, sulphate-resisting cements. If OPC (*Ordinary Portland Cement*) is to be used, a maximum $C_3A$ content of 8 per cent should be allowed.

Attrition by shingle moved by waves and sometimes by wind-blown sand may damage concrete armour units. Attrition may also occur when the armour units are rocking. Fooke and Poole (1981) give some guidelines on the selection of concrete components to limit attrition. Attrition of armour units may lead to loss in hydraulic stability both in terms of packing density and interlocking. Survey of existing structures with cubes, tetrapods and

Accropode units shows that attrition and wear of angles and corners under wave attack can be serious, particularly on active shingle beaches, and should be considered at design stage. It is recommended to check that the units have been tested for attrition and that consequences of wear have been identified and the design developed accordingly. If attrition is expected, the mass of the units should be increased to account for probable loss of mass. In very severe cases it is advisable to use very bulky units. In France, a specific method for testing the resistance of concrete samples against abrasion was developed in the BHP 2000 project (ENPC, 2005).

## 3.12.2 Widely used units

In this section several of the most commonly used concrete armour units are presented using the classification as given in Sections 3.12.1.1 and 3.12.1.2. A summary of their characteristics is presented in Section 3.12.2.5.

### *3.12.2.1 Cubic-type blocks*

**Cubic block/cube** (see Figure 3.91)

The cubic block or cube is the simplest substitute to natural stone and its main stability arises from its mass. Stability is also influenced by friction between the blocks.

Cubes are fabricated with unreinforced concrete on a simple horizontal surface, often at a rate of one block per day per mould. The formwork is made of four faces joining at the corners. The recommended concrete grade is C25/30 with slump S2 and cement with a low hydration heat.

Cubes are traditionally placed in two layers, where the lower layer acts as a separator for the blocks of the upper layer. This can help prevent the tendency for cubes to reorientate during settlement to form a more regular placement pattern with lower roughness and permeability. Recent research (Van Gent *et al*, 2000 and 2001, and Van Gent, 2003) suggests that single-layer cubes may exhibit some advantages over double-layer armouring in certain cases (see also Section 5.2.2.3).

The method of placement of cubes is important for the hydraulic performance and structural response of the armour layer. Randomly placed cubes lead to better hydraulic performance because wave overtopping and reflection may be reduced. More uniformly placed cubes may lead to a lower porosity and subsequently to a higher risk of cubes being lifted by excess pore pressures that develop inside the breakwater. Also, the material consumption rates of more uniformly, and hence more densely, placed cubes can add significantly to costs. Cubic blocks are commonly gripped with clamps for placement.

**Figure 3.91**

*Example of cubic blocks being placed by cable crane during Barcelona breakwater construction (courtesy S Dupray)*

**Antifer cube** (see Figure 3.92)

The Antifer cube is a development of the simple cube. It has one groove on each of the four lateral sides of the unit. These grooves improve the interlocking and the hydraulic stability while decreasing the risk of face-to-face rearrangement.

Units are made of unreinforced concrete on a simple horizontal surface at a normal rate of one unit per day per mould. Formwork is made of four faces joining at the angles. No formal standard dimensions exist. The recommended concrete grade is C25/30 with slump S2 concrete with a low hydration heat because of the thickness of the unit.

Antifer cubes are generally used in two layers. The lower layer acts as a separator for the blocks of the upper layer. Antifer cubes are commonly placed using clamps. The unit orientation is usually not specified, although most Antifer cubes are placed with the smallest face upwards. Although the risk of unwanted face-to-face placement is still possible, it is less probable than with the cube. The placement of Antifer cubes in accordance with the recommended standards is important so as to guarantee the porosity of the armour layer.

**Figure 3.92**

*Example of Antifer cubes – Antifer breakwater (courtesy S Dupray)*

**Other related units**

Parallelepiped units have been used. Some cubes and Antifer cubes with a central hole to decrease the consumption of concrete have also been used to decrease the risk of internal stresses due to overheating during hydration of the concrete.

### *3.12.2.2 Hollow units*

**Cob, Shed, Seabee, Haro and Diode** (see Figure 3.90)

This family of units is derived from the massive cubic block. By providing a void in the centre of the unit, concrete volumes (and mass) are reduced and a good hydraulic performance due to energy dissipation is achieved. The units are placed as if in a pavement with the faces of adjacent units touching one another. The armour layer resists wave action by the friction between the blocks and wave forces are reduced by the high armour porosity of these units.

The units are either fabricated without structural reinforcement, or may include non-corrodible integrity reinforcement. The formwork for producing these units is made of several inner and outer shells.

Specific attention should be paid to placement of the units to ensure that they are closely placed in parallel lines. This operation may be difficult and slow and will require special care at roundheads and curves. If such close placement is not achieved, the stability of the entire layer is compromised. Accurate placement of the bottom row is also essential to ensure good organisation of the subsequent rows on the slope, and toe details should be specially designed to provide a regular, smooth surface for support.

### 3.12.2.3 Interlocking units used in a double layer

**Dolos** (see Figure 3.93)

The Dolos unit is characterised by a relatively light body and long members that allow a very high degree of interlocking. The slenderness of this unit can vary, with different relative waist thicknesses defined as ratio of the width of the octagonal central stem relative to the longest dimension of the unit. The waist ratio (diameter in centre part to height) is typically $r = 0.32$ and an increased waist ratio is recommended for larger units ($r = 0.34$ for units of 20 t and 0.36 for units of 30 t). The waist ratio for larger Dolos units (≥ 20 t) can be assessed by using Equation 3.94:

$$r = 0.34\left(\frac{M}{20}\right)^{1/6} \tag{3.94}$$

where $M$ is the unit mass (t).

The Dolos unit was initially developed with unreinforced concrete until damage was observed, attributable to the slenderness of the members. In response to the observed damage, steel reinforcement has been used at some sites. Design of such reinforcement may be difficult because of the dynamic loading. Potential problems are corrosion of the reinforcement, which can lead to cracks, and the increase in cost due to the reinforcement. The formwork for producing the Dolos unit is made of several shells and may allow a production rate of one unit per day per mould with experience.

**Figure 3.93**

*Example of Dolos used on slope with heavy basalt armourstone on crest (courtesy S Dupray)*

The Dolos unit was a step forward in terms of interlocking between units. Its shape gives good hydraulic stability of the armour layer as tested in the laboratory. Dolos units are placed randomly in two layers with a given packing density. The second layer is necessary to create interlocking.

The good hydraulic stability has not always been supported by good structural strength, and cases of severe damage and the need for repair have been reported. Extensive research to minimise integrity problems of the Dolos unit and to understand its structural weakness has been reported (Lin *et al*, 1986; Hall *et al*, 1987; Howell *et al*, 1989; Luger *et al*, 1995).

For existing structures, regular monitoring, at least after storms, should be carried out and broken armour units may need to be replaced. Rather than repairing a Dolos armour layer the US Army Corps of Engineers has developed the Core-loc, which can fulfil this role.

**Tetrapod** (see Figure 3.94)

The tetrapod unit was the first concrete unit with a special shape. This unit has been used extensively and projects with units up to 50 $m^3$ can be found. The tetrapod has recently been used mostly in Japan in multi-layer systems.

Analysis on the structural resistance of the unit and its hydraulic stability led to comprehensive guidance (Sotramer-Sogreah, 1978) for manufacturing of the formworks, the fabrication of the units, their storage and placement of the units in two layers. The formwork for producing tetrapods is composed of a bottom shell and three lateral shells.

Wear and breakage have been experienced in several structures caused by rocking of the units in the top layer. The placement of the units as per the recommended standards is essential to guarantee the interlocking and the required porosity of the armour layer.

**Figure 3.94**

*Example of Tetrapods used as armour on breakwater with crown wall (courtesy Sogreah)*

### *3.12.2.4 Interlocking units used in a single layer*

**Accropode** (see Figure 3.95)

The Accropode unit was developed from experience of the tetrapod and the observation that double-layer systems may allow unwanted movements of units in the upper layer. This unit has been used extensively and blocks up to 20 $m^3$ have been employed in some projects.

Analyses of structural resistance of the block and of its hydraulic stability has led to comprehensive standards for manufacturing of formworks, fabrication of blocks, storage and placement of units in one layer (Sogreah, 1988). Formwork is made with two lateral shells, allowing a production of one unit per day per mould.

Accropodes are placed in a single layer in a predefined grid whereby the orientation of the blocks has to be varied; the latter is typically specified. Various sling techniques are recommended for placement. The best interlocking of Accropodes can be achieved on steep slopes (3:4 or 1:1.5). For further details see also Sogreah (2000).

For situations where a natural rock appearance is required, the Ecopode (a unit closely related to the Accropode) has been developed.

**Figure 3.95**

*Example of Accropode and Ecopode used in combination (courtesy Sogreah)*

**Core-loc** (see Figure 3.90)

The Core-loc unit was initially developed by the US Army Corps of Engineers for the repair of damaged structures armoured with Dolos units. The shape of the legs is a true copy of the Dolos so Core-locs can be applied as repair units for Dolos armour layers, or as is more usual, for complete armouring systems. The hydraulic stability of Core-loc armour units is better than that of Accropodes (see Section 5.2.2.3), but the recommended stability coefficients for design are close to those for Accropodes. The Core-loc is more slender, so its structural integrity may be less than that of Accropodes.

The placement procedures for Core-locs and Accropodes are similar; various sling techniques are applied for both types of armour units. For further details see also Melby and Turk (1997).

**Xbloc** (see Figure 3.96)

The Xbloc is a compact armour unit with high structural strength (similar to the Accropode unit). The hydraulic stability of Xbloc armour layers is similar to that of Accropode and Core-loc armouring.

Xblocs have to be placed on a predefined grid. The orientation of individual blocks is allowed to vary randomly and so is not prescribed. This is the main difference between Xbloc and other single-layer interlocking armour units. For further details see also DMC (2003).

**Figure 3.96**

*Example of Xbloc during handling (courtesy Delta Marine Consultants b.v.)*

### 3.12.2.5 Layer placement dimensions

Table 3.47 presents values for the characteristic geometric and armour layer parameters defined in Section 3.12.1.3 for some of the most widely used concrete armour units.

**Table 3.47** *Characteristic geometric and armour layer parameter values of randomly placed concrete armour units*

| | | Layer coefficient | Shape coefficient | Distance between units: Horizontal | Distance between units: Slope-parallel | Porosity | Packing density coefficient | Modified layer coefficient | Recommended slope |
|---|---|---|---|---|---|---|---|---|---|
| Armour unit type | Size (m³) | $k_t$ (–) | $k_s$ (–) | $\Delta x/D_n$ (–) | $\Delta y/D_n$ (–) | $n_v$ (–) | $\phi$ (–) | $k_c$ | cot $\alpha$ (–) |
| Cube (two layers) | | 1.10 | 1.0 | 1.70 | 0.85 | 0.47 | 1.17 | 1.10 | |
| Tetrapod | | 1.02 | 0.280 | 1.98 | 0.99 | 0.50 | 1.02 | 0.667 | 4/3 to 1.5 |
| Dolos ($r$ = 0.32) 1) | | 0.94 | 0.16 | 2.19 | 1.10 | 0.56 | 0.83 | 0.51 | 2 to 3 |
| Accropode | < 5 | 1.29 | 0.341 | 1.77 | 0.86 | 0.491 | 0.656 | 0.9012 | 4/3 to 1.5 |
| | 5–12 | | | 1.82 | 0.91 | 0.531 | 0.605 | | |
| | > 12 | | | 1.86 | 0.93 | 0.552 | 0.578 | | |
| Core-loc | < 5 | 1.516 | 0.2236 | 1.83 | 0.91 | 0.606 | 0.598 | 0.9201 | 4/3 to 1.5 |
| | 5–8.5 | | | 1.85 | 0.92 | 0.613 | 0.587 | | |
| | 8.5–12 | | | 1.85 | 0.93 | 0.618 | 0.580 | | |
| | > 12 | | | 1.87 | 0.94 | 0.624 | 0.569 | | |
| Xbloc | < 5 | 1.40 | 0.333 | 1.87 | 0.92 | 0.587 | 0.578 | 0.97 | 4/3 to 1.5 |
| | 5–12 | | | 1.92 | 0.94 | 0.606 | 0.552 | | |
| | > 12 | | | 1.96 | 0.97 | 0.623 | 0.528 | | |
| Cube (one layer) | high 2) | 1.0 | 1.0 | 1.33 | 1.00 | 0.25 | 0.75 | 1.0 | |
| | low 2) | | | 1.70 | 0.85 | 0.31 | 0.69 | | |

**Notes**

1 $r$ = waist-to-height ratio (waist diameter of central section and total height of unit).

2 Packing density.

## 3.12.3 Production and placement

The production process for concrete armour units is similar to that for any precast concrete, and reference should be made to the national concrete production standards in every case. In Europe, the European standard EN 206-1:2000 applies. The conditions of fabrication may vary significantly from northern Europe to the Arabian peninsula or south-east Asia. It is therefore impossible to define a single specification for the fabrication of the units. However, this section gives general good practice and guidelines for most of the units and describes their fabrication and placement. Further information on unit placement is given in Section 9.7.2.6.

### 3.12.3.1 Formworks and moulds

Most armour units are cast in steel or glass-reinforced plastic moulds. Only cubes and other parallelepiped blocks are made using simpler wooden or steel formworks. The moulds should be easy to use and are made of two or more shells depending on the type of unit. Appropriate measures are required to ensure perfect sealing between half-moulds such as rigid frames at joints and short spacing between connecting bolts.

Tolerances for all formwork dimensions should be ± 2 mm to ensure good fitting of the shells and consistency with the volume specification for the armour unit. The volume is the most important parameter that controls, with the mass density, the mass of the unit and its stability.

Complex armour units require precise formwork drawings from the unit developer. Usually sheet steel 5–8 mm thick can be used for the fabrication of the moulds. Maximum deflection produced by the thrust of fresh concrete should not exceed 1/1000 of the span measured for any dimension. Stripping angles should be provided for easy form removal without excessive tensile strength.

Forms can be erected on either a compacted platform or a concrete platform. If using a compacted platform, particular attention should be paid to the stability of the forms and of the cast units. Differential settlement of the soil may lead to tilting of the units and may be a health and safety issue. Appropriate stiffeners should be installed to avoid any deformation of the forms and to ensure safety of the workers during the fabrication process. Working platforms should be provided for pouring operations and to ensure complete safety.

Insulated moulds are required in very cold conditions where frost may damage the freshly poured concrete.

### 3.12.3.2 Casting of concrete armour units

**Production of concrete**

Concrete is produced in standard batching plants. Daily production can vary from a few cubic metres up to several hundreds of cubic metres. The output rate and the characteristics of the batching plant need to be adapted to the project size. It is recommended to use batching plants with automatic recording of the material mass, using equipment as described in EN 206.1:2000 Appendix G with a class III automatic recording device.

The batching of concrete needs to be synchronised with the pouring operations. A new batch should never be started if a risk exists of delays in the pouring activity. A cold joint in unreinforced concrete is not tolerated, since it will undoubtedly lead to breakage of the unit.

**Transport of concrete**

Concrete should be transported by special trucks to prevent segregation. Distance from the batching plant to the fabrication yard should be kept to a minimum to ensure there is no risk of initial setting of the cement and should never exceed 45 minutes.

**Pouring concrete**

Concrete is usually poured in layers not exceeding 50–60 cm. Each lift is vibrated up to the previously poured layer until air is completely removed from the fresh concrete. Cold joints between layers are not permitted. The number and size of the internal vibrators should be adequate for immediate vibration of the concrete introduced into the mould. External vibration units may also be used in addition to internal vibration, but performance should be checked in each case. External vibration cannot be used alone and must be associated with internal vibration.

**Stripping formwork and curing**

Production is often set up with the intention of reusing a mould each 24 hours, implying that the formwork is stripped after 18–20 hours.

Thermal shock during the hydration process in mass concrete can be expected with massive and bulky units. Thermal shocks can occur when the difference in temperature between the centre of the block and the skin is too high. Thermal protection of the unit at the time of stripping the mould is required when cold, windy conditions are encountered.

For units with protruding non-self-supported elements, stripping of the formwork can be done only when a minimum structural strength is obtained. Tilting of units may become a safety hazard on non-stabilised platforms. Supporting devices should be placed after stripping of the formwork.

The exposed surfaces of newly placed concrete should always be kept damp or protected by applying a curing product. Curing should start as soon as possible after pouring of the concrete for non-shuttered parts and immediately after removal of formwork in other cases. Similarly, insulation against frost or cold wind effects should start immediately after stripping. See Figure 3.97 for illustration of pouring and stripping.

**Figure 3.97** *Example of concrete armour unit prefabrication site with preparation of moulds (front left); pouring and vibrating (front right); curing and stripping (back view) (courtesy Port du Havre)*

**Repairing defects**

Three types of defects are found in concrete armour units.

- mass defects can be honeycombs, laitance losses, bubbling, and surface bubbling. Repair of such defects should be carefully assessed when the unit is made of unreinforced concrete. There is a severe risk that the repair will be less durable than the original defective concrete. If the unit is made of reinforced concrete, repairs are possible and particular attention should be paid to the risk of seawater ingress at the repair and future corrosion of the steel. When the volume of the defective concrete is less than 5 per cent of the volume of the unit, the unit should be registered as a defective unit and it may be used in the armour layer provided that it is separated from any other defective unit. If units displaying mass defects are widely spread in the armour layers, this should not affect the hydraulic stability. If the volume of the defective concrete is more than 5 per cent the unit should be declared as unsuitable and should either be carefully repaired or used as a lower mass of unit
- cracking can take the form of either shallow hairlines or deeper cracking. Shallow hairline spread surface cracking of a few millimetres depth is tolerated. Deeper cracking may be a source of breakage if concentrated along a zone typically exposed to high tensile stresses and should always be avoided. Causes of such cracking should be

investigated and eliminated. Cracking should be investigated by core drilling across the crack. Repairs with epoxy grout, or a similar agent, are not considered a valid alternative. Cracks should preferably be avoided at the source. Units with deep cracking have to be rejected or can be used in areas of lesser wave action

- surface defects such as bubbles or bleeding cannot be considered as defects and do not need repair, because they do not affect the units' structural resistance. Such defects are really a sign of poor fabrication methods or concrete mix design and so should alert the contractor to the need to improve the fabrication methodology.

### 3.12.3.3 Control of the production

**Concrete materials**

Concrete control methods for the mix design and the production of concrete are described in EN 206-1:2000. This standard is valid in European countries, but should also be used in other countries where appropriate local guidance is not available. Proper specifications should be developed for the concrete production plant in accordance with the standards. The variability of the cement and other concrete constituents should be taken in account when preparing a design mix.

Standards for the quality control of aggregates, cement, water, fresh concrete and hardened concrete can be directly derived from EN 206-1:2000.

**Casting armour units**

Each unit is given a unique identification number from stripping time to the placement of the unit. This identification allows reference to be made to the day of fabrication and any other data related to the concrete production.

Quality control implies verification of unit volume (or mass) and concrete density. At the start of the fabrication process, the volume of the unit can be checked by measuring the inside volume of the mould. Alternatively the unit can be weighed and the concrete density measured with accuracy. During day-to-day production, the concrete density should be checked regularly at the batching plant. A minimum of 2 per cent of the units produced should be individually weighed. The actual mass should be within +2/-1 per cent of the expected mass.

Structural integrity, including cracking and defects, is the second aspect of the armour unit acceptability. All the units should be scrutinised. Armour units can be damaged during fabrication or during placement. Any unit with more than 10 per cent loss of mass should be discarded. A loss in mass is defined by an effective loss after breakage or by a potential loss due to default in integrity produced by honeycombs or deep cracks. Units with non-conforming mass, ie a loss of mass between 1 per cent and 10 per cent should be rejected. Units with mass loss less than 5 per cent might potentially be used in the armour layer, providing damaged units are not concentrated in a single area.

### 3.12.3.4 Storage

Areas available and the ability to stack units for storage will have been considered early in the design and construction planning process. The units are either stored at the place where they were cast or moved to a storage yard (see Figure 3.98). Storage can be in one or several layers, vertically on their base or on three points. Most units can be stored in two or more layers, depending on their stability. The number of layers can be decided after analysis of the safety conditions for the handling of the unit for storage and removal. A key parameter is the stability of the soil platform for long-term storage.

**Figure 3.98** *Example of units yard in Barcelona with dedicated high capacity handling frame. Note that units are casted alongside the yard and cylinder moulds for concrete quality control (courtesy S Dupray)*

### *3.12.3.5 Placement*

Most concrete armour units are placed according to a predefined placement grid that defines the location of each individual unit in relation to other units. In addition, specific orientation of units may be required. The placing or packing density needs to be specified and strictly maintained during placement of the units and every effort should be made to achieve maximum interlocking. During placement, the packing density can be maintained by specifying a mean and allowable deviation for the centre-to-centre distance between units, or it can be maintained by counting the units in a specified area.

Placement grids for interlocking units are generally specified, with each subsequent row of armour units offset laterally from the previous lower row to avoid failure planes. Single-layer armour units are placed on a staggered grid – see Figure 9.62 in Section 9.7.2.6. The horizontal and vertical upslope grid dimensions (centre-to-centre distances $\Delta x$ and $\Delta y$, see Equation 3.87) can be specified with values presented in Table 3.47.

Special attention is required for armour unit placement on exposed points and at junctions and transitions. Experience in detailing is available from licensees and in many cases three-dimensional model tests need to be carried for detailed design. Further discussion on transitions is given in Section 6.1.4.3.

Placement rates can vary depending on armour unit size, placement tolerance, visibility, water depth, and the type of crane and platform. At Sohar, Oman, 80 000 units were placed at six units per hour, although at more difficult sites two to three units per hour may be more realistic. Placement of concrete armour units is discussed further in Section 9.7.2.6.

## 3.13 RECYCLED AND SECONDARY MATERIALS

In civil engineering works, a vast range of granular materials are viable alternatives to natural aggregates. In road foundations, for example, many materials are utilised that have already been used or are recovered from the waste stream of other activities. These are normally named **secondary materials** or *residues* (Masters, 2001). Substantial energy savings accrue from using locally available secondary materials instead of primary production. The terms used in this section (alternative materials, secondary materials, recycled materials, reuse) are defined in the glossary at the front of this manual.

1 2 3 4 5 6 7 8 9 10

Waste materials are used to only a very limited extent in hydraulic engineering because of the difficulty in estimating the environmental risk they represent. An example of such use is shown in Figure 3.99 and a case study is given in Box 3.42. This section provides a summary of available information to enable granular material alternatives to primary quarried rock to be assessed for use in hydraulic structures. More information can for example be found in CIRIA publication C590 *Potential use of alternatives to primary aggregates in coastal and river engineering* (Brampton *et al*, 2004).

**Figure 3.99**
*Example of the use of crushed concrete in a dike*

To investigate the possible use of various secondary materials in hydraulic structures, their setting and function in the structure should be considered (see Table 3.48). The use of such materials, if enclosed in a membrane or bound by a matrix of bitumen or cement grout, will lower the environmental impact. Direct use as loose granular material requires environmental characterisation for which documented previous experience will be most helpful. Fine unbound material, whether of natural or secondary origin, may be considered a pollutant if it makes clear waters cloudy or causes a build-up of fines.

**Table 3.48 Setting and function of materials**

| Setting within structure | Function |
|---|---|
| Granular components enclosed in geotextile/geomembrane, clay liner, or bound by bitumen or cement grout (low leaching potential) | • Volume-filling (core and reclamation fill)<br>• Armouring (fixing secondary armourstone gradings by grouting – Section 3.15)<br>• Armouring (absorbing waste as filler in the cement or bitumen grout) |
| Loose granular components in contact with circulating water (high leaching potential) | • Armouring (surface layers)<br>• Volume filling, filtering (core and underlayers) |

Combining recycled materials with binders will considerably reduce overall leaching potential and permeability thereby hindering the ingress and egress of water to and from the structure (Hill *et al*, 2001).

Depending on the type of binder, the mobility of the different pollutant species will be affected:

- potential pollutants can be **physically trapped** within the binder structure
- potential pollutants can **chemically interact** with one of the binder components leading to changes in chemical composition and solubility. This interferes with their expected mobility.

The potential for extra biological impacts caused by using alternatives to primary aggregates will need to be assessed, and these impacts can arise because of the chemical and physical effects discussed above.

The aesthetics of coastal and river environments can be very important, particularly if tourism, recreation and related activities depend upon them. There is already some resistance to the use of novel types of structures in river and coastal engineering works, for example rock groynes, because of the perceived aesthetic effects, and in areas designated because of their scenic qualities there are often guidelines on appropriate forms and types of structure. These sensitivities may limit the use of secondary and recycled construction materials in coastal and river engineering, particularly the use of waste tyres, or of construction and demolition waste, if these materials become visible. For most applications and alternative materials, however, any aesthetic impact may be more perceived than actual. In Cornwall in the UK, for example, many beaches formed largely of mine waste are regarded as not only acceptable but also as an asset to the landscape and tourism.

Both primary and alternative aggregates require processing to ensure their consistency and quality, for example removing contaminants. These are likely to be very similar for primary and secondary aggregates but may be higher for recycled materials, for example demolition waste.

### 3.13.1 Types of alternative material

The recycled aggregates (made of waste materials) most commonly used in civil engineering are listed in Table 3.49.

**Table 3.49** *Different types of recycled materials (characteristics and existing uses)*

| Type | Characteristics | Main existing uses in civil engineering |
|---|---|---|
| Construction and demolition waste<br>Recycled concrete | • solid waste resulting from the construction, remodelling, repair, or demolition of structures (ODPM, 2001)<br>• such wastes may include any of the following: scrap lumber, bricks, concrete, stone, glass. | • roads structures<br>• embankments<br>• other earthworks. |
| Dredged materials | • sediments collected from the bed of a river, lake, harbour or sea by dredger, dragline or scoop. | • road construction<br>• beach/nearshore nourishment<br>• habitat creation or restoration landscaping<br>• topsoil creation or enhancement |
| Steel slag<br>Blast furnace (BF) slag | • the steel industry has traditionally produced by-products, which have been successfully used in many fields of application.<br>**Note**: because of the swelling risk inherent to low-density steel slag, its use can be limited. | • roads structures<br>• embankments. |
| Foundry sand | • clean, uniformly sized, high-quality silica sand or lake sand that is bonded to form moulds for ferrous and nonferrous metal castings<br>• the iron and steel industries account for approximately 95 per cent of foundry sand used for castings. | • roads structures<br>• embankments. |
| Municipal solid waste incinerator (MSWI) residue | • most significant by-product from municipal solid waste incineration<br>• has been used in civil engineering structures for more than a decade (the first experiments were carried out in the 1970s)<br>• their effective geotechnical and environmental characteristics as well as their long-term behaviour have been well studied so that the limits of their uses can be described.<br>**Note:** the long-term behaviour of MSWI bottom ash is not yet fully understood. | • roads structures<br>• road embankments<br>• subgrade. |
| Used tyres | • increasing numbers of tyres are being used and even more are expected over the next 25 years. | • drainage systems<br>• roads structures. |
| Other materials | • colliery spoils, minestone, phosphogypsum, glass bullets, fly-ash. | |

Existing experimental data and recommendations will limit the direct use of certain materials.

Typically, recycling of materials like MSWI residues or foundry sands in a water environment will require the addition of a binder to stabilise their leaching potential. Fly-ash or BF slags can be used as a binder.

Up-to-date information on different types of recycled materials can also be found at the following websites:

- <http://ofrir.lcpc.fr>: contains the OFRIR database (Observatoire Francais du Recyclage en Infrastructure Routiere)
- <www.ciria.org/cwr>: CIRIA construction waste and resources website
- <www.wrap.org.uk>: WRAP is a not-for-profit company supported by funding from UK government. It works to promote sustainable waste management by creating stable and efficient markets for recycled materials and products.

## 3.13.2 Mechanical and chemical properties

In this section, parameters required for the design of hydraulic structures are compared with parameters likely to interfere with the use of recycled materials.

**Required parameters for design**

As mentioned in Section 3.1.2, the main property according to the function of the material in the structure is as given in Table 3.50.

**Table 3.50** *Material properties versus function in hydraulic structures*

| Function | Volume-filling | Piping control/filtering | Armouring |
|---|---|---|---|
| Main property | Mass density | Porosity | Mass distribution |

It is not possible to present the range of values of the property parameters, as these will depend not only on the type of materials but also on the complexity of the processes to be performed. The general considerations are summarised in Table 3.51.

**Table 3.51** *Usual texture of the main recycled materials*

| Type | Usual texture |
|---|---|
| MSWI residue | Gravel |
| Construction and demolition waste | Gravel |
| BF slag | Sandstone |
| Steel slags | Gravel |
| Foundry sand | Sandstone |
| Used tyres | Various (unprocessed, granulated, bales etc) |

### Weathering

Weathering may result from physical disintegration, chemical decomposition or a combination of both. Physical weathering causes existing discontinuities to open, new discontinuities to form and the grain boundaries to separate. Chemical weathering results from changes in the chemical composition of the materials and is usually a slower process (Skarzynska, 1995a and b). This parameter should be taken into account in recycled materials because of their complex chemical composition. Weathering can be evaluated by the changes in particle size. Note that for some materials weathering can also result in carbonation, leading to binding.

In a research project, Gardner *et al* (2003) developed the hypothesis that weathering reactions in industrial by-products will change the environmental and physical behaviour of the by-product materials. It is expected that weathering reactions will improve the environmental performance of the material, although it remains unclear in what way the physical performance will be changed.

### Resistance to chloride corrosion

When considering materials for marine environments, the use of recycled concrete is limited because of its limited resistance to chloride corrosion. Specifications concerning compositions and properties of concrete in saline environments are defined in the European standard EN 206-1.

### Swelling

Various studies and experiments have confirmed the swelling capacity of many artificial materials (eg demolition waste), which should be taken into account when considering their use. No standard yet exists for characterising swelling capacity for these materials.

### Resistance to freeze and thaw

Particular attention needs to be paid to the frost susceptibility and frost-heaving values of alternative materials intended for use in hydraulic structures in cold regions. These values depend greatly on their porosity and have to be tested when required (see European standard EN 13383).

Municipal incinerator bottom ash has already shown little resistance to freeze-thaw (Arm, 2003). Test results show that the resistance to freeze-thaw of municipal solid waste incinerator (MSWI) bottom ash can be good, as reported by François *et al* (2003).

### Chemical characterisation

In Europe, the relevant hazardous properties of the materials processed from waste that are under consideration should be identified in relation to the European Council Directive on hazardous waste 91/689/EEC.

For the other materials (not originating from waste), chemical characterisation should be investigated in the literature (such as Al-Masri *et al*, 2004, for phosphogypsum and Chen *et al*, 2002, for glass).

### 3.13.3 Experience from existing uses in hydraulic structures

The different technical and environmental properties mean that use of recycled and secondary materials varies between 10 and 100 per cent. The greatest volumes are currently used in earthworks applications such as road bases, structural fills, embankments and general fills, as reported in Table 3.49. Very few reported cases focus on the use of waste materials in hydraulic structures.

Motz and Geiseler (2001) reported the following uses of steel slags in hydraulic structures:

- dams and dikes
- stabilisation of river beds
- refilling of erosion areas on river beds
- stabilisation of riverbanks.

Recycled aggregates from steel slags – typically larger than 10 mm – are commonly used to prevent the erosion of fine particles. **Steel slags** are charaterised by a high density, a high level of strength and abrasion resistance and a rough texture that ensure long-term resistance to dynamic forces from waves and river flow.

In the mid-1990s a large quantity of copper slag produced in Hamburg, Germany, was routinely used as riverbank protection rip-rap and fine gradings. These materials can still be used within the framework of EN 13383 for mechanical and grading properties. Local regulations should be taken into account for the environmental assessment (see Figure 3.100).

The properties of steel slag armourstone have been investigated and are comparable to those of natural stone such as basalt.

Skarzynska (1995b) mentions existing applications of **minestone wastes** in the following scenarios:

- as the **core** of river embankments without any previous characterisation of the materials
- as **bed protection**
- as **impoundment dams** and dikes.

Skarzynska (1995b) tested the influence of minestone hydraulic structures on the adjoining environment and made the following recommendations:

- hydraulic structures made of minestone waste should be constructed so that the water will quickly run off the surface of the crest and slope
- they should be covered with turf so that the surface will allow ecological colonisation.

It was also pointed out that the intensity of the washing-out of harmful substances by surface water infiltrating through the body of the structure depends on the quantity of the water flow. The following cases should be considered when evaluating environmental risk:

- **flood embankments**: the groundwater movement usually occurs below the embankment
- **surface embankments**: constant water filtration takes place through the body of the embankment
- **river embankment** functioning simultaneously as a dike for sediment ponds: filtration can be towards the river or towards the nearby pond

- embankments or dikes for **water reservoirs**: the water in the reservoir is always above the groundwater level and the infiltration occurs through the dike or body of the embankment.

Skarzynska (1995b) suggested incorporating polyethylene sheeting or clay screens together with drainage to remove the infiltrating water.

Skarzynska and Michalski (1998) have investigated model embankments made of **colliery spoil** and fuel ash and established the following recommendations:

- it is best to choose material with a high content of fine fractions and with a high value of uniformity coefficient to achieve a low permeability coefficient
- the geometry of the embankment cross-section must be designed such that the maximum drop of water level produces a hydraulic gradient not higher than 0.3
- the use of appropriate sealing such as fuel ash or other clay materials can allow the use of materials presenting a higher water permeability.

### 3.13.4 Environmental risk analysis

A methodology for environmental risk analysis is presented in Figure 3.100 based on the prestandard ENV 12920:1998 *Methodology for the determination of the leaching behaviour of waste under specified conditions*.

### MAIN QUESTIONS

- What is the flux of leached (specified) contaminants from a (specified) material in a (specified) utilisation scenario under (specified) climatic conditions as a function of time (cf long term)?
- How can the relationship between the resulting concentration of contaminant in the water at a certain distance downstream of the application and the results of laboratory leaching tests on the material used in the application be established?

**PROBLEM FORMULATION**

- Construction scenario
  - geometry of the structure and role of the material
- Hazard identification: in accordance with the European Waste Catalogue
  - Chemical and physical characterisation
  - European/local regulation linked to the solid waste
  - Identification of the hazardous properties in the materials that are relevant in the scenario in relation to Council Directive on Hazardous Waste 91/689/EEC

**ENVIRONMENT**

- Environmental and climatic scenario
  - Geotechnical conditions, hydrogeological conditions, biological conditions, use of the site over time, exceptional conditions
  - Exposure assessment: source (release) + path (transport) + target points (exposure)

**MATERIAL**

- Sampling
  - Representivity of the materials tested (visual inspection...)
  - Selection of the correct leaching methods to investigate the leaching properties as a function of liquid-to-solid ratio L/S and pH as well as the influence of various internal material properties and external factors on the release of contaminants. Chemical analysis depending on the chemical characterisation of the waste as collected from the European waste catalogue or from the literature
- Data required by regulation (when existing): turbidity

**RISK EVALUATION**

- Choice/development of a suitable model describing the problem under investigation
- If possible validation of the model with on-site chemical analysis
- Comparison to standards or reference values *when existing*
- Assessment of health risks (ingestion, inhalation)
- Assessment of the risk to the environment (ecotoxicity): see local regulations

### CONCLUSION

**RISK MANAGEMENT**

- Decision-making based on risk assessment (authorities, municipalities, companies or organisations)
- Risk communication

**Insufficient information:**
*The project does not go forward*

**Feedback**

**No solutions because:**
*Material not appropriate.*
*No mitigation found*

**Solution found:**
*May include monitoring*

**Figure 3.100** *Environmental risk assessment methodology, based on ENV 12920 (1998)*

### 3.13.4.1 *Status of knowledge*

The engineering properties of many waste materials are often comparable or even better than traditional aggregates and armourstone. The contamination risk implied by the use of these elements is characterised through a quality control process during the processing of the material or can be assessed following a relevant evaluation method, such as that presented in Figure 3.100.

Even if the use of certain waste materials in a water environment is unsuitable (eg hazardous industrial wastes), an adaptation of the design of the hydraulic structures can lead to an increase in the use of many of the alternative granular materials. Certain recycled materials can also be stabilised by the addition of a hydraulic binder before being integrated into a project. This operation extends the possible uses of recycled materials in such structures.

It is anticipated that further full-scale experimentation to examine specific scenarios will extend the body of experience and provide further evaluation of performance. Potential users of these novel environmental engineering solutions are encouraged to both consult and submit case histories to this important growing field. A typical case study demonstrating the use of colliery spoil as beach fill is given in Box 3.42.

**Box 3.42** *Betteshanger Colliery, Kent: colliery spoil used as bulk fill in beaches for sea defence/flood prevention (after Hamilton, 1984, in Brampton et al, 2004)*

Colliery spoil has been utilised as bulk fill for quite substantial flood and coastal defence structures. When the sea defences failed in front of the Betteshanger colliery, near Deal in Kent, during a winter storm and high tides in January 1978, about 2 000 000 m³ of water flowed inland overtopping secondary defences, flooding structures and covering 300 ha of farmland. The Betteshanger tip (approximately 500 ha in area, 10 m high) was within 3 km of the site and closer than any quarry or borrow site. This convenient resource was used as a large-volume beach core material, displacing the equivalent volume of shingle for redeployment on the seaward face. It also supported a new road of crushed rock laid slightly to landward on the top of the bank (see Figure 3.101) to provide access for machinery involved in replenishment and other maintenance schemes in the future. The whole scheme used 85 000 m³ of colliery spoil and 20 000 m³ of rip-rap.

**Figure 3.101** *Typical cross-section of the Betteshanger Sea Defence, Deal, Kent*

## 3.14 GABIONS

Gabions are robust, versatile composite structures generally comprising double-twist wire-mesh baskets filled with hard, durable stone. They can perform a variety of functions within coastal, estuarial and fluvial environments. Applications are well documented in river engineering, where the flexibility, permeability and durability of gabion structures have been exploited to provide robust, sustainable and aesthetically pleasing solutions. Gabions are routinely used to construct retaining structures, for scour protection, channel linings and weirs for hydraulic structures, and for erosion protection on riverbank revetments.

Like many other construction technologies, gabions require proper engineering, design, and installation to perform at their best and this is particularly so in high-energy hydraulic environments. The selection and placing of suitable stone fill and the specification of appropriate wire mesh size, wire diameter and corrosion protection are important steps in this process. Figure 3.102 summarises key gabion elements, their required properties and some typical applications. Much useful guidance is available in manufacturers' documentation, but some of the important properties of hexagonal double-twist wire gabions and the hard durable stone used to fill them are presented below, together with some examples of where gabion structures have been used successfully.

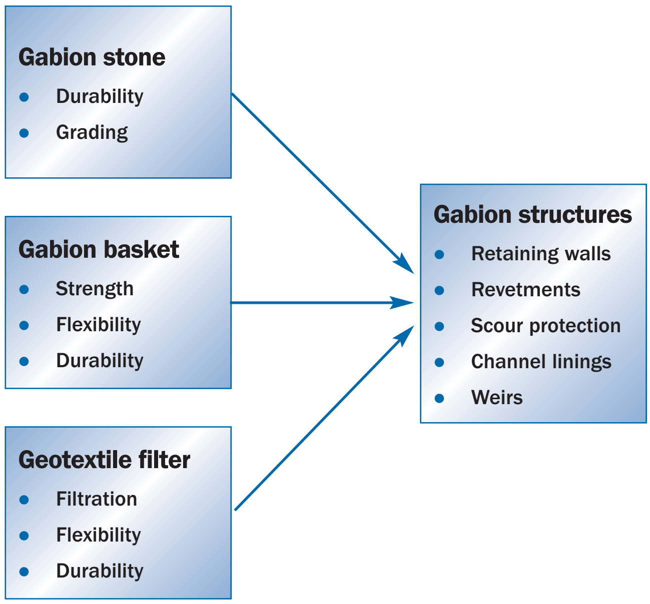


**Figure 3.102** *Key features and applications of gabion structures*

## 3.14.1 Classification of gabions

Gabions can be classified into *box gabions*, *gabion mattresses* and *sack gabions*, as defined below (definitions based on ASTM A975-97, 2003):

- **box gabions** are double-twisted wire-mesh containers of variable sizes, uniformly partitioned into internal cells, and filled with durable stone (see Figure 3.103). A typical box gabion would have dimensions of 2 m (length, $l$) × 1 m (width, $w$) × 1 m (height, $h$) and comprise mesh type 80 mm × 100 mm
- **gabion mattresses** are gabions with relatively small height dimensions compared to length and width and would usually be of smaller mesh type (see Figure 3.103). A typical gabion mattress would have dimensions of 6 m (length) × 2 m (width) × 0.15–0.30 m (height) and comprise mesh type 60 mm × 80 mm. Gabion mattresses rarely exceed 0.5 m in height for practical reasons
- **sack gabions**, rock rolls or tubular gabions are names adopted to describe sausage-like gabions that are used mainly in fluvial engineering for the toe protection of a bank. These types of gabions are not specifically discussed in this section.

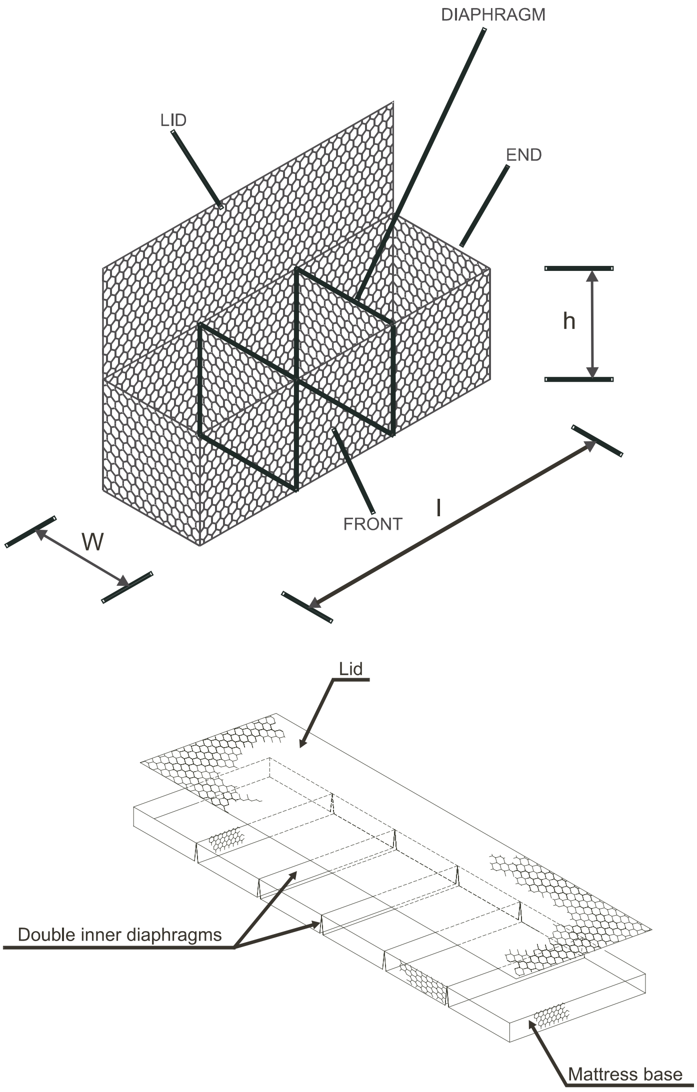


**Figure 3.103**

*A typical box gabion (top) and gabion mattress (bottom)*

## 3.14.2 Gabion components

### *3.14.2.1 Properties of gabion mesh*

Most gabions are manufactured using double-twisted wire mesh, which enables the completed structures to deform significantly without failing and also prevents unravelling in the event that the mesh is cut (see Figure 3.104).

**Figure 3.104** *The advantage of double-twisted over chain link mesh*

The double-twisted wire mesh and the lacing wire or split rings used to construct the gabions should conform to the relevant standards. Current European standards refer only to the mechanical and corrosion protection properties of the wire and the mesh, and none exists for the factory manufacture of gabions. The most relevant existing standard for gabion manufacture is ASTM A975-97 (2003), which has been adopted in the United States. A summary of the relevant European standards and their scope is presented in Table 3.51.

**Table 3.51** *European standards for double-twisted wire mesh*

| Wire properties | European testing standards | Content |
|---|---|---|
| Steel wire composition | EN 10218-2:1997 | Steel composition, strength |
| Steel mesh composition | EN 10223-3:1998 | Wire diameter, *d* (mm), depends on mesh size:<br>mesh 60 × 80 mm → wire: $d$ = 2.2 or 2.4 mm<br>mesh 80 × 100 mm → wire: $d$ = 2.7 mm<br>mesh 100 × 120 mm → wire: $d$ = 2.7 or 3 mm |
| Corrosion protection (galvanising) | EN 10244-1:2001<br>EN 10244-2:2001 | Thickness of the coating conforms to class A, mass of coating, $m_c$, depends on wire diameter, $d$ (mm):<br>$d$ = 2.2 and 2.4 mm: $m_c$ = 230 g/m²<br>$d$ = 2.7 mm: $m_c$ = 245 g/m²<br>$d$ = 3.0 mm: $m_c$ = 255 g/m² |
| Corrosion protection (polymer coating) | EN 10245-1:2001<br>EN 10245-2:2001<br>EN 10245-3:2001 | Requirements for organic coatings, PVC or PE: thickness, composition, strength, durability, flexibility |

The most common mesh types and wire diameters used in river and coastal works are summarised in Table 3.52.

**Table 3.52** *Common mesh types*

| Mesh type (mm) | Wire diameter (mm) | Ultimate tensile strength (kN/m) |
|---|---|---|
| 60 × 80 | 2.2 | 35 |
| 80 × 100 | 2.7 | 43 |
| 80 × 100 | 3.0 | 51 |
| 100 × 120 | 3.0 | 43 |

Corrosion protection for the mesh is provided in two ways: first by the process of **galvanising** the wire and second by an additional polymer **coating**, typically PVC.

For river and coastal works the wire should be of heavy galvanised type (Class A, EN 10244) and may comprise conventional zinc galvanising or, more commonly in recent years, a Galfan alloy comprising 95 per cent zinc, 5 per cent aluminium and traces of *rare earth* mischmetal. The Galfan technology was developed by the International Lead and Zinc Research Organization (ILZRO) in the mid-1990s, and laboratory tests showed that a Galfan coating is three to four times more durable than the same amount of conventional zinc protection, particularly in aggressive saline conditions. The galvanised wire is often further protected with an additional polymer coating, usually PVC, manufactured in accordance with EN 10245:2001.

Conventional galvanised zinc PVC-coated gabion mattresses have been in place and shown to be durable in chemically aggressive hydraulic environments for more than 40 years to date. Where problems have occurred in coastal works, these have been shown to be the result of physical attrition from stones thrown up by waves or caused by poor construction where wave action has caused internal abrasion of the wire as stone moves within the gabion. Successful examples exist where properly engineered gabion mattress revetments have been constructed to protect eroding sandy beaches and problems are rare in river and estuarine environments, where wave and scour energy levels are significantly lower.

#### 3.14.2.2 *Specification for durable gabion stone*

Gabion stone should be strong and durable and typically it will be convenient to specify quality using EN 13383. Mudstones and other argillaceous weak rocks should be avoided if possible, primarily because they tend to degrade once placed. A suitable grading is the EN 13383 standard coarse grading 90/180 mm, (see Table 3.5, Section 3.4) specifically designed for gabion use. In France, stones used for gabion filling should conform to NF P 94-325-1 (2004).

Guidance on the stone quality to be used in gabions is given in Table 3.53.

**Table 3.53** *Suggested requirements for stones used in gabion boxes and mattresses*

| Property | European standard reference | Suggested requirements |
|---|---|---|
| Mechanical strength of rock [1] | Compressive strength (EN 1926:1999)<br>EN 13383–1:2002 | Class EN 13383-1:2002: $CS_{60}$<br>(see Section 3.7.1) |
| | Los Angeles, *LA* (EN 1097-2:1998)<br>Fragmentability, *FR* (EN 1097-2 :1998) | $LA < 45$<br>or $LA > 45$ and $FR < 7$ |
| Resistance to attrition | Micro-Deval (EN 1097-1:1996)<br>Fragmentability *FR* (EN 1097-2:1998) | $M_{DE} < 45$<br>or $M_{DE} > 45$ and $FR < 7$ |
| Resistance to freeze and thaw | EN 13383-1:2002 | Category for *FTA*:<br>Loss of mass < 0.5 per cent |
| Density of rock | EN 13383-2:2002 | Apparent density > 2.2 t/m$^3$ |
| Armourstone grading | EN 13383-1:2002 [2] | $CP_{90/180}$ or equivalent (see Section 3.4.3.2)<br>(or $CP_{90/130}$ for mattresses) |
| Shape | – | No specific requirement |
| Type of rock | Petrography | Calcareous, siliceous, metamorphic or igneous rock |

**Notes**

1 Either test may be considered.

2 In France, NF P 94-325-1 also applies.

### 3.14.3 Properties of gabion stone

#### 3.14.3.1 *Physical properties of gabions*

The void porosity of gabions varies depending upon the type of rock fill and the nature of the filling operation. Values can vary from 25 to 35 per cent. Values of 25 per cent would be appropriate when stone fill is carefully hand-placed, while 35 per cent would be typical of gabions filled for the most part by mechanical means. For the design of retaining structures a conservative value of 40 cent is often adopted. A consequence of their high porosity is that gabions are highly permeable.

Tests have been undertaken on gabions to assess their compression and shear strength characteristics. The compression strength of a gabion depends on the type of mesh, wire

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diameter and rock used to fill the baskets. Currently there is no standard for testing the compression strength of gabions, but testing on gabions with 80 × 100 mm mesh and 2.7 mm wire diameter, filled with 80/200 mm stone fill, has indicated an ultimate compression stress of 4.5 MPa at failure, with strains of 50–60 per cent, highlighting the flexible but robust nature of gabions (see Figure 3.105).

The shear strength of gabions also depends on the type of mesh, wire diameter, and type of stone used to fill the baskets and experience has suggested that gabions have a shearing resistance very similar to an equivalent soil with a relatively high friction angle (35–45°) and an apparent cohesion (up to 40 kPa) provided by the confining effect of the wire basket. Currently there is no standard for testing gabion shear strength.

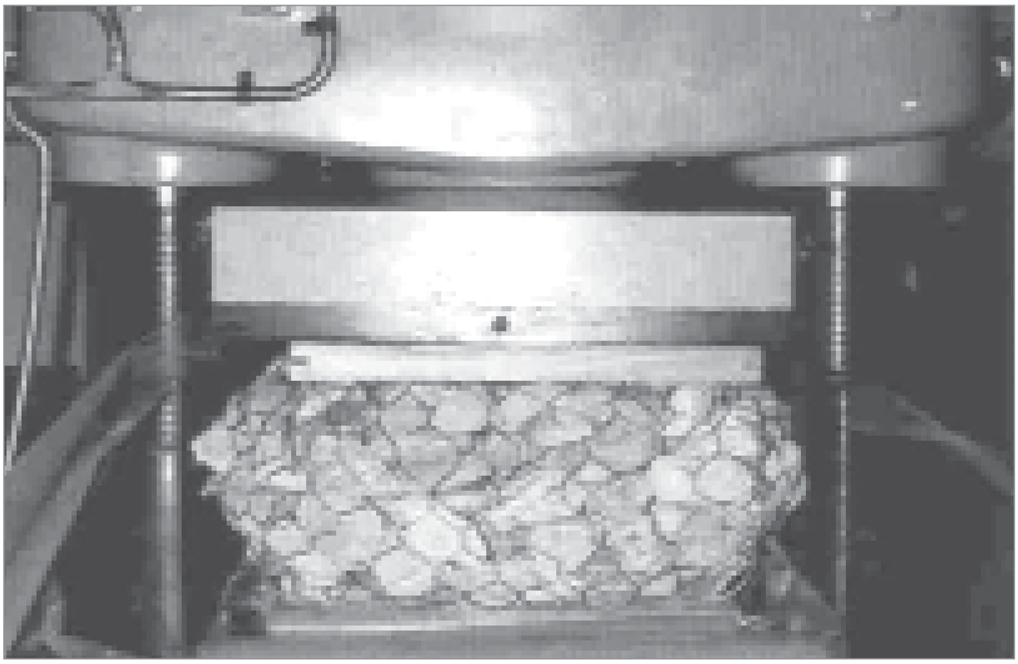

**Figure 3.105** *A compression strength test on a gabion, showing failure of the gabion*

### 3.14.3.2 Hydraulic properties of gabions

The response of gabions and gabion mattresses to hydraulic loading has been studied by a number of commercial and research organisations. For gabions under current attack, this research has led to critical and limiting flow velocities and design equations that take into account effects of turbulence. The critical velocity is defined in literature as the velocity required to initiate movement of the stones within the gabion mattress and the limiting velocity is the velocity at which the gabion mattress reaches the acceptable limit of deformation. For gabion mattresses under current attack it was found that mattresses with a thickness of 150 mm have a limiting velocity of 2–3.5 m/s, while mattresses with a thickness of 300 mm can resist velocities of 4–5.5 m/s. Box gabions can be suitable for the protection of river beds and banks subject to heavy current attack and can be stable at flow velocities of the order of 5–6 m/s (or more, depending on the quality of construction and assembly).

Section 5.2.3.1 presents two design equations, developed by Pilarczyk (1995) and Escarameia and May (1992) for gabions under current attack that take into account effects of turbulence.

For gabions under wave attack, design equations are presented in Section 5.2.2.7. These equations developed by Pilarczyk (1990, 1998) can be used to determine the required gabion thickness, $D'$ (m), and stone size of the filling material, $D_{n50}$ (m), for moderate wave conditions.

More information on hydraulic properties of gabions can also be found in Escarameia (1998).

## 3.14.4 Applications of gabions

Applications of gabions and gabion mattresses in fluvial applications are discussed in Chapter 8. Typically in these applications gabions will be exposed to currents and vessel-induced waves. Examples of gabion applications in rivers are shown in Figures 3.106 and 3.107.

**Figure 3.106** *Gabion riverbank protection*

**Figure 3.107** *Gabion protection to a river channel – the bank is exposed to current attack only under high flows during flood conditions*

In the marine environment, waves repeatedly strike the shore all year round and are much more aggressive than vessel-induced waves. Because of the aggressiveness of the marine environment arising from wave and salt action, the following precautions should be followed if gabions are to be used:

- gabions should not be exposed directly to sea waves (waves tend to make stones move within the gabions and the wire mesh can be eroded and cut). The solution is to place heavy armourstone as the primary defence to dissipate a large proportion of the wave energy (see Figure 3.108)
- in the event of exposure to sea waves, bituminous grouting may help prevent stone displacements in the gabions
- the most highly corrosion-resistant galvanisation process should be used, together with plastic coating.

**Figure 3.108** *Gabion baskets used as retaining wall behind primary armour*

## 3.15 GROUTED STONE MATERIALS

The stability of loose granular materials (gravel or crushed stone) or open blockwork elements in new or existing rock structures can be improved by grouting. The grouting binds smaller grains, stones and elements together. Stone or element sizes may therefore be reduced, making more economic use of available granular materials. The grouting can be executed with cement- or bitumen-based materials. Cement-based grouting, which is most commonly used in association with hand pitched stone, is discussed in Section 3.15.1, bitumen-based systems are discussed in Section 3.15.2.

### 3.15.1 Concrete grouts

The main cement-bound material that is used for stability improvement in hydraulic engineering is colloidal concrete grout. Concrete grout for stone pitching requires good flow behaviour and optimal resistance to segregation. This last factor is very important for underwater applications, particularly when exposed to currents and wave motion. Normal concrete is susceptible to segregation and washing out of fine aggregates in these situations. Colloidal concrete has been specially developed to meet this requirement.

The colloidal character of concrete grout is achieved by addition of modified natural polymers. The mix is optimised to meet specific requirements depending on the penetration depth and coarseness of the stone layer to be grouted, or the spacing between stone pitching. Colloidal concrete has good flow behaviour, although it is relatively stiff compared with normal concrete mixes. Because of the low workability and the desired density the optimal slump is usually 180–200 mm, although the water/cement ratio is relatively high because of the inclusion of special additives.

Two types of colloidal concrete are used: dense and open-textured. The dense variety is mostly used for grouting applications, while the open variety is also used in open layer revetment construction (where a thickness of at least 150 mm is required to ensure sufficient strength). The dense variety has a (system) density of 2200–2350 kg/m$^3$ and the permeability, $k$, is less than that of normal concrete. Open-textured colloidal concrete uses very little fine aggregate and has a (system) density of 1700–2000 kg/m$^3$. The penetration is limited and the permeability, $k$, is between $3 \times 10^{-3}$ and $5 \times 10^{-3}$ m/s. Grouting depths achievable with the open-textured variety are less than with the dense mortar.

Dense colloidal concrete is available in the same crushing and tensile strengths as normal concrete, but open colloidal concrete is only available in lower crushing strengths. The modulus of elasticity, $E$ (N/mm$^2$), of colloidal concrete is about 20 per cent lower than normal concrete and shrinkage is greater. The usual tests for normal concrete, such as slump, air content and density, are applicable to colloidal concrete, but a special test has been developed for resistance to washing out.

The stiffness (low workability) of colloidal concrete means that although it has the advantage of not segregating during transport, the potential for pumping of the dense variety is less than for normal concrete and the open variety cannot be pumped at all. Despite the colloidal character, special methods need to be introduced for underwater grouting, to avoid washing out of fines and to ensure accurate placing. Before application of the concrete, the stone to be grouted should be cleaned if there needs to be a good adherence between the grout and stones.

For a more extensive discussion of cement-bound materials reference is made to CUR Report 156 (CUR, 1992).

### 3.15.2 Bituminous bound materials

Asphalt mixtures are used extensively in hydraulic engineering, including as revetments to protect dikes, dams and groynes, as bottom or foreshore protection, as a water-sealing layer in canals, reservoirs and dams and as a core material in bunds. Some asphalt mixtures are used as a component for rock revetments, other mixtures are used directly as a revetment. The most commonly used asphalt mixtures are:

- asphaltic concrete
- asphalt mastic
- asphalt grout
- open stone asphalt
- lean sand asphalt.

In the following paragraphs a description is given of mixture-specific properties, the most commonly used compositions and uses by type of asphalt mixtures. More information can be found in the TAW *Technical report on the use of asphalt in water defences* (TAW, 2002).

#### *3.15.2.1 Asphaltic concrete*

Asphaltic concrete is a continuously graded mixture of crushed stone or gravel, sand and filler in which the pores (voids) are almost entirely filled with bitumen. The mixture usually consists of crushed stone or gravel (50 per cent), sand (42 per cent), filler (8 per cent) and bitumen (6.5 per cent).

The high stone content makes the mixture very stable and it is watertight and sandtight because of the small proportion of voids (3–6 per cent), resulting in a very durable material. Asphaltic concrete is therefore extremely suitable for use in revetments. It is preferably constructed in one layer (even when the required layer is very thick) and compacted mechanically. Asphaltic concrete is only applied above the high tide level.

After it has been applied, asphaltic concrete forms a rigid slab, which is particularly resistant to hydraulic loads such as wave impacts. Nevertheless, because of the high bitumen content, the slab is still flexible enough to be able to follow some settlement of the ground. An asphaltic concrete revetment is accessible to vehicles and pedestrians, for example tourists. It is common to apply a seal coat of bitumen emulsion and grit to increase durability.

### 3.15.2.2 *Asphalt mastic*

Asphalt mastic is a continuously graded mixture of sand and filler with an excess of bitumen. The mixture usually consists of sand (66.5 per cent), filler (16.5 per cent) and bitumen (17.0 per cent *in*). Due to the excess of bitumen, at the application temperature (100–190 °C) it is a pourable and dense mixture that is not compacted mechanically (indeed it cannot be compacted). After cooling, it is a stable, flexible and dense mixture, as a result of which it is particularly durable.

Asphalt mastic is used as a flexible bottom and toe protection (slab) and as a penetration material, both above and underwater. It is also used for grouting joints of stone pitching, as a repair agent and as a sealant.

### 3.15.2.3 *Asphalt grout*

Asphalt grout is a mixture of gravel and an excess of asphalt mastic. The mixture usually consists of gravel 4/16 (30 per cent) and asphalt mastic (70 per cent). The gravel serves as a filler to prevent sagging and segregation of the mixture and sometimes to limit the depth of penetration. The gravel also reduces the expensive bitumen content. The excess of asphalt mastic means that, at the application temperature (100–190 °C), it is a pourable and dense mixture that is not compacted (like asphalt mastic, it cannot be compacted). After cooling, it is a stable, flexible and dense mixture, and so is particularly durable.

Asphalt grout is primarily used as a penetration material for rock revetments (only above water) and also as a flexible bottom and toe protection (slab) and as a repair agent for damaged revetments. It is also extremely suitable for making temporary repairs to damaged rock revetments (even under extreme conditions).

Asphalt grouting can be applied in different ways (see Figure 3.109). With *full penetration* all the voids in the stone layer are filled with asphalt grout, while with *pattern penetration* the stone layer is partly penetrated following a set pattern. Pattern penetration can be done in strips or dots. TAW (2002) recommends not to use *surface penetration*, a method where the grouting is uniformly spread over the whole surface, as this may lead to a build-up of hydraulic pressures beneath the impermeable surface layer.

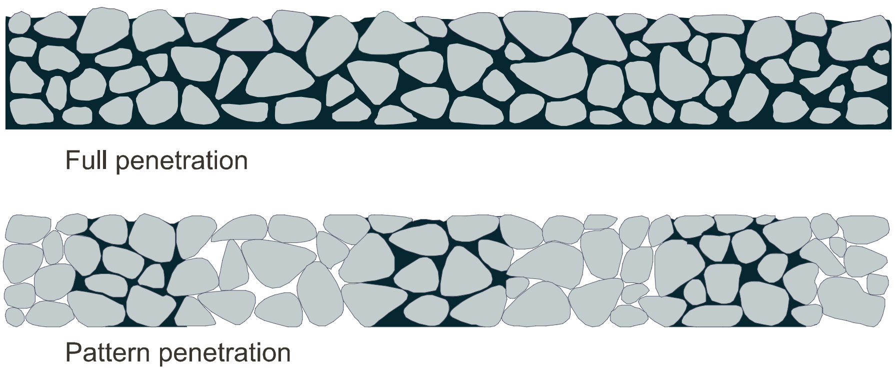


**Figure 3.109** *Grout penetration methods for a rock revetment*

In Section 5.2.2.7 design guidance is given for using asphalt grouting on slopes under wave attack.

### 3.15.2.4 *Open stone asphalt*

Open stone asphalt is a mixture of coarse and gap-graded crushed stone that is coated with asphalt mastic. The mixture usually consists of 80 per cent crushed stone and 20 per cent asphalt mastic. Because of the high crushed stone content, the asphalt has a large number of voids, making it permeable to both water and soil. A soil-tight filter (geotextile or lean sand asphalt) ought therefore to be placed below an open stone asphalt revetment. Open stone asphalt is used as a porous cover layer and its stability (resulting from the high stone content) means that it can be applied on steep slopes.

For open stone asphalt to be durable, the stone needs to be coated with a thick, bitumen-rich asphalt mastic. Materials that prevent sagging are sometimes added to the asphalt mastic, making it possible to apply a thicker cladding that does not drip off the stone. Open stone asphalt can also be applied as a prefabricated mattress.

Vegetation can develop easily on revetments made of open stone asphalt because the material has a high proportion of interconnecting pores. Animal organisms such as barnacles, mussels and oysters can also attach themselves easily to the material, which thereby can combine water defence with other functions such as the enhancement of nature and landscape.

#### 3.15.2.5 Lean sand asphalt

Lean sand asphalt (bituminous sand) is a mixture of sand and a small amount of bitumen. Usually sand extracted at the site is used, which is clad with 3–5 per cent bitumen. The small amount of bitumen barely fills the voids, so the material is very porous and water-permeable. The void rate of this very underfilled asphalt is 30–40 per cent.

The high sand content means that the stability of this material is comparable with the sand that has been used. However, this only applies if the load has a long duration; for loads of short duration, the bitumen makes lean sand asphalt far more stable than sand. Because of the open structure and the small amount of bitumen, lean sand asphalt is less durable than mixtures such as asphaltic concrete and asphalt grout. The bitumen coats the sand with an extremely thin layer and is therefore concentrated at the contact points.

Lean sand asphalt is used in bulk underwater and above water as a core material for bunds and breakwaters. Its lasting cohesion makes this an attractive material for use in a bund. It is also used as a filter layer and sometimes as a (temporary) revetment. In general, lean sand asphalt is not compacted; this is recommended only if it is used as a (temporary) revetment. Non-compacted lean sand asphalt has the same permeability as the sand from which it is made. Adding a filler to the mixture and compacting increases the durability of the material but reduces its permeability.

## 3.16 GEOTEXTILES AND GEOSYSTEMS

Geotextiles are often underestimated in their contribution to the stability of a hydraulic defence structure partly because their unit cost is so small compared with armourstone. The consequences of not designing and specifying them correctly can be disastrous and can jeopardise the stability of the whole structure. With proper specification and installation they can provide, in some instances, enormous savings to a project and increase the life of the structure significantly. Material specification is discussed in Section 3.16.5 and guidance on construction specification is given in Appendix A1.

Design information on geotextiles is presented in Section 5.4.3.6. Further details can be found in Pilarczyk (2000), Van Herpen (1995), Van Santvoort *et al* (1994), Koerner (1990) and PIANC (1987 and 1992). Reference is also made to the proceedings of the EuroGeo conferences and the proceedings of the International Conferences on Geosynthetics.

## 3.16.1 Functions of geotextiles

Geotextiles are permeable sheet materials commonly made from synthetic polymer-based materials. They are used in hydraulic engineering in conjunction with granular materials as an integral part of hydraulic structures. Geotextiles are part of a family of sheet materials known as geosynthetics that are used in many geotechnical applications. There are five main categories of geosynthetic – geotextiles (non-woven and woven), geogrids, geonets, geomembranes and related products such as erosion control mats and engineering cuspates (void spacers). There are many grades of each type and these basic types can be combined in many ways to form specially enhanced geocomposites. In some instances the materials can be formed into gabions or bags of different shapes. Geotextiles are generally supplied in roll form.

Geosynthetics perform five basic geotechnical functions:

- separation
- filtration
- transmission
- reinforcement
- protection.

The most common functions used in hydraulic engineering are:

- **filter/separators.** A geotextile is placed on lower permeability beach material to prevent the escape of fine particles while allowing the free passage of water. The geotextile provides a stable and consistent bedding layer, often saving the need for one of more layers of armourstone and potentially resulting in cost savings.
- **reinforcement**. Each geotextile has tensile properties and in some instances the reinforcing function is dominant when used either to reinforce the toe of a structure or to secure breakwaters placed on soft, low-load-bearing soils. The geotextile prevents deep-seated slips in the embankment and allows the embankment to be built without the need for removal or reconsolidation of the soft soil.

The most commonly used geosynthetics in hydraulic engineering are non-woven and woven geotextiles. These are delivered to site on thick cardboard tubes up to 6 m wide up to 200 m long and sheathed in a plastic, light-resistant sleeve to protect the material from sunlight while it is being stored before use.

## 3.16.2 Types of geotextile

### *3.16.2.1 Non-woven geotextiles*

Non-woven geotextiles are textile structures produced either mechanically (needle-punching) or by thermal bonding; see example in Figure 3.110. They can be categorised by the fibre types and bonding method used.

- **needle-punched staple fibre fabrics** are made from short (staple) fibres, which are carded (combed), layered into various thicknesses and then needle-punched to mechanically interlock the fibres into an even, thick fabric
- **needle-punched continuous-filament fabrics** are laid in an even pattern to form a sheet and then needled-punched. Needle-punched fabrics are usually made from polypropylene (PP), high-density polyethylene (HDPE) or polyester (PETP)
- **thermally bonded continuous-filament fabrics** are hot-extruded into even layers and are hot-rolled together, causing fibres to bond together by surface contact to form a sheet. They are made either from a mix of polymers, one having a lower melting point than the

other, or from sheathed fibres where the outer coating has the lower melting point. Typical polymers used are polypropylene (PP) or high-density polyethylene (HDPE).

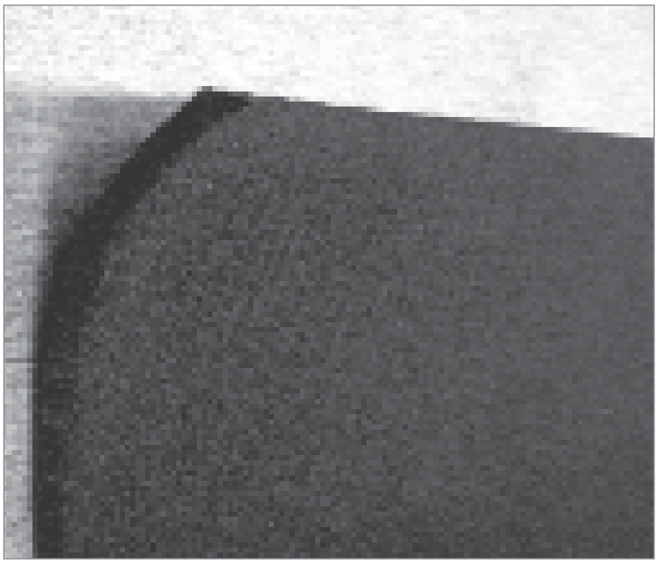

**Figure 3.110** *Non-woven geotextile (courtesy Geofabrics)*

#### 3.16.2.2 *Woven geotextiles*

Woven geotextiles are flat structures of at least two sets of threads woven at right angles; see Figure 3.111. The sets of threads are referred to as the warp running lengthwise and the weft running across. Woven geotextiles can be categorised by the type of thread and the tightness of the weave.

- **monofilament fabrics** are gauze meshes that offer small resistance to through-flow. The mesh size must be adapted to the grain size of the material to be retained. Monofilament fabrics are principally made from HDPE or PP
- **tape fabrics** are made form very long strips of stretched HDPE or PP film, which are laid untwisted and flat in the fabric. They are laid closely together, resulting in limited openings in the fabric
- **split-film fabrics** are made from fibrillated yarns of PP or HDPE. The size of the openings in the fabric depends on the thickness and form of the cross-section of the yarns and the fabric construction. Split-film fabrics are generally heavy. Tape and split-film fabrics are often called slit-films
- **multifilament fabrics** are often described as cloth because they tend to have a textile appearance and are twisted or untwisted multifilament yarns. These fabrics are usually made from polyamide (PA 6 or PA 6.6) or PETP.

These thread types can also be mixed to form other families of wovens.

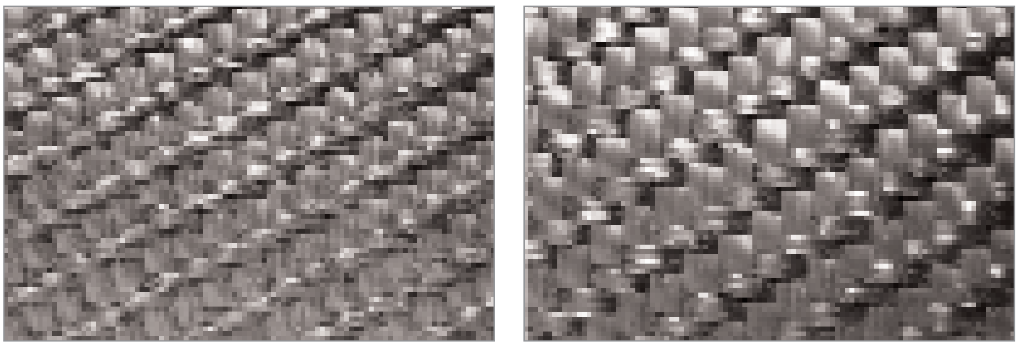

**Figure 3.111** *Non-woven geotextiles (courtesy Ten Cate)*

### 3.16.3 Geotextile properties and testing

Measurement of the various basic properties of geotextiles is carried out in the laboratory using specially designed tests to give the designer index values for comparison of one geotextile to another and to ensure consistency of product delivered to site. The European (CEN) and International Standards (ISO) committees have devised tests and the relevant tests should be used to define the properties required for the application in question. In Europe generic recommendations are given in the standard EN 13253:2001: *Geotextiles and geotextile related products: Characteristics required for use in erosion control works (coastal protection, bank revetments)*.

The relevant index tests should be used to ensure acceptable performance both from an in-service and an installation perspective.

For a filter/separator the following requirements should be considered in order of priority.

**Permeability**

Classic filter rules state that each layer of a filter system must be more permeable than the layer beneath (see Section 5.4.3.6). Similar rules developed for geotextiles suggest a coefficient of permeability 10 to 100 times greater than that of the filtered soil, especially in wave environments. It is important that the geotextile should maintain or exceed its index permeability while under load, ie any reorientation of the fines should not decrease permeability. When considering drainage elements such as in dams, filtration systems and slope protection in rivers where single directional flow is likely, the *permittivity* of the geotextile should be considered. The permittivity is the discharge perpendicular to the geotextile per unit pressure head difference and per unit area, expressed in units of 1/s. Blocking and clogging in single directional flow resulting from biological or chemical build-up (residues) can reduce the permittivity considerably. As a general rule, the correct geotextile is used where there is no significant pressure drop over the geotextile (taking into account possible blocking or clogging).

**Filtration**

The characteristic pore size of the geotextile has to be less than the average grain size of the soil to be filtered to prevent loss of material through the geotextile. Established design rules for reversing flow applications and for a typical geotextile state that the pore or opening size, $O_{90}$, of the geotextile should be less than the sieve size, $D_{50}$, of the soil to be filtered. There are variations for different geotextiles, however, so this should be checked against recommendations made in EN ISO 12956.

**Extensibility**

The load imposed on a geotextile by overlying armourstone is not evenly distributed. The highest stress concentrations will be at locations where the stones are in contact with the geotextile, which will impose high localised strains. The geotextile needs to have a high strain capacity to allow it to deform around the stones without rupturing and without loss of hydraulic properties. Although design drawings show the geotextile in a single plane, in reality it is forced to take up a highly deformed shape.

**Puncture resistance**

The geotextile must be able to withstand puncturing loads imposed both during installation and then during service. The mass, angularity and drop height of the armour stones being placed directly on the geotextile, together with the haste with which the contractor has to work in the short tidal windows available, all contribute to the puncturing load the geotextile will experience. Wave action causing movement of overlying armour stones may cause puncturing or wear of the geotextile while in service. Differential settlement in the subsoil may also locally increase strain on the fabric.

**Thickness**

Thickness is required to cushion penetrating loads under the angular points of the overlying rock and also to provide a lateral drainage path where the surface is occluded by the overlying armourstone. The lateral drainage capacity is defined by the geotextile's transmissivity under load.

**Durability**

Strength and puncture resistance reduce over time by oxidation and in some instances hydrolysis. Durability may be influenced by temperature, UV radiation, pollution in the water, air or soil.

The relevant index tests that most closely match these requirements are:

- **water flow normal to the plane** (EN ISO 11058) – closely linked to permeability. Water is passed through the geotextile under a constant head of water
- **pore size** (EN ISO 12956) – defines the opening size of a geotextile and its ability to trap particles and prevent their passage through the geotextile. The geotextile is clamped and measured sand particles are washed through the fabric and the percentage passing is calculated
- **minimum tensile extension** (EN ISO 10319) – defines the total extension or elongation at break in all directions allowing differential movement without break under the armour stones
- **tensile strength** (EN ISO 10319) – simulates the geotextile's ability to be handled on site using heavy excavators or equipment. The geotextile is clamped between two jaws and stretched until break and the tensile strength and elongation (above) is recorded
- **cone drop perforation** (EN 918) – simulates the dynamic impact of stones dropped on to the surface during installation. A metal cone is dropped on to a sample clamped in O-rings and the resultant hole is measured
- **static puncture test** (CBR) (EN ISO 12236) – simulates the biaxial strain of a rock attempting over time under heavy load to push through the fabric. A sample is clamped in O-rings and a plunger is pushed through it. Break strength and displacement are recorded
- **thickness** and thickness reduction under load – this simulates heavy localised compression of a thick geotextile that has been designed to retain some in-plane flow to relieve pore water pressures. Thickness is measured under loads of 2 kPa and 200 kPa.

Specification of geoxtiles in accordance with these test requirements is discussed in Section 3.16.5.

The ultimate test for a geotextile is a simulation of site conditions in either an on-site performance test or a trial installation. To prove the efficacy of the installation method the designer can specify a site damage test such as a rock drop test where a pad of geotextile is laid on prepared beach material and held taut by at least nine stones around its perimeter. A rock similar to those used in the revetment is dropped on to the surface from a maximum construction height likely, say 2 m, as a worst case and then the armourstone is carefully removed. There should be no damage holes occurring. This can be carried out at the site of the quarry which ever is easiest to set up simulation conditions.

1 2 3 4 5 6 7 8 9 10

Different characteristics are important where a geotextile is primarily used as reinforcement, for example as base reinforcement to the underside of a breakwater constructed on soft silts.

Where the geotextile is expected to be experience high load and prevent spreading or slip failure of the embankment, there is a requirement for high tensile strength with low extension. When a geotextile is subjected to high load over a period of time, especially in saline conditions, the long term creep (elongation over time under constant load) should be considered.

Most index tests are short-term, low-cost and repeatable and ensure consistency of product in production. Each manufacturer must have a recognised and independently audited quality control system. Tests relevant to the application should be carried out at agreed regular intervals on batches of geotextile. Certificates should then be produced to confirm consistency of the supplied product. The laboratory, either in house or external, should be regularly monitored by a recognised standards regulator. In addition, the designer should request samples taken from materials delivered to site for additional testing if required.

In most European countries, geotextiles are required to be CE marked for the application. This will, for example, certify the geotextile for “F” filtration applications and “R” reinforcing applications specifically for coastal and river applications. A CE mark certificate is supplied, which guarantees that the geotextile meets published values. Independent laboratories monitor testing carried out by any manufacturer with CE marked products.

To establish durability requirements there are a series of abrasion, UV resistance, oxidation and chemical immersion tests defined in EN and ISO standards, that should be selected based on the specific site conditions. One of the most common issues regarding durability is exposure to UV light and the designer is advised to specify a proven method of protecting the fibres, such as a certain percentage of carbon black in the fibres. Properties of the polymers used in the geotextile will depend on the immediate environment, in particular temperature and whether water is saline or polluted. Properties may also differ in the short and long term. Tests to prove the stability of geotextiles in the short and long term should be undertaken.

### 3.16.4 Construction issues

In addition to the general properties of the geotextile, special attention should be made to transitions including seams between geotextile elements, overlaps, transitions to other elements and connections to anchoring systems. Geotextiles are usually jointed with a hand-sewing machine using the *prayer* seam in a double line of durable thread. Overlaps should take account of subsoil movement, placement methods and visibility.

Careful consideration should also be given to the placement method for the geotextile. Geotextiles can be placed in the structure separately from the other materials. This can be quite complicated, however, if done underwater, especially with waves and currents. Therefore, in some cases the geotextile may be connected to other materials or prefabricated elements which can be placed more easily, for example:

- enclosing sand in a large sandbag (geocontainer or geotube) or other geosystem
- connection to mattresses of other materials such as wooden fascines, concrete blocks, steel or (open) asphalt, gabions (*Reno* mattresses).

Further discussion on construction issues for geotextiles is given in Section 9.7.1. Appendix 1 covers specification requirements for the installation of geotextiles. There is significant specialist experience in design and construction techniques. Many manufacturers and specialist installers have developed and published techniques that aid the performance and installation of geotextiles in the hydraulic environment.

### 3.16.5 Geotextile specification

Geotextile filter fabric should be an approved proprietary geotextile. The common material property parameters that need to be specified are form (woven or non-woven), type of polymer, weight, thickness, tensile strength, CBR puncture resistance, pore size, $O_{90}$ (mm), and permeability (see Section 3.16.3). Tables 3.54 and 3.55 provide material specification templates for non-woven and woven geotextiles respectively. The typical values should be inserted for the specific application in question. Design guidance is given in Section 5.4.3.6. Detailed design guidance for geotextiles is given in BAW (1993).

The following clauses may typically be used to specify the properties of the geotextile material:

**Non-woven geotextile, for example as a filter/separator beneath rock armour**

The geotextile shall be a non-woven fabric manufactured by needle-punching virgin, staple fibres of polypropylene incorporating a minimum of 1 per cent by mass of active carbon black. Geotextiles manufactured from fibres of more than one polymer will not be permitted.

The geotextile shall have the properties as given in Table 3.54.

**Table 3.54** *Specification template for a non-woven geotextile*

| Test description | Approved test method | Unit | Typical value (see note) | Allowable tolerance for typical value |
|---|---|---|---|---|
| Water flow normal to the plane of the geotextile @ 50 mm head | EN ISO 11058 | $l/s/m^2$ | ……… | -10% |
| Coefficient of permeability | EN ISO 11058 | m/s | ……… | -10% |
| Apparent pore size – 90% finer, $O_{90}$ | EN ISO 12956 | mm | ……… | +10% |
| Tensile extension | EN ISO 10319 | % | ……… | -10% |
| Tensile strength | EN ISO 10319 | kN/m | ……… | -10% |
| Cone drop perforation hole diameter | EN 918 | mm | ……… | – |
| Static puncture strength, *CBR* | EN ISO 12236 | kN | ……… | -10% |
| Push-through displacement | EN ISO 12236 | mm | ……… | -10% |
| Thickness reduction for pressure increase from 2 kPa to 200 kPa | EN 964 | % | ……… | +10% |
| Thickness @ 2 kPa | EN ISO 964-1 | mm | ……… | -10% |

**Note**

Typical values to be inserted for specific application.

**Reinforcing geotextile used beneath bedding stone for reinforced toe**

The geotextile to be used as a reinforcement beneath the bedding stone as a reinforced toe structure shall be a woven fabric manufactured using virgin, high-tenacity fibrillated yarns of polypropylene incorporating a minimum of 1 per cent by mass of active carbon black. Geotextiles manufactured from fibres of more than one polymer will not be permitted.

The geotextile shall have the properties as given in Table 3.55.

**Table 3.55** *Specification of a woven geotextile*

| Test description | Approved test method | Unit | Typical value (see note) | Allowable tolerance for typical value |
|---|---|---|---|---|
| Tensile strength | EN ISO 10319 | kN/m | ......... | -5% |
| Tensile extension | EN ISO 10319 | % | ......... | +5% |
| Creep over 10 000 hours of testing | EN ISO 13431 | % | ......... | +1% |
| Apparent pore size – 90% finer, $O_{90}$ | EN ISO 12956 | mm | ......... | +10% |
| Water flow normal to the plane of the geotextile @50 mm head | EN ISO 11058 | l/s/m² | ......... | -10% |
| Static puncture strength, *CBR* | EN ISO 12236 | kN | ......... | 5% |
| Push-through displacement | EN ISO 12236 | mm | ......... | +5% |
| Thickness @2 kPa | EN ISO 964-1 | mm | ......... | -5% |

**Note**

Typical values to be inserted for specific application.

In addition to the minimum characteristics given in Tables 3.54 and 3.55, the Contractor should ensure that the geotextile (woven or non-woven) is sufficiently robust to withstand, without being damaged, the working method of placing the geotextile and the subsequent placing of the rock layer on top.

Samples of the proposed geotextile, typically of minimum size 300 mm × 300 mm, should be submitted for approval together with a material property data sheet. The data sheet should be supported by an index and performance compliance certificate issued by an accredited geotextile filter fabric testing organisation, eg the German Bundesanstalt für Wasserbau (BAW).

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## 3.17.2 Standards

### 3.17.2.1 *ASTM*

ASTM A975-97 (2003) *Standard specification for double-twisted hexagonal mesh gabions and revet mattresses (metallic-coated steel wire or metallic-coated steel wire with poly(vinyl chloride) (PVC) coating)*

ASTM C88-99a *Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate [superseded]*

ASTM D3967-95a (2004) *Standard test method for splitting tensile strength of intact rock core specimens*

ASTM D4992-94 (2001) *Standard practice for evaluation of rock to be used for erosion control*

ASTM D5313-04 *Standard test method for evaluation of durability of rock for erosion control under wetting and drying conditions*

ASTM D5779-95a (2001) *Standard test method for field determination of apparent specific gravity of rock and manmade materials for erosion control*

ASTM D6092-97 (2003) *Standard practice for specifying standard sizes of stone for erosion control*

ASTM D6711-01 *Standard practice for specifying rock to fill gabions, revet mattresses, and gabion mattresses*

### 3.17.2.2 *British standards*

BS 5930:1999 *Code of practice for site investigation*

### 3.17.2.3 *Euronorms*

EN 206-1:2000 *Concrete. Specification, performance, production and conformity*

EN 918:1998 *Geotextiles and geotextile-related products. Dynamic perforation test (cone drop test)*

EN 932-3:1997 *Tests for general properties of aggregates. Procedure and terminology for simplified petrographic description* (AMD 14865)

EN 933-9:1999 *Tests for geometrical properties of aggregates. Assessment of fines, methylene blue test*

EN 1097-1:1996 *Tests for mechanical and physical properties of aggregates. Determination of the resistance to wear* (Micro-Deval) (AMD 14864)

EN 1097-2:1998 *Tests for mechanical and physical properties of aggregates. Methods for the determination of resistance to fragmentation*

EN 1097-6:2000 *Tests for mechanical and physical properties of aggregates. Determination of particle density and water absorption* (AMD Corrigendum 14306)

EN 1367-2:1998 *Tests for thermal and weathering properties of aggregates. Magnesium sulfate test*

EN 1744-1:1998 *Tests for chemical properties of aggregates. Chemical analysis*

EN 1744-3:2002 *Tests for chemical properties of aggregates. Preparation of eluates by leaching of aggregates*

EN 1926:1999 *Natural stone test methods. Determination of compressive strength*

EN 1936:1999 *Natural stone test methods. Determination of real density and apparent density and of total and open porosity*

EN 10218-2:1997 *Steel wire and wire products. General. Wire dimensions and tolerances*

EN 10223-3:1998 *Steel wire and wire products for fences. Hexagonal steel wire netting for engineering purposes*

EN 10244-1:2001 *Steel wire and wire products. Non-ferrous metallic coatings on steel wire. General principles*

EN 10244-2:2001 *Steel wire and wire products. Non-ferrous metallic coatings on steel wire. Zinc or zinc alloy coatings*

EN 10245-1:2001 *Steel wire and wire products. Organic coatings on steel wire. General rules*

EN 10245-2:2001 *Steel wire and wire products. Organic coatings on steel wire. PVC finished wire*

EN 10245-3:2001 *Steel wire and wire products. Organic coatings on steel wire. PE coated wire*

EN 12390-6:2002 *Testing hardened concrete. Tensile splitting strength of test specimens*

EN 12620:2002 *Aggregates for concrete*

EN 13253:2001 *Geotextiles and geotextile-related products. Characteristics required for use in erosion control works (coastal protection, bank revetments)*

EN 13383-1:2002 *Armourstone. Specification*

EN 13383-2:2002 *Armourstone. Test methods*

EN 13450:2002 *Aggregates for railway ballast*

EN 14579:2004 *Natural stone test methods. Determination of sound speed propagation*

EN ISO 10319:1996 *Geotextiles. Wide-width tensile test*

EN ISO 11058:1999 *Geotextiles and geotextile-related products. Determination of water permeability characteristics normal to the plane, without load*

EN ISO 12236:1996 *Geotextiles and geotextile-related products. Static puncture test (CBR-Test)*

EN ISO 12956:1999 *Geotextiles and geotextile-related products. Determination of the characteristic opening size*

ENV 12920:1998. *Methodology for the determination of the leaching behaviour of waste under specified conditions*

### 3.17.2.4 French standards

NF P 94-325-1 (2004) *Exécution des travaux géotechniques spéciaux – Ouvrages en gabions – Partie 1: ouvrages hors site aquatique*

P 18-011 (1992). *Bétons – Classification des environnements agressifs*

### 3.17.2.5 ISO

ISO 3310-2:1999 *Test sieves. Technical requirements and testing. Test sieves of perforated metal plate*

ISO 9000:2000 *Quality management systems – Fundamentals and vocabulary*

### 3.17.2.6 EC Directive

Council of the European Communities, 1991. Council Directive 91/689/EEC of 12 December 1991 on hazardous waste. Official Journal L 377 , 31/12/1991 pp 20–27