Guide to the Selection & Testing of Stone Panels for External Use

CENTRE FOR
WINDOW AND
CLADDING
TECHNOLOGY

This document was written and revised by representative members of the Centre for Window & Cladding Technology. The document was reviewed by members of the CWCT.

Centre for Window & Cladding Technology
October 1997

ISBN 1 874003 09 2

Published by
Centre for Window & Cladding Technology, University of Bath, Claverton Down, Bath BA2 7AY

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1st edition

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'A Guide to the Selection and Testing of Stone Panels for External Use' is written as a guidance document giving recommendations as to best current practice. In drafting this document it has been assumed that the guidance will be applied intelligently, that design and selection will be undertaken by appropriately qualified and experienced professionals, and that the testing will be carried out by appropriate accredited laboratories.

FOREWORD

This document has been prepared under the direction of the Natural Stone Working Group of the CWCT for the use of stone cladding panels as part of a rainscreen or curtain wall design. It reviews current standards relative to the use of natural stone in buildings, focusing on the guidance for stone selection and the required testing regime.

At present the stone industry and specifiers appear to be in some confusion as to the necessity of stone testing and selection of appropriate tests for fitness of purpose. The current position needs to match changes in the global market and this will not be solely a matter of choice as harmonised standards from the European Commission will require stone to conform to a variety of tests and specifications, some of which will be mandatory.

Technological changes and increased knowledge amongst structural engineering consultants have led to thin stone cladding becoming wide-spread for large buildings. Current guidance within BS 8298 gives sufficient design and installation procedures for mechanically-fixed facing units of natural stone for panel sizes dependent on joint and fixing arrangement up to 900mm x 600mm of specific thickness. Larger panel sizes may be used if proven by structural calculation and testing. However, it is for these larger panels, or where durability of the stone is questionable because of adverse environmental conditions or lack of available data, that the testing and selection procedure within this guidance document may be followed, as the British Standard only gives limited guidance on the required testing regime.

This document addresses the issues construction professionals are faced with when considering natural stone as an external cladding material. Specific guidance has been developed through a series of preliminary and production tests to ensure that the selected stone meets the required aesthetic, durability and strength requirements. The principal aim of the testing regime is not to prove the strength of the stone, rather to establish its weakness to ensure that the stone is not over-stressed during its design life.

The testing regime is not representative for ultra-thin stone panels forming a composite panel structure or for traditional hand set cladding in the form of stone masonry as a facade to an existing wall. No guidance is given for the design and selection of fixings, the design of joints between stone panels or the integration of the cladding system with the building.

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1 STONE SELECTION

1.1 Introduction

In recent years natural stone materials have experienced a marked revival in use, most obviously as external cladding to steel or concrete framed structures. The Broadgate and Canary Wharf developments in London are notable examples of such construction. One of the reasons for this renaissance in the use of stone has been the improved cutting technology used by stone processing companies which allows stones to be cut into thin panels, making it both affordable and relatively light-weight. Another reason is the ease with which stone is available from around the world.

Against this background there is a growing requirement from construction professionals for an increased understanding of the physical, mechanical and durability properties of any stone proposed for use in building facades. In addition to construction professionals, reassurance about the fitness for purpose of the stone is frequently being sought by building owners and tenants of large office buildings who will find themselves responsible for the maintenance of the cladding for perhaps a twenty-five year period. Under such circumstances questions concerned with the strength and durability of the stone are no longer an academic consideration but one with serious commercial implications.

The cladding system developed for a specific project depends upon a combination of economic, structural and architectural factors. This interaction clearly indicates that close co-operation between the client, architect, engineer and manufacturer are necessary at an early stage of the design process.

The construction professionals involved in the design of the facade must take account of the height and size of the building, environmental conditions, appearance and building design life before considering the selection of the stone. This will affect the choice of stone and also the method of fixing to the primary frame and of forming and sealing the joints.

1.2 Lead times for stone selection

It is important that technical and planning considerations should be given to the stone selection process so that it does not inhibit the building programme. The required lead-in time for testing may vary depending on the engineers knowledge of the proposed stone's characteristic strengths and weaknesses. However, because of the inherent complexities of natural stone it is often necessary to test the stone for project specific applications. As a guide Table 1.1 sets out the minimum time scale required to conduct the preliminary tests, including sample preparation.

The preliminary testing should be carried out at least three to six months before the stone is to be installed on site, allowing sufficient time for further selection and testing of an alternative stone or modification of the stone specification if the initial stone is found to be below the specified minimum requirements. All the preliminary tests should run concurrently to check that the strength and durability test data do not vary greatly from the expected values based on historic data or previous experience. If the preliminary results indicate the stone to have sufficient strength and durability for its purpose, only at this stage would it be appropriate to test the long term behaviour of the stone via the freeze-thaw and thermal stability tests. These durability tests are laboratory based tests used to give an indication of the long term performance of the stone. However, a true representation, and one that has an advantage over laboratory tests, would include an inspection of various buildings which have been constructed using the same stone and exposed to similar environmental conditions. Inspection may not be possible for some of the more 'exotic' stones that have not been previously used in the UK, but where applicable will act as a good indicator of the performance of the stone in the long term.

Type of test	Estimation of duration
Petrographic description	2-3 weeks
Water absorption	1 week
Porosity	1 week
Saturation coefficient	1 week
Compressive strength	1 week
Modulus of rupture	1 week
Flexural strength	1 week
Acid immersion	3 weeks
Salt crystallisation	3-4 weeks
Freeze-thaw	4 weeks
Wetting/drying	3 weeks
Thermal stability	10 weeks

Table 1.1 *Test times for preliminary stone testing*

Production testing should be used as part of an on-going quality check of the quarried stone. Current good practice is to number each quarried block as it is extracted with a number that it retains throughout the quarrying, testing and cutting process. Each stone block should be stored at the quarry in the orientation that it was extracted to enable the production testing to be conducted systematically. Section 5.6 sets out an appropriate methodology as part of an ongoing quality check where water absorption and density are used as early indicators of a stones possible weaknesses. If there is a discrepancy between the production and the preliminary results it is at the discretion of the engineer to conduct further testing of adjacent blocks of stone to find the extent of the weakness through the quarried stone and if appropriate modify the specification accordingly before further production of the stone commences. As production tests continue a stock-pile of the stone will be cut, shaped and collated ready for transportation to site. This procurement route will limit the potential for substandard stones being transported to site with the possibility of the panels failing prematurely.

1.3 Design of fixings and joints

Selection of a particular stone will depend on the method of fixing and fixing spacing. These cannot be finally designed until the stone has been selected; however, a preliminary fixing design is required before the stone can be selected. This document is concerned with the selection, testing and appraisal of strength of natural stone beyond that which is set in BS 8298.

The final design of fixings needs to be considered once the panel size, thickness and finish have been tested for durability and strength in the orientation that they are designed to be used. The stages in selecting an appropriate fixing should be considered in the order of type, size and material corrosion protection. Guidance is currently available on performance of fixings in the form of manufacturers literature, BS 8298 and assessment of the performance of fixings within the guidance documents from the Construction Fixings Association (CFA). However, little guidance is available specifically for the application of thin stone cladding in the form of rainscreen or curtain wall designs.

Jointing between the individual stones will depend on the type of stone selected and method of fixing. Joints may be sealed, or left open as in a rainscreen, in which case they may or may not contain a baffle. Further information on the performance of rainscreens is given in *Walls with Ventilated Rainscreens* (CWCT, to be published).

The form of joint selected may affect the overall appearance of the wall and may be decided at an early stage. However, final joint design can not be finalised until a stone has been selected. For instance, sealants have to be compatible with the stone and porous stones may be susceptible to staining from the sealant. Appropriate tests for assessing the susceptibility of the stone to staining can be carried out in accordance with ASTM C1248 or ASTM D2203 depending on the stone type. The results from these tests may in fact preclude the use of such stones.

The selection of stone thus has to proceed in parallel with the design of fixings and joints; Figure 1.1 highlights the implications a change in design may have on the other component parts of the facade. The associated implications of the changes must also be considered under the Construction (Design and Management) Regulations 1994 (HSC 1995) by all parties involved in the design/construction process, which are used to provide a mechanism to ensure that the health, welfare and safety of all those involved during construction is managed through all the stages of development.

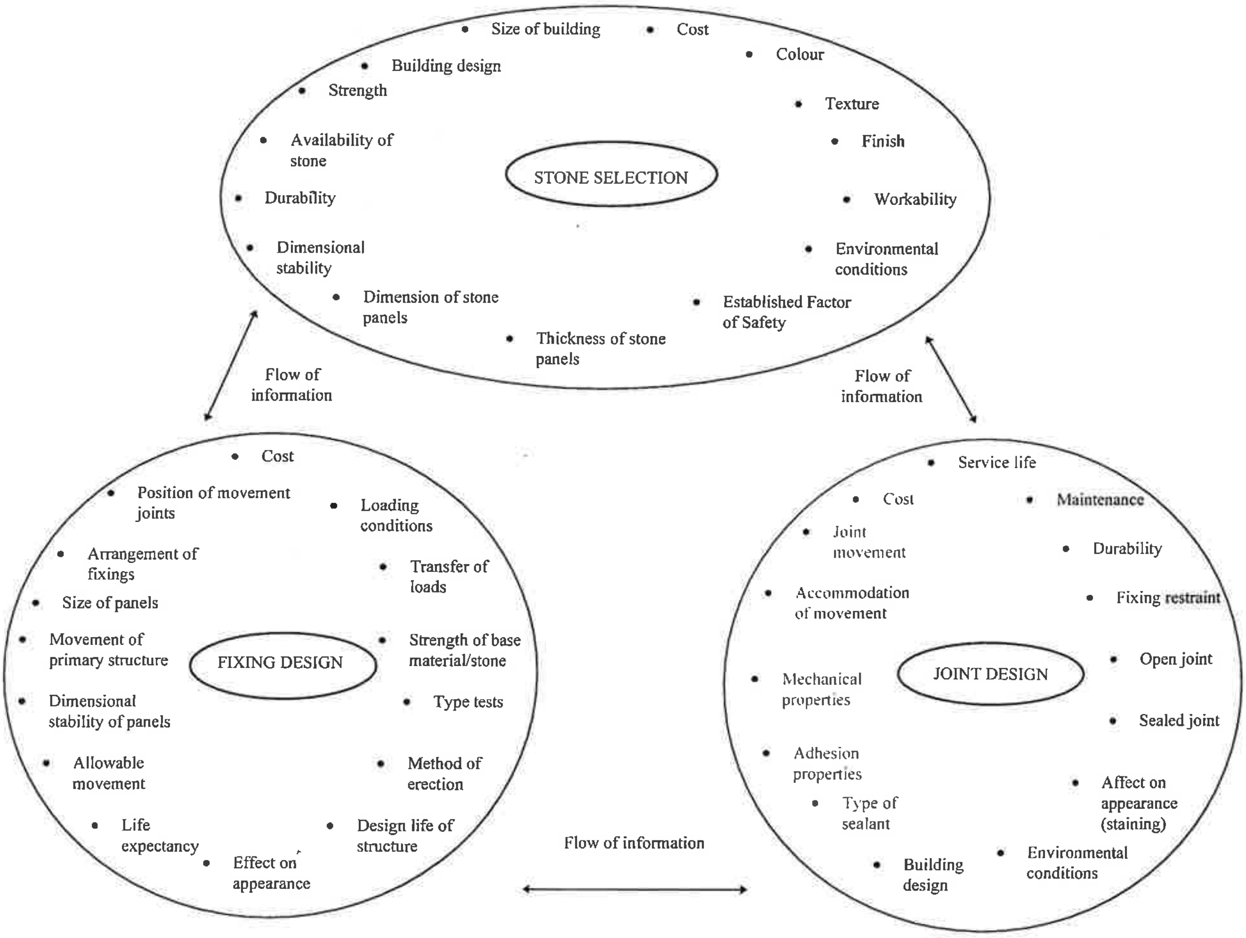


Figure 1.1 *Relationship between stone/fixings/joints*

1.4 Factors specific to the stone

In contrast to the tradition where buildings were built from locally available materials, a typical modern office block may use a combination of granites from Scandinavia and South America for the cladding with flooring materials from Italy or Greece. These materials would probably have been cut and processed in Italy before delivery to the UK. Although some of these materials may have a record of use in the UK many may be 'exotic' with no record of adequate performance in service in the environmental conditions of the UK.

1.4.1 Stone selection

The decision to use stone for cladding purposes is governed by the desire to provide a solution for the life span of the building. Factors leading to the choice of the stone are:

Architectural expression

Cost

Availability

Durability

Strength

Dimensional stability

Relation to support and joint type

The selection of stone is only a single part of the design process of a facade but has large implications for the joints and fixings which have to be designed to accommodate all movements of the stone panels, to resist cracking. The stone selection procedure can be divided into two parts, namely preliminary selection and testing as shown in Figure 1.2.

1.4.1.1 Preliminary selection

Stone selection at the outset may appear to be an involved process; Figure 1.2 goes some way to try and summarise the necessary procedures an architect or specifier should consider when selecting natural stone. The preliminary choice of a stone is dependent upon cost, availability, colour, surface finish and workability. It is also important to check at the preliminary selection stage that the maximum panel size determined by the cladding layout and proposed fixing assembly will not exceed what can be processed from the quarried blocks.

It is necessary that close collaboration between the construction professionals and stone producers takes place during the preliminary selection procedure to avoid testing stone that is visually correct but structurally weak in the orientation that it is to be used on the building.

In the case of sedimentary rocks (e.g. limestone) the size of the stone panels is limited by the depth of the bedding layer. It is also a prerequisite that this type of stone should be orientated such that the stone is used in the natural bedding plane. An igneous or metamorphic rock is not restricted by the presence of bedding layers but is controlled by the presence of natural joints within the rock.

The process of communication between the construction professionals should answer the list of questions below before considering any stone for testing:

Does the chosen stone have the required design strength?

Is the desired surface finish achievable?

What is the most suitable thickness of the stone for use?

Can the size of stones for cladding panels be cut from the quarried blocks?

Can the quarry guarantee the quantity and quality of the material?

Can the quarry guarantee the delivery time for the project?

Durability and strength data on the stone should be gathered either from the quarries or by viewing similar stone facades. Stone is a natural material liable to variation in strength within a single bed. In some quarries these beds are sufficiently regular in character for selection to present no difficulty. In other quarries the variations are such that individual blocks from which the units are cut will need to be considered on their merits. Taking this into consideration, it is important while planning the selection and testing programme to take account of the time-scale involved so as not to delay construction.

1.4.1.2 Testing

Testing will be carried out on selected stone(s) to determine their suitability as an engineering material. The design criteria within BS 8298 cover stone cladding slabs up to 700 x 1000mm of specific thickness; however, panels limited to 900 x 600mm of specific thickness do not require additional testing. Panels outside this size or where durability is considered an issue because of the thickness of the panel or surface finish, BS 8298 requires panels to be selected by test and calculation. The selection and testing procedure specified within this document gives a full representative test regime to follow for selection of such panels. During the testing procedure it may become apparent that a stone has a more than adequate strength and large factors of safety can easily be assumed within the design. Alternatively a stone may be loaded almost to its full strength for the design to work. However, one can design to accommodate the strength or weathering qualities of a stone rather than discard a stone that does not seem suitable at first. This can be achieved by either consistent use of smaller panels, thicker panels, improved support conditions or a combination of these factors.

Where strengths have to be accurately known because low factors of safety are required to make the design feasible, or where limited data is available for the selected stone(s) then a more extensive test programme may be required. Conversely a modified test regime involving fewer tests may be more appropriate for a stone that is not stressed so close to the point of failure or where strength and durability characteristics are well documented.

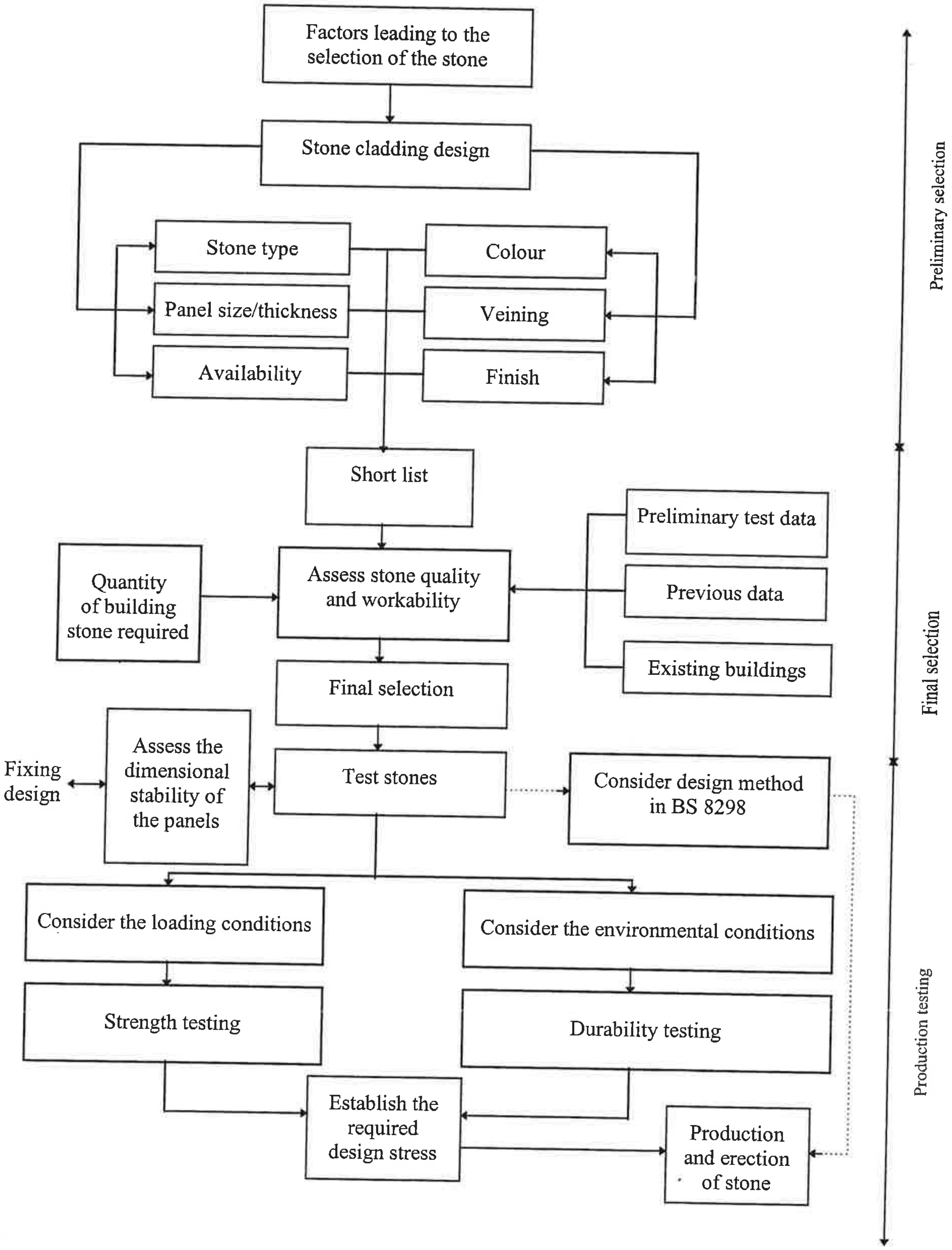


Figure 1.2 *Stone cladding procurement*

2 DURABILITY OF STONE FOR CONSTRUCTION

2.1 Introduction

All natural stones weather and change with time. The rate of weathering and the form it takes are controlled by the characteristics of the stone and the severity of the environment that it is to be placed in. In order to provide reassurance to the construction professionals testing of such materials is a fundamental requirement, particularly with 'exotic' foreign materials. However, it is also a natural progression to assume that UK materials should not be treated any differently. Although such materials may have a known service record, stone is accepted as being a naturally variable material and sufficient examples of stone failures in the UK are known for the testing requirement to be extended to all stone proposed for use in buildings no matter what its origin.

2.2 Current guidance

2.2.1 British Standards

A number of British Standard Codes of Practice include some coverage of the use of natural stone although these include little guidance of any value in respect of the properties of the stone materials themselves.

BS 8298 includes recommendations for the design, installation and maintenance of mechanically fixed stone cladding. However, the Code of Practice is unable to make reference to other British Standards for test methods or quality specifications. The generalised recommendations in respect of stone quality could lead to misinterpretation, for instance:

> 'The stone to be used should not normally be affected by frost. Alternatively suitable measures should be taken to provide reasonable protection. With certain stones, including the softer limestones, the use of thin open jointed construction is not recommended. With these stones the use of lead flashing on cornice, string or other projecting courses is recommended to avoid saturation on horizontal surfaces and subsequent frost damage'.
>
> 'It is essential that the stone selected is sound, durable and of proven suitability for relatively thin cladding on external faces. Care should be taken to ensure as far as possible freedom from vents, cracks, large fissures, sand and clay holes and other defects likely to affect durability'.

In contrast with other construction materials, such as steel, concrete or asphalt, there are few British Standard tests for natural stone, nor standard specifications defining minimum quality requirements. Those which do exist are concerned with the more traditional uses of stone such as slate roofing (BS 680), slate sills and copings (BS 5628) and stone kerbs and setts (BS 435), rather than with cladding.

2.2.2 Other authoritative guidance

The Building Research Establishment (BRE) has long been a source of information on the use and properties of stone, one of its most notable early works being the study of weathering by Shaffer published in 1932 and reprinted in 1972. More recent works include BRE Digest 269 (1983), by Ross and Butlin, and BRE Report 141 (1989) which considered certain durability tests for stone and went some way towards providing at least outline guidance on durability testing. The test methods recommended are mainly for use on limestone, sandstone or slate and do not help with the evaluation of the many granite, marble and other stone varieties which are available.

In the USA the American Society for Testing and Materials (ASTM) publishes national standards for the testing of a variety of materials including stone for use in construction. A range of test methods is given by ASTM along with a complementary series of standard specifications covering the main groups of building stones (slate, granite, limestone, marble and sandstone). In the absence of other guidance these standards are used extensively on an international basis. ASTM, however, does not include any procedures to assist in the direct assessment of durability apart from methods for roofing slate.

Various Standards have been produced by certain European countries, for example the German standard for freeze-thaw testing given in DIN 52 104. In France there are also various tests for the assessment of limestone durability.

For the future, harmonised standards for the European Union are being produced by CEN (Comité Européen de Normalisation); these European Standards will be known as ENs and include test methods and specifications. These Standards should also describe when and how products are to be tested.

2.3 Testing for durability

2.3.1 General

With regard to durability it is important to realise that once worked and used as a building material any stone will be liable to change in appearance and undergo at least some decay as a consequence of weathering. The important question to be answered will be 'is the degree of weathering acceptable'. For example, where a weathered granite is used in a more traditional form of construction the loss of some 20 mm of material from the face of the stone may be acceptable, but where such a stone is used as a 32 mm thick cladding such decay would be disastrous. In addition the design life of the cladding may vary and a supermarket may require a shorter design life than a cathedral. The concept of weathering has to be put into the context of the end use of the stone.

Unfortunately there are many different tests, each attempting to measure durability by measuring different stone properties. Some of the tests, such as the salt crystallisation test, will not reproduce the environment in which the stone is expected to perform but rather accelerate the effects of isolated aspects of the natural stone environment. Such effects include, for example:

- Dissolution of calcium carbonate in limestones and calcareous rocks by acidic rain water
- Damage caused by repeated freezing and thawing of water in certain weak stones
- Damage caused by repeated expansion and contraction of clay minerals in certain rocks caused by cyclic wetting and drying
- Cracking and bending induced by thermal changes of particular minerals in certain stones, notably marble
- Damage caused by the crystallisation of salts within some porous stones.

Considering the available knowledge from other published works and foreign standards a suggested regime of durability tests is given in Table 2.1.

	Igneous	Sedimentary		Metamorphic	
Type of test/ Method	**Granite**	**Limestone**	**Sandstone**	**Marble**	**Slate**
Petrographic description (ASTM C295)	✔	✔	✔	✔	✔
Water absorption (ASTM C295)	✔	✔	✔	✔	✔
Porosity (Ross & Butlin 1989)		✔	✔		
Saturation coefficient (Ross & Butlin 1989)		✔	✔		
Acid immersion (Ross & Butlin 1989)			✔		✔
Salt crystallisation (Ross & Butlin 1989)		✔	✔		
Freeze Thaw (DIN 52104)		✔	✔		✔
Wetting/drying (BS 680)					✔
Thermal Stability (Ad hoc)				✔	

Table 2.1 *Durability tests for various rock types*

2.3.2 Petrographic examination

A petrographic examination may range in scope from a simple description of a hand held specimen to a comprehensive microscopic description based on the examination of thin sections. There is no specific British Standard for the examination of building stone although specifications for the description of rocks in general do exist, for example BS 5930, which deals with rock descriptions in site investigation and BS 812: Part 104, which deals with the examination of aggregates. Other standards include the American ASTM C 295 and the Italian UNI 9724.

The basic requirement described in the Code of Practice BS 8298, that the stone should exhibit 'freedom from vents, cracks, large fissures, sand and clay holes and other defects likely to affect durability' could be largely assessed macroscopically. However, the examination of a stone using thin-sections is an additional and very valuable technique for the evaluation and classification of a stone in general and a starting point for the assessment of durability in particular. The following attributes of a stone can be determined by petrographic techniques:

- The presence of potentially unstable constituents such as clay-like minerals which may undergo volume change on wetting and drying;

- The presence of iron bearing minerals which may be prone to oxidation and cause discolouration;

- The determination of potentially frost susceptible stones, for example oolitic limestones with particularly fine grained minerals;

- Microbrecciated (fractured) rocks or the presence of particularly weak veins or seams within rocks.

A proper petrographic examination of a proposed building stone is therefore a starting point for the evaluation of the stone in general, not just for its durability, and it may dictate which other tests will be relevant. Obviously the petrographic description will only be specific to a certain bed and a separate description would be required for each specific location during the preliminary selection stage and production testing.

2.3.3 Water absorption, porosity and saturation coefficient

There are various methods currently in use for the measurement of water absorption, but only one method is a British Standard, BS 680, which is specifically for roofing slates. Most water absorption testing of building stones currently undertaken in the UK uses ASTM C 97, which involves soaking the samples in water at room temperature (a similar method is also given by Ross and Butlin (1989)). Details of the measurement of porosity and saturation coefficient are also given by Ross and Butlin (1989).

Stones which exhibit low water absorption or porosity values are generally found to be more durable. Water, which may be one of the main agents of weathering (either by freezing or thawing in the pores of a stone or by the transportation and deposition of soluble salts) will be less able to penetrate non-porous stone types, and therefore less able to cause damage.

When considering durability the vulnerability of porous building stones such as limestone and sandstones is more dependent on pore size and distribution than upon the absolute pore volume. The BRE has used the concept of saturation coefficients (also known as Hirschwald's Coefficient), which is the ratio of the water absorption to total pore volume. Porous stones with a saturation coefficient of more than 0.8 (1 is the maximum possible) are believed to be more susceptible to frost damage. The saturation coefficient can be used in conjunction with porosity (although no critical value is defined for porosity) as a comparative guide to durability. According to the BRE the saturation coefficient is only of limited usefulness for sandstones.

For slates the water absorption acceptance criteria are given in BS 680. The maximum permissible value is 0.3%; slates with values above this are thought to be potentially frost susceptible.

Measurement of water absorption by capillarity, which involves partial immersion of a stone in water to allow moisture to move up into the stone by capillary action, is another method that may be of value. No British Standard method is available but Standards such as NFB 10.502 are available.

2.3.4 Salt crystallisation

The cyclic crystallisation of salts within a porous building stone has often been used to assess the susceptibility of the material to frost action, although such a relationship is somewhat contentious. The BRE salt crystallisation test is mainly intended for use on limestone or sandstone, although theoretically there is no reason why the method could not be applied to other stone types. In the test, small cubes (40 mm) of stone are repetitively soaked in sodium sulphate solution and then oven dried for a total of 15 cycles. The durability of the stone is then assessed by the magnitude of the weight loss which occurs.

By using past observations of stone weathering and the test results from these stones the BRE was able to provide a classification of limestone based on their weight loss, as follows:

- Class A weight loss <1%
- Class B weight loss <5%
- Class C weight loss <15%
- Class D weight loss <35%
- Class E weight loss ≥35%
- Class F shatters before 15 cycles

These durability classes can then be related back to the various basic zones of a building, and the resulting exposure conditions of varying severity, for which the stone might be considered suitable for use. The classification of stones by BRE has only been applied to limestone and no similar classification is provided for sandstone, as it has traditionally been assumed to be frost-resistant.

This has been perhaps the most contested test method in the UK stone industry at present with the Stone Federation of Great Britain advocating the abandonment of the test as a misuse of overall durability. However, the theory of the tests using either sodium or magnesium sulphates is not restricted to building stones; a similar method exists for aggregates within BS 812. It would appear that it is the interpretation of the test results which is the most difficult area. Examples of potential problems with interpretation include:

- Many problems arise from the poor techniques used by some laboratories
- The definition of weight loss; if a cube parts along a natural plane during the test should that be regarded as weight loss, or should weight loss be more closely defined perhaps by a grading criteria
- The use of control stones; these will also be subject to natural variation which will not be quantifiable and may penalise the stones being tested in comparison with them
- Are the Classes well defined? For example, is the real difference between stones with a weight loss of 0.8% (Class A) and 5% (Class C) sufficient for the stone to be treated so differently in the BRE guidance (for example in an exposed coastal area subject to frost but with no pollution, the Class A stone could be used on any part of a building but the Class C stone could only be used as plain walling - in an area of high pollution the class C stone would be unusable, even as plain walling according to the BRE criteria)
- To what extent do the BRE criteria take into account the required design life of the stone?

Not withstanding the criticisms of the test and its interpretation it is accepted that the crystallisation test itself does have some merit as a measure of salt resistance and further work into the interpretation of the results and the classification of the stone is currently being undertaken. Despite the problems of interpretation the salt crystallisation test is still a valuable aid to the determination of the durability of the stone in salty environments.

2.3.5 Acid immersion testing

The effect of pollution can lead to the precipitation of slightly acid water (acid rain) and in some areas this may be a major cause of damage to stone on the buildings. All limestones (which are predominantly composed of calcium carbonate) will be particularly vulnerable to such damage, leading to the erosion of the surfaces and profiles and in some cases to the delamination of planes of stone due to the crystallisation of reaction products within the stone itself. Other stones which have calcite as a cement between sand grains will also be vulnerable to acid attack.

The effects of acid attack on sandstones is assessed using the Acid Immersion Test outlined by Ross and Butlin (1989); this test can use various acid strengths depending upon the durability period required. Such a test is not used on limestones as the results would be meaningless given their chemical composition.

Slates are also tested to determine their resistance to acids using the methods described in BS 680 (for roofing slates) and BS 5642 (for slates used as sills and copings).

2.3.6 Freeze-thaw testing

The frost resistance of stone is not covered by any British Standard test method; some believe that the salt crystallisation test is an indirect measure of frost resistance. However, various overseas methods can be used to determine the frost resistance; for example, DIN 52 104 is sometimes used in the UK to determine the frost resistance of some limestones and sandstones. There are no pass or fail criteria specified but the condition of the stone is visually assessed throughout the test and any defects noted. The test, which involves cycling the specimens of stone between -20 and +20° C, is certainly able to cause breakdown in some weak limestones, for example, which may show cracking or spalling after as few as five cycles of freezing and thawing whereas more dense, less porous, limestone can survive the test visually unaffected. As with the salt crystallisation test it is useful to use control stones for comparison purposes. Different criteria can be used to interpret the effects of freeze-thaw; in addition to visual examination French and American methods use the measurement of sonic velocity carried out on the specimens at certain stages of the test to determine the effects of the freeze-thaw cycles.

2.3.7 Thermal stability

There is no specific test method to cover thermal stability of stones as most building stones are thought to be dimensionally stable. Although this may be true in many cases it is not true of certain marbles when used as external cladding or even paving at certain thickness. Bowing or dishing of marbles, when used as external cladding panels, is thought to be due to a process known as thermal hysteresis whereby the thermal expansion of the calcite crystals in the marble causes irreversible deformation; others consider the effect may be due to the heat releasing built-in geological strain. Whatever the cause the effects were measured in experiments by Erlin in the USA and more recently by Messrs Sandberg in the UK (unpublished data) where the effects were found to be markedly different for varying thickness' of stone. The most important factors appear to be a temperature of between 20 and 60° C and occasional wetting of the stone panels under test. After only 50 cycles in the tests carried out by Messrs Sandberg, one commonly used marble had cracked and shown an overall expansion of 0.5%; such performance on a building may lead to a failure of the stone in service.

2.3.8 Dye testing

One of the tests that has significantly improved the visual inspection of cut stone is dye penetration testing. This technique works very well with polished stones such as granites and marbles. These are particularly prone to induced cracking due, for example, to blast damage caused by explosives during quarrying, or to mechanical damage during handling and transportation of blocks and cut panels.

Dye testing allows induced cracks to be seen more easily and also enables them to be distinguished from the normal pattern of micro-cracks on the basis of size, width, orientation and overall morphology.

2.4 Summary

2.4.1 Interpretation of results

The concept of a single test which could address all the various mechanisms of weathering will almost certainly be impossible to realise, so the assessment of durability will have to be taken on the basis of the results of a series of tests such as those described in the previous sections.

BRE have recently put forward the concept of 'Expected Life':

Expected Lifetime (Elt) = (Lifetime) x (Exposure) x (Pollution) x (Use)

These terms are defined in the BRE paper but the interpretation has been left open and there is scope for error or mis-interpretation:

> 'However, it is not always possible to make a precise estimate of the expected lifetime and it will be necessary to make some generalisations. If generalisations are required then it can be said that if the expected design life of a building is 60 years only stonework intended for harsher exposures (e.g. string courses or copings) or more severe environments will require testing for durability.'

This seems to suggest that a stone used for plain walling will in some cases not require testing; this seems a rather rash generalisation and will not be acceptable to many parties having to guarantee the finish of a building. For the present we are left with the situation where durability is assessed on the basis of the standard tests.

The tests required for each stone group are given in Table 2.1 and the results may be interpreted to some extent using the criteria given in Appendix A.

2.4.2 Testing requirements

The tests required to carry out an assessment of durability have been fully described within this section and the required number of tests are set out in Section 5. It is suggested that every quarry producing dimensioned stone should have available certain fundamental index properties (including properties beyond durability). Such tests include:

- Petrographic data
- Water absorption or porosity
- Density
- Compressive strength
- Historic data

This should be the minimum requirement and each quarry should carry out the tests at some regular interval and have both current and historic data available. Such very basic data may be sufficient for the purpose of giving architects or designers the basic information of whether a particular stone could even be considered for a particular project. If the project were sufficiently large, it would be prudent to repeat the basic testing and to test for durability as described above. For particularly large projects where many tens of blocks of stone are used in the construction then assessment of the stone properties will also be required at certain intervals during production of the stone.

It should be noted that the testing and the evaluation of stone will only be as reliable as the samples are representative. In the particular case of building stone it will always be important to establish that the samples submitted for testing derive from that part or level of the quarry from which the contract supply will be produced.

3 STRENGTH OF NATURAL STONE FOR USE AS A CLADDING MATERIAL

3.1 Introduction

Natural stone might well be considered an unusual choice for a cladding material in modern building construction. Firstly, in not having been manufactured to any designated quality standard, and secondly, because its breadth of visual character often reflects a wide variability in engineering performance behaviour, particularly strength.

Strength can vary by several orders of magnitude between different types of stone as outlined in Table 3.1 and to a lesser extent between stones of the same type. Even within a single stone, measured strength can vary by a factor of 2 or more, depending on such variables as:

- Moisture content
- Sample orientation
- Type of test

Strength can also vary with time.

Material	Flexural strength (MPa)	Compressive strength (MPa)
Granite	8-20	120-240
Sandstone	2.5-15	30-200
High Limestone	6-15	55-180
Low Limestone	2-10	10-90

Table 3.1 *Typical variation in stone strength*

Note: This table shows a typical range of values of flexural strength of stones on buildings. Stones of lower strength may be used from time to time.

It is important that construction professionals understand and work within the appropriate strength range of the material, in view of the fact that:

- The cost of stone cladding frequently represents a significant proportion of the total building cost
- Stone is used in a variety of different ways and supported on the building by a variety of different fixing methods
- There is a significant safety hazard and financial risk associated with failure of the stone.

3.2 Purpose of testing

This section deals specifically with strength testing. However, it is important to bear in mind that the strength testing criteria are interdependent with durability and dimensional stability and all need to be considered together.

The requirement for strength testing may present itself in a number of different ways:

- An architect may wish to use a new and untried stone for which there is no available test information
- Two or more stones may be visually suitable, and a decision on procurement may rest on selecting the one with the best engineering behaviour
- A particular fixing system, panel size and/or location on a building may impose unusually high loads on the stone; the long term strength of the stone will need to be verified in order to confirm its suitability
- Strength performance data provided by the supplier often relate to the stone cut to a particular orientation; for visual reasons the architect may wish to use the stone in a different orientation and the strength in this orientation should be checked
- The stone on an existing building appears to have failed by cracking at the fixing points; in order to establish the cause of failure, the strength of the stone on the building has to be checked
- A particular application demands a consistent high strength stone; strength testing may need to form part of the quality assurance check during production.

In considering the various ways in which the stone can be important to building construction, it is helpful to have in mind the diagram in Figure 3.1. This shows a typical normal frequency of the strength that generally occurs when a large number of identical tests are performed on the same stone. Such variations result from intrinsic differences in physical and chemical bonding within the material and are influenced by moisture content, temperature, type of test and sample orientation. The small number of recorded lower strength results highlights the significant loss of strength that can occur when discontinuities or weathering influence the test results.

It is important to bear in mind that published performance data on stone issued by suppliers will generally tend to accentuate the higher strength range of the material. For design purposes, it is more appropriate to work to a lower strength and this is the methodology adopted within this document.

Where substantial and frequent low strength results are obtained a stone will normally be rejected, both by the procurer because it does not comply with specified performance criteria and by the supplier because it will be susceptible to breakage during production.

More problematical will be the intermittent, visually difficult to detect flaws, which may manifest themselves as an occasional low strength value in a set of otherwise acceptable test results. It is often tempting to dismiss such low strength as spurious and irrelevant. However, it should always be borne in mind that the principal aim in performance testing is not to prove the fundamental strength of the material, but rather to establish its weakness. On the building it will be primarily the weakness which gives rise to failures and which may only show up some years after the building is completed.

Accepting that it will rarely be practical or economically feasible to test a truly representative sample of the total area of stone on a building, and that it will be difficult to test the stone under true working conditions, the engineer is faced with the decisions of what type of tests to perform, when to undertake the testing and how many tests are needed. Section 5 outlines a method of preliminary and production tests and gives guidance on the required number of tests to perform.

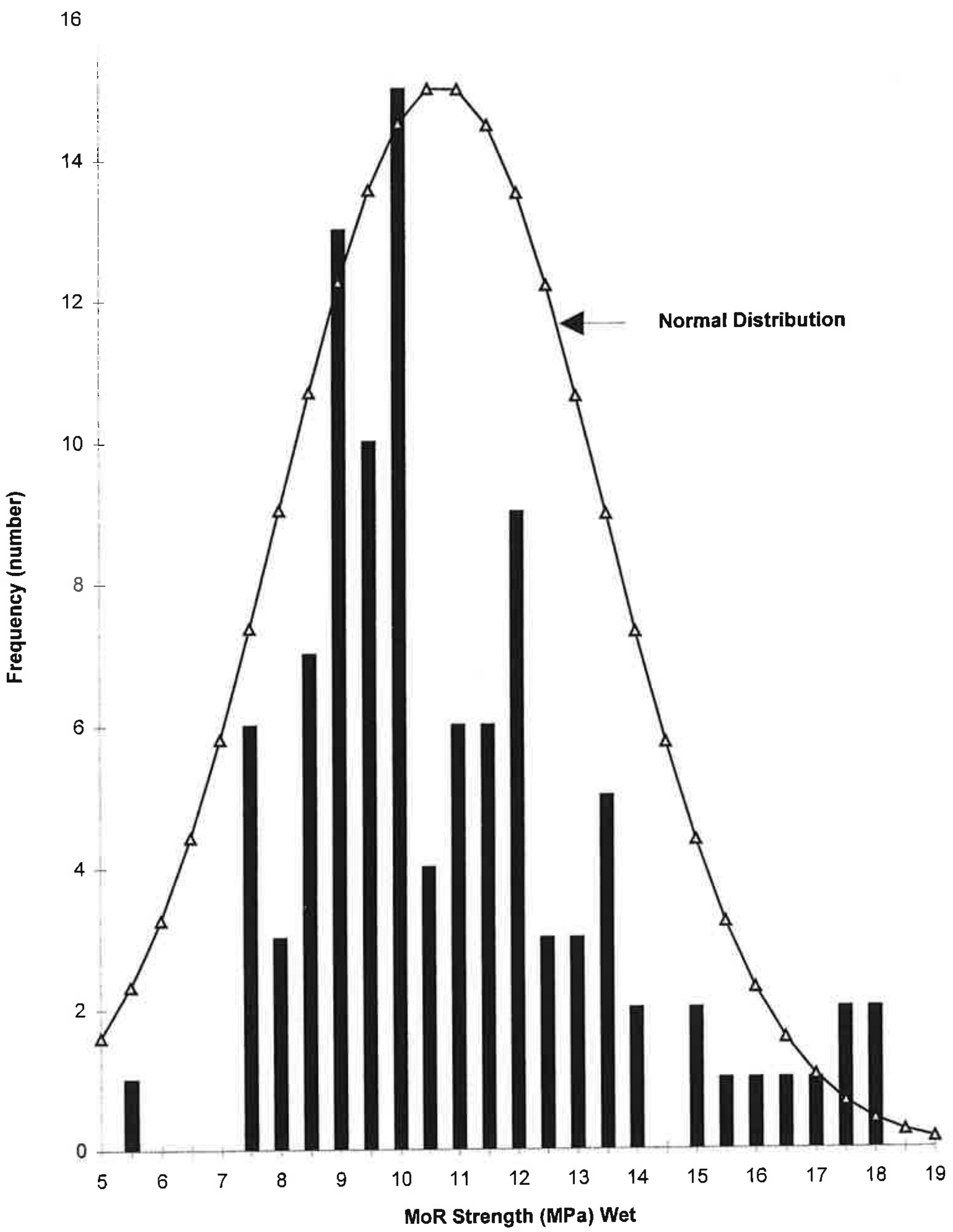


Figure 3.1 *Typical normal frequency distribution of strength tests on natural stone.*

3.3 Types of strength test

A wide variety of strength tests are available, which may be applied at different stages during stone selection and production, for different specific strength testing purposes. The stone industry has, however, largely standardised around a limited number of specific strength tests, namely:

- Flexural strength (ASTM C 880)
- Modulus of rupture (ASTM C 99)
- Uniaxial compressive strength (ASTM C 170)

While application of a common standard set of tests has certainly helped in the wider dissemination of more accurate strength data with a common basis of comparison, it has also resulted in:

- An over-reliance on a small number of tests to characterise the stone
- An element of strait-jacketing

In order to come to the correct decision about what strength tests to perform, it is important to consider the full range of available test methods (see Table 1.1). The most widely used test methods for assessing the strength of the stone are summarised in Table 3.2.

Test Method	Summary of Test
Petrographic analysis	Evaluate the minerals present within the stone. The analysis is repeated at every location for each specific stone type.
Water absorption/porosity	Assess the vulnerability of the stone to weathering and frost damage.
Bulk specific gravity	This test as specified within ASTM C 97 gives a convenient means of calculating the unit weight of the stone.
Flexural strength	A series of four-point bending tests required to test stone samples which may have intermittent discontinuities or weakness.
Modulus of rupture (MOR)	Obtain the tensile strength of the stone by three point loading.
Compressive strength	Simple test to perform. However, the comparison of the compressive strength of wet and dry samples is not fully understood and interpretation of the results must be considered carefully.

Table 3.2 *Summary of available strength related tests*

3.3.1 Index testing (preliminary testing)

Index strength tests include such tests as scratch hardness and geological hammer impact, which can be useful for differentiating between different types of strength category of the stone.

These tests are of particular value at an early stage in the selection of the stone, when carried out as part of an initial geological assessment at the quarry. Many of the more significant features that impact on strength can be identified and tested at this stage.

When index testing is carried out under more controlled conditions in the laboratory, it can also be used as a means of rapid and inexpensive quality testing prior to or during production. For example, where core samples can conveniently be taken prior to production at a particular quarry, point load testing on the core can be used to obtain an advanced measure of strength consistency.

If a correlation can be established between, for example, MOR strength and Brazil tensile strength, the latter can be used as proxy for the former during production quality testing.

3.3.2 Routine (standard) laboratory testing

Considerable care is required with routine strength tests, both in their application and in the interpretation of the results. This is because a standardised test is rarely the most ideal for assessing a variable parameter such as strength or for accurately simulating the variable loading conditions under which the stone will operate.

To illustrate the pitfalls that can occur, examples are given below for each of the three standard test procedures:

3.3.2.1 Uniaxial compressive strength

Because of its simplicity, this was the first test to be widely applied for strength measurements on stone (first ASTM Standard 1941). The test has also found wide application in rock mechanics (ISRM 1972) and in concrete testing (BS 1881: Part 118).

Over the years, many of the idiosyncrasies of the test method, in relation to sample dimensions and platen affects, have been well documented, including:

- Physical size of test sample (smaller samples generally give higher strength values; size can be particularly important in relation to grain size/ crystal size)
- Platen end effects (the roughness of the loading surfaces and their parallelism will have an impact on the results)

Less well documented and understood is the apparently large variation in compressive strength of certain stone types, particularly sandstones, when tested wet and dry. Wet compressive strength may be less than half of the dry strength, although the corresponding influence of moisture variation on MOR and flexural strength, in the same stone, may be more reserved

Table 3.3 shows the range of compressive strengths of various natural stones that can be expected, and should be used as a guide when considering stone as an external cladding material.

Material Types	Compressive Strength (MPa)	
Basalt, dolerite, some quartzites	250	Strongest
Fine-grained granite, diorite, basalt; well-cemented limestone, quartzite, limestone	160 - 250	↑
Sandstone, limestone, marble, medium and coarse-grained granite, granodiorite	60 - 160	
Porous sandstone, limestone, serpentine, travertine, mudstone	30 - 60	
Tuff, chalk, very porous sandstone/siltstone	< 30	
Fired clay bricks	10 - 60	↓
Concrete	Typically 48	Weakest

Table 3.3 *Variation in the compressive strength of natural stone and other building materials*

Recent compressive strength testing on a range of sandstones, where stress and strain measurements have also been made, have revealed that the mode of failure appears to change, depending on the degree of saturation. In wet conditions, failure occurs by vertical splitting, and is accompanied by an increase in Poisson's Ratio. In the dry condition, failure occurs by internal shearing on conical failure surfaces.

A similar effect has also been reported in concrete testing, where strong concrete tends to fail in shear while weak concrete or concrete made with smooth rounded aggregate tends to fail by tensile splitting at a lower than expected strength and higher Poisson's Ratio.

Under certain conditions, therefore, it would appear that tensile strain becomes the limiting criterion in compressive failure, the strain being marked by the formation and growth of vertical cracks which form along the interface between the large particles and the matrix.

A thin section micrograph of a typical sandstone shown in Figure 3.2 indicates that many sandstones exhibit similar characteristics to concrete in comprising particles of quartz (aggregate) floating in a fine grained matrix (mortar).

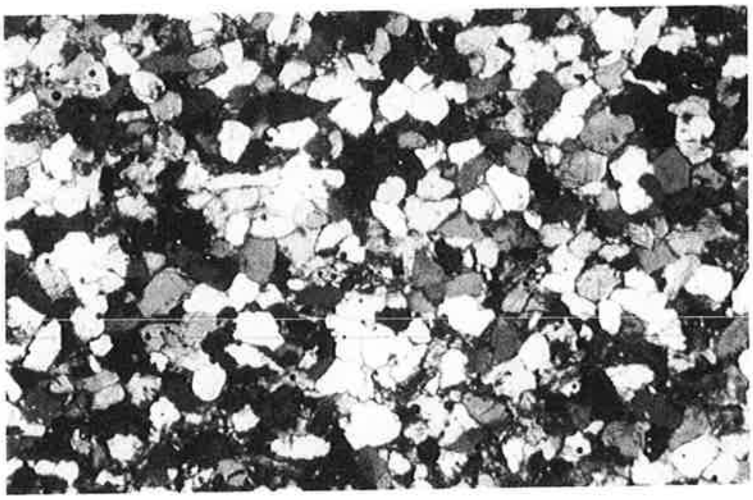


Figure 3.2 *Thin section micrograph of York Sandstone*

3.3.2.2 Modulus of rupture strength (MOR)

The MOR test essentially measures the tensile strength of a deep beam section in three point loading. It is a commonly used strength test for cladding stone and the results are often used as the basis for design on modern stone cladding projects. The standard test (ASTM C 99) uses a fixed size sample, the test being carried out wet and dry and parallel and perpendicular to the rift. There is also provision in the test standard for testing samples cut in different orientations to check for strength anisotropy.

It is a presumption of the test and of the determination of the MOR strength, that failure takes place beneath the central loading point along the neutral axis, where the applied stress is a maximum. In uniform isotropic materials this would normally be expected to be the case. However, many types of stone experience strength anisotropy (rift) and strength inconsistency. Strength anisotropy can occur as a result of:

- Preferred orientation of minerals in igneous and metamorphic rocks, or of grains in sedimentary rocks
- Depositional layering in sedimentary (and some igneous) rocks where weak and strong minerals alternate in repetitive fashion
- Microstrain cleavage fabric, where rocks (particularly igneous and metamorphic) subjected to large tectonic stresses have suffered internal micro-cracking

Strength inconsistencies include:

- Localised weathering (often of particular minerals)
- Intermediate incipient joints

In a programme of MOR testing on Rosa Porrino granite from Spain, it was noticed that many of the samples broke on a failure plane that was at an angle to the central loading axis as shown in Figure 3.3. A smaller number broke on a failure plane parallel to, but displaced from, the central loading axis.

Rosa Porrino exhibits a pronounced microstrain cleavage fabric which is, however, difficult to detect visually. Although samples were prepared from quarry blocks orientated for gang sawing in sympathy with this fabric, it is evident that a degree of out-of-parallelism can easily occur.

Plotting measured MOR strength values against the angle of breakage, revealed this to be the case, and helped to explain the large variation in measured strength, as illustrated in Figure 3.4. The occasional lateral breakage was thought to be due to an intermittent secondary cleavage developed at right angles to the main fabric.

It is of interest to note that although the central-point loading MOR test was previously used for assessing the tensile strength of concrete both in the UK (BS 1881: Part 117) and USA (ASTM C 99) it has since been discontinued in favour of a four point loading arrangement (BS 1881: Part 118, ASTM C 880), similar to the flexural strength for stone.

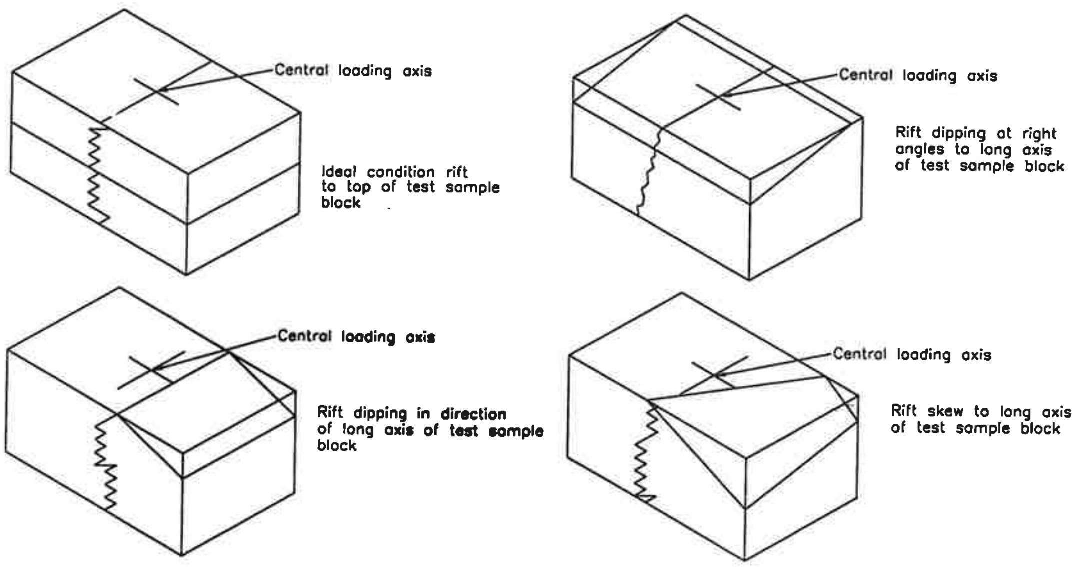
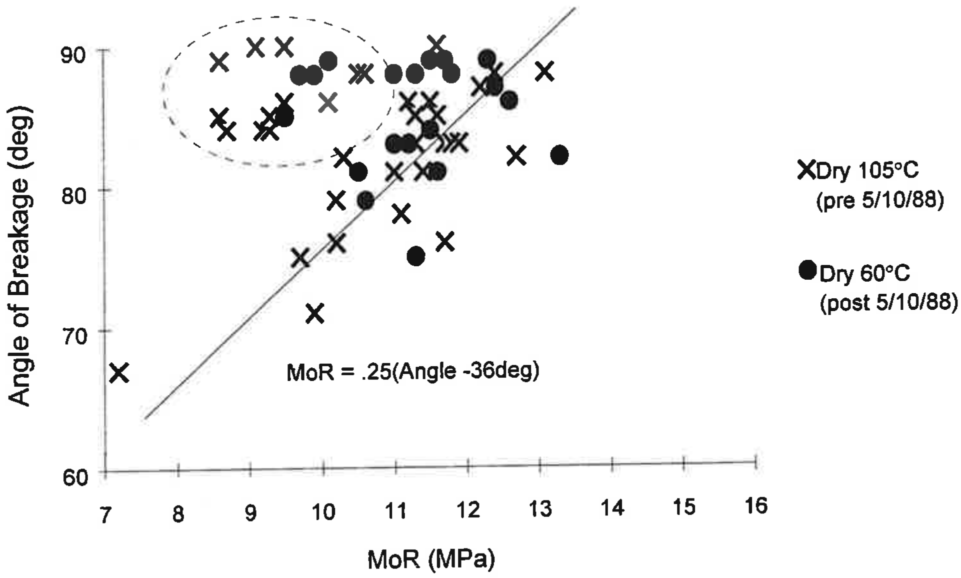


Figure 3.3 *Rift orientation controlling angle of breakage and distance from midpoint of Rosa Porrino granite*



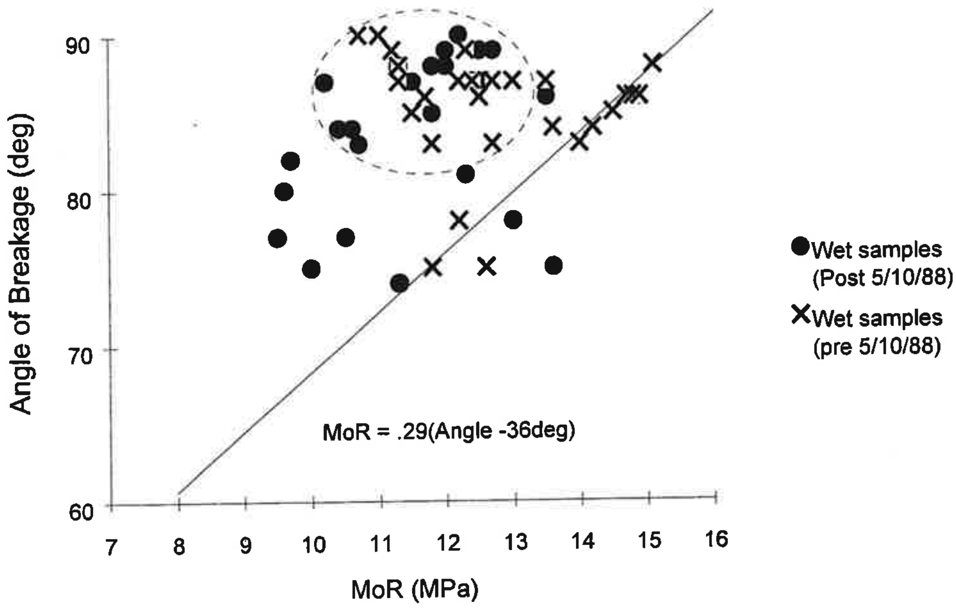


Figure 3.4 *Plot of Modulus of rupture (MoR) against angle of breakage of Rosa Porrino granite*

3.3.2.3 Flexural strength

The flexural strength test (ASTM C 880) measures the strength of the slender beam in four-point loading as shown in Figure 3.5. The standard size of the specimen is 38mm wide, by 25mm thick, by 300mm long, and there is provision in the test for measuring strength on wet and dry specimens and on specimens cut parallel and perpendicular to the bedding or rift.

It is a feature of a standard specimen that the grain size of the stone can have an undue influence on the measured strength. For instance, many coarse grained granites have large individual crystals (phenocrysts) which can occupy much of the total sectional area of the specimen, while keeping the overall dimensional ratio the same. It is now accepted practice when testing stone for use in cladding of a particular thickness, to match the thickness of the specimen to that of the cladding. The ASTM specification has recently been modified to allow for this, as well as for testing of specimens of different geometry.

The very nature of the flexural strength test produces a constant bending moment between the central loading points. This loading arrangement inherently produces a greater probability of a weak element being subjected to the critical stress than when a central load acts (i.e. in the MOR test). The flexural strength test is therefore more appropriate for testing stones which may have intermittent discontinuities or weakness. A feature of very strong stones, such as granites, is that they are very stiff and brittle. It requires very little deflection of larger panels or slender elements, for them to crack. This compares to weaker and more deformable stones, such as porous sandstones, which can undergo considerable deflection with no sign of structural failure.

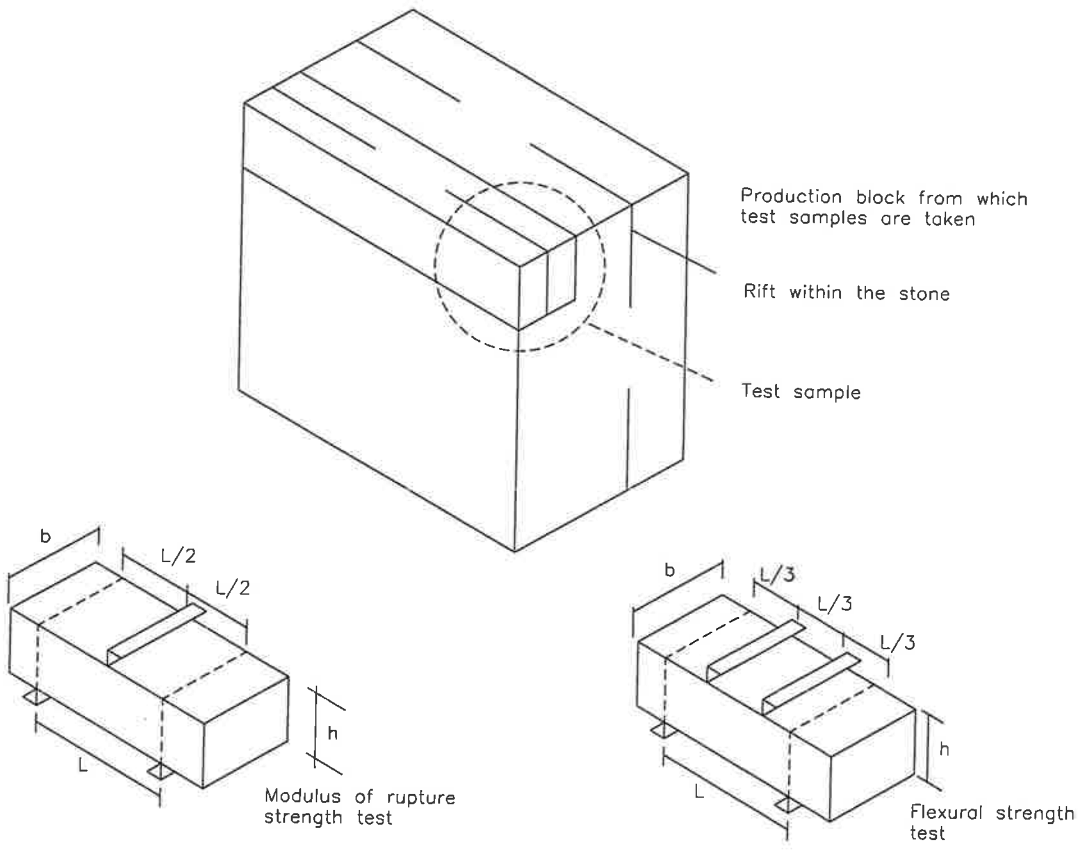


Figure 3.5 *Three/four point bending strength tests*

3.3.3 Specialist testing

There are a variety of other specialist laboratory tests that might be considered as a means for extending the data on strength for a particular stone. These are more often used in rock mechanics and geotechnical testing, but their application is no less valid.

3.3.3.1 Deformation characteristics in uniaxial compression

This test involves measuring the stress-strain behaviour, Young's Modulus and Poisson's Ratio of a specimen subjected to uniaxial compression. A test procedure is described by the ISRM (1972).

As mentioned in Section 3.3.2.1, the test data can be of value in trying to understand the failure mechanisms and mode of failure in uniaxial compression, particularly in sedimentary rocks where moisture content, clay content and matrix content are likely to be important.

The standard ASTM flexural strength test (C880) provides a suitable basis for measuring elastic modulus, provided that a dial gauge is used to measure the deflection at the mid-point for each increment of load. The standard ASTM C 120 gives a procedure.

3.3.3.2 Tensile strength

Indirect measurement of tensile strength may be made with the Brazil 'split cylinders' test and also with the MOR test. However, for certain uses, for instance, where a slender stone element is to be rigidly fixed across a structural gap or to a structural member which may be liable to expansion, it may well be appropriate to measure tensile strength directly. A suitable test procedure is described by the ISRM (1972).

It has to be recognised that stone is at its weakest in tension and that discontinuities such as joints, bedding, cleavage as well as grain and crystal orientations will have a significant influence over the measured strength on specimens cut with different orientations. The test can therefore be used to determine the effect of these features on the strength of the stone. However, because of the inherent difficulties in performing a direct tensile test, it will generally be more appropriate to use the MOR or Brazil 'split cylinder' test.

3.3.3.3 Shear strength

For most non-load-bearing applications, estimation of the shear strength from compressive strength data, or pull-out tests, will be adequate. For certain load bearing applications, where there are discontinuities or planes of weakness, direct measurement of shear strength may be necessary.

A suitable test procedure is described by the ISRM (1972).

3.3.3.4 Creep

The process of creep can be defined as the gradually increasing permanent deformation of a material under stress. A number of stone types, marble in particular and sedimentary rocks in general, exhibit a propensity for creep under load. Marble and other limestones are well known for their tendency to deform under relative low differential stress induced by, for example, moisture and temperature variations, self-weight and wind loading.

Measurement of these effects can be undertaken by suitably modifying the test procedures previously described.

3.3.3.5 Fatigue and ageing behaviour

Many rock types, granites included, are known to suffer loss of strength through a combination of repeated stress fatigue and long term environmental exposure (ageing). Thus in addition to the standard tests, other specific tests should be made to establish:

- The residual static flexural strength after the application of a sequence of fatiguing loads
- The static residual resistance of the stone around the fixing points after the application of a sequence of fatiguing loads

These tests are significant since the wind is variable and can strain and therefore cause gradual damage to the stone over time. This is particularly evident at fixing points where the concentrated load produced by the fixings combine with the stress concentrations leading to deterioration of the stone and possible detachment of the panels. A loading regime for fatigue/age strength tests is given in section 5.4.1g of this document.

3.3.4 Non-standard strength testing

Where assessment of strength-controlled performance under a variety of working conditions is required, it may be appropriate to undertake purpose design tests. Such tests might comprise:

- Pull-out tests on epoxy-cemented pin fixings
- Pull-out test on undercut anchors
- Lateral load tests on side-pin fixings
- Lateral load tests on kerf fixings
- Soft/hard body impact testing

As with all such tests, it is important to conduct the tests at the working scale, on representative samples of stone which are sufficiently large to avoid edge effects. Nevertheless, care will still be required in interpreting the results and relating them to the working conditions.

4 DIMENSIONAL STABILITY

4.1 Introduction

The primary cause of movement is due to temperature change but some stones exhibit movement due to moisture for instance marble. Recognition of the location and extent of movements in natural stone is essential for the satisfactory design of joints and fixings to prevent cracking of the stone panels.

Dimensional changes of stone during its use are of two forms. The first is irreversible movements resulting from stress release at the time of quarrying and subsequent thermal movement of some marbles (see Section 2.3.7). The second is reversible movements resulting from environmental changes.

It is essential that the engineer and architect recognise where inherent deviations are liable to occur and determine the order of magnitude of their effects, so that adequate provision can be made in the design of the fixings and method of restraint. The true net effect of moisture and thermal movements may be difficult to estimate accurately and some engineering judgement will be necessary.

4.1.1 Stability of stone cladding

In nearly all cases the overall change in size and shape will be relevant, by reference to the extreme conditions to which the material may be subjected. The movement of thin stone panels leads to two forms of deflection:

- Uniform changes in temperature of the stone lead to uniform movement of the stone panels. This results in a uniform change in length and width of the panel so that it retains its original shape but changes dimensions if unrestrained

- Where stone cladding panels experience different thermal and moisture conditions on their exposed and protected faces, temperatures and moisture gradients develop through the thickness of the panel. These gradients within the stone lead to differential thermal and moisture movements on each face of the panel, causing the overall panel to bow or dish if unrestrained

4.1.1.1 Uniform thermal expansion and contraction

In this case of thermal movement, dimensional changes of the stone panels lead to a closing or opening of any joints between adjacent panels. If the panels are tightly butted against each other then expansion is prevented and a thermal compressive stress occurs in the panels.

Estimation of expansion / contraction of the stone is calculated as:

Thermal strain = $\alpha \times t$
Change in length = $L \times \alpha \times t$
Thermal stress = $\alpha \times t \times E$

Where:
α = coefficient of linear thermal expansion
t = temperature difference considered
L = length of dimension considered
E = Young's Modulus

Typical values of the Coefficient of expansion and Young's Modulus are given in Table 4.1

Stone type	Coefficient of thermal expansion (a) (10-6/K)	Elastic modulus (E) (kN/mm2)	Reversible moisture movement (%)	Porosity (%)
Granite	8-10	30-70	Not known	0.4-2.3
Limestone	3-10	7	0.01	0.5-35.0
Marble *	3-15	30-60	Not known	0.6-2.3
(Travertine)	7	Not known	Not known	Not known
Quartzite	9-12	74-77	Not known	Not known
Sandstone	7-12	5-20	0.07	0.5-35.0

Table 4.1 *Typical range of properties of natural stone for cladding purposes*

* This does not demonstrate the variability of movement that is apparent within calcite marble. Marble inherently has a high degree of anisotropy resulting in a nonscalar coefficient of thermal expansion apparent within bowing or dishing of the cladding panels. Marbles are also particularly susceptible to acid atmospheres (acid rain) and the cyclic process of dissolving and precipitating the vulnerable minerals can create greater porosity and cracking of the stone which may lead to premature failure.

If thermal movements are considered to be a problem on the basis of the typical values given then the Young's Modulus of the stone can be established (Section 4.3.3.1) and the Coefficient of linear expansion can be measured to give an indication of the possible movement likely to occur within the stone.

4.1.1.2 Differential thermal expansion and contraction

The differential expansion/contraction of a stone panel will lead to dishing if unrestrained. For a uniform isotropic material this will cause the stone panel to inherently become spherical in shape. If the panel is restrained by its fixings in such a manner that the panel is restrained from adopting a spherical shape then compressive and tensile thermal stresses will be generated in the panel and cracking may occur. Whilst many stones exhibit anisotropy and non-uniformity a working assumption is often made that the stone panel will deform to a spherical shape. The panel fixings are then arranged to allow that movement to take place. This requires all fixings to occur on a circle in the plane of the panel and to allow for small rotations of the plate at the fixings. Retaining the stone panel in a frame around its edge or using multiple fixings on a regular grid will not allow the necessary movement and may result in cracking of the panels.

If reversible thermal movements/stresses are a concern for the designer then it may be appropriate to test a full panel complete with fixings and support system. A thermal testing regime is given in *Standard and Guide to Good Practice for Curtain Walling* (CWCT, 1996).

4.1.1.3 Moisture movement

Some natural stones are capable of absorbing water or water vapour, resulting in a small increase in size as the moisture content increases. Table 4.1 shows the likely extent of moisture movements as a percentage of the size of stone.

4.1.2 Combination of thermal and moisture movement

Natural stone when exposed to the environment will be subjected to concurrent or interdependent changes in temperature or moisture content. Since moisture content tends to fall as temperature rises, the dimensional effects to some extent can be compensated for and in the majority of cases movements would be over-estimated if both effects are added. As a guide it is advisable to estimate the overall magnitude of the dominant type of movement and then to assess whether the subsidiary type of movement is likely to increase the overall magnitude.

5 TESTING OF NATURAL STONE FOR CLADDING

5.1 Introduction

Test results on natural stones are particularly prone to scatter because of intrinsic variations between the physical and chemical bonding within the material; it is therefore essential to carry out a sufficient number of tests to be confident of the lower limit strength of the stone. Either method of assessing stone test data as described below may be used to assign the factors of safety when designing a natural stone facade.

5.2 Testing methodology

When specifying natural stone for a project there is a need for a formal testing programme to evaluate the strength and durability of the stone for the specific requirements of the project.

Preliminary tests are carried out to establish the suitability of a stone within the quarry and production tests are carried out as part of an on-going quality assurance check to monitor the consistency of the stone properties. There is currently no standard guidance available in the UK specifically addressing a stone selection test regime. However, Figure 5.1 outlines when the production test should be conducted and the implications that the test results may have on the design of the facade. Set out below is a testing and analysis methodology to adopt in the absence of current guidance: it is not mandatory and may be varied depending on the way the quarried stone is orientated and attached to the primary structure.

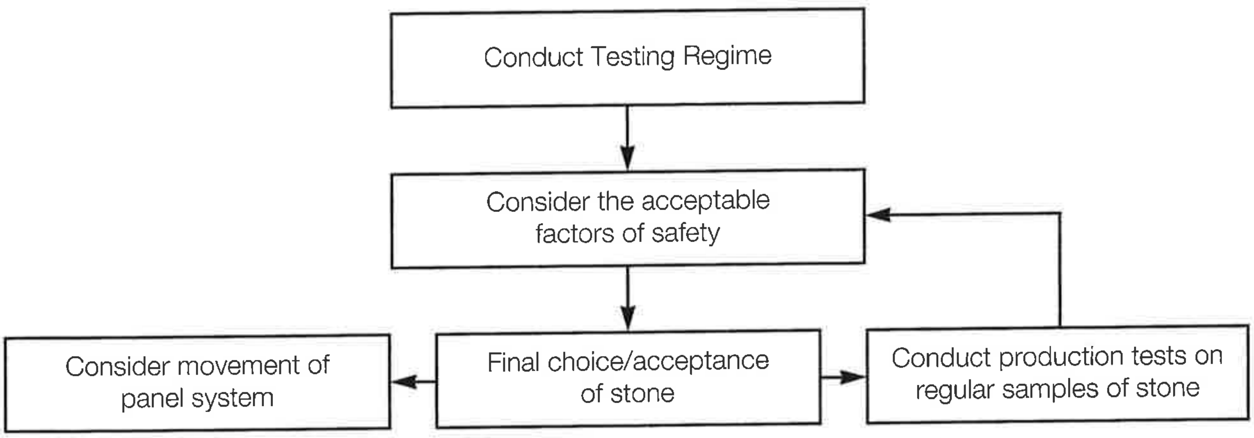


Figure 5.1 *Production testing*

5.3 Performance criteria

5.3.1 Analysis of test data

The two methods described below can be used to estimate the stone strengths and factors of safety for a programme of stone testing.

Method 1 is based on North American practice and gives guidance on factors of safety to use, taking into account the variability of the test results and stone type. For certain applications where durability of the stone is questionable or where a large volume of stone is to be quarried, then aged-strength testing of the stone should be considered within the testing programme. All the factors of safety specified are based on experience and have been taken at face value.

Method 2 is based specifically on a statistical approach where the test strength results vary depending on the sample size used for the analysis. Hence, if a higher safe load is required for a design, a greater number of tests may need to be specified so that one can be certain of the test strength of the stone. A 95% confidence limit has been taken in common with other testing methods within the construction industry. No factors of safety are recommended, however; this method of analysis is more transparent than the first method and it is left to the construction professionals to select appropriate factors of safety for the stone design. No account has been taken of ageing with this method and if strength reduction through ageing is a concern then either aged-strength tests have to be performed or an appropriate factor of safety selected on the basis of experience.

5.3.2 Method 1

5.3.2.1 For projects with aged-strength testing

This method of analysis is suitable where greater confidence is needed of the test results or for large projects where a greater number of samples are required for the purpose of testing.

The minimum factor of safety to be used for the flexural design of stone and the design of the stone at the fixings should be based on preliminary stone test data, which gives an initial indication of the test strength. The safety factors incorporated within this design method comprise of two separate entities: the variance factor (VF) and the durability factor (DF).

The variance factor (VF) is defined as a measure of the natural range of flexural strength test results. To evaluate the preliminary tests it is necessary to calculate the coefficient of variance (n) and use the relevant safety factor according to Table 5.1.

The mean ($\bar{x}$) of the sample tests is calculated based on the number of test samples (n) actually tested and is given by the following expression:

$$\bar{x} = \frac{(x_1 + x_2 + x_3 + .. + x_n)}{n}$$

The standard deviation is the positive square root of the variance (v) which is a measure of the dispersion of the test results about the mean. For a series of (n) tests ($x_1, x_2, x_3, .., x_n$) with an arithmetic mean ($\bar{x}$), the square of the standard deviation or variance of the test population is given by the following expression:

$$s^2 = v = \frac{1}{(n - 1)} \sum_{i=1}^{n} (x_i - \bar{x})^2$$

The coefficient of variation (V) may be expressed as a percentage of the mean and used to obtain a safety factor depending on the type of stone being quarried. Table 5.1 shows the relationship between the coefficient of variance of the test data and the required factors of safety required for design purposes, where:

$$V = \frac{100s}{\bar{x}}$$

Coefficient of variance V	Granite	Limestone	Marble
0%-5%	2.0	3.0	2.5
5%-10%	2.5	3.5	3.0
10%-20%	3.0	4.0	3.5
above 20%	3.5	4.5	4.0

Table 5.1 *Variation Factor (VF)*

The durability factor (DF) is defined as a measure of the effect of accelerated-ageing test results. To obtain a durability factor for a stone type it is necessary to calculate the flexural strength from the thermal cycling test regime as a proportion of the original strength in accordance with ASTM C 880:

(Average after 300 thermal cycles/average before 300 thermal cycles) x 100%

From this expression a durability factor can be chosen according to the loss in flexural strength as shown in Table 5.2.

Fraction of Initial Flexural Strength (%)	Durability Factor
100%	1.0
95%-75%	1.2
75%-60%	1.5
Less than 60%	1.8

Table 5.2 *Durability Factor (DF)*

Stone flexural safety factor (FSF)

The minimum safety factor to be used in the flexural design of stone panels should be calculated as follows:

$FSF = (VF) \times (DF)$

Stone anchorage safety factor (ASF)

The minimum safety factor to be used in checking stone stresses at anchorage zones should be calculated as follows

$ASF = (FSF) \times 1.4$

To establish stone allowable stresses, the safety factors calculated, or greater safety factors if deemed appropriate by the engineer responsible for the design of the stone panels shall be applied to the average flexural strength.

5.3.2.2 For projects without aged-strength testing

Where the safety factors are not required to be high or when specifying exterior stone for small projects the procedure specified below would be more appropriate. The construction professional should review the production test data and may further modify the safety factors as deemed appropriate.

Stone Flexural Safety Factor (*FSF*)
The minimum safety factor to be used in the flexural design of stone panels should be specified as shown in Table 5.3

Stone Type	Factor of Safety
Granite	4.0
Limestone	6.0
Marble	5.0

Table 5.3 *Stone Flexural Safety Factor (FSF)*

Stone Anchorage Safety Factor (*ASF*)

The minimum safety factor to be used in checking stone stresses at anchorage zones should be calculated as follows:

$ASF = (FSF) \times 1.4$

To establish allowable stone stresses the safety factors should be applied to the average stone flexural strength.

5.3.3 Method 2

The statistical method involves carrying out a specified number of tests as described in the preliminary and production test methodology. It is important that each batch of test samples are prepared and tested under similar conditions and within a specified time of each other to eliminate the comparison of two sample means and variances within a single batch of stone samples.

For the purpose of the stone tests the construction professional will only use the lower tolerance limits (test strength) for the purpose of design. For this application it is assumed that the true standard deviation (σ) and true mean strength (μ) of the stone are unknown and required to be estimated from the sample size for each specific test.

One can assume for statistical purposes that:

$$\bar{x} = \frac{(x_1 + x_2 + x_3 \ldots x_n)}{n}$$

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{(n - 1)}}$$

Where:

$\bar{x}$ = mean of the sample

s = standard deviation of the sample

n = sample size

To calculate the lower tolerance limit of the sample size it is necessary to introduce a K-factor to account for the uncertainty arising from the sample size and the tolerance interval in relation to the true population. The other uncertainty to account for is the chosen confidence level, which is the probability that the statistical tolerance interval will contain at least a proportion of the population. For the purpose of the stone test data it may be appropriate to take the values of K that imply a confidence level of 95 per cent.

Knowing the standard deviation (s) and the mean ($\bar{x}$) of the sample, and assuming the tolerance level and confidence level, one can obtain a representative K-factor depending on the number of tests conducted, (see Table 5.4).

Number of Tests (n)	**K-factor***
5	3.41
10	2.36
15	2.07
20	1.93
30	1.78
40	1.70
50	1.65
∞	1.645

**values of K are adopted from BS 2846: Part 3 and are specific to a confidence level of 95%*

***Table 5.4** One-sided statistical tolerance interval with true mean (μ) and true standard deviation (σ) unknown*

5.3.3.1 Limits of test results

The tolerance limits of the strength tests are defined as the measure of the natural range of flexural strength of the test results and can be described as:

$L_{95} = \bar{x} + Ks$ or $L_5 = \bar{x} - Ks$

Where:

L_{95} = Upper limit

L_5 = Lower limit (design strength)

Factors of safety

Having calculated the lower tolerance level of the natural stone an appropriate factor of safety should be applied to give a design load. The construction professional should use discretion when applying a safety factor, dependent upon the type of stone and level of confidence of the test results:

$$\text{Design load} = \frac{\bar{x} - Ks}{FOS}$$

FOS = Factor of Safety

The construction professional should review the test data and select appropriate safety factors to account for the choice of stone, intended use, durability and effect of ageing on the strength of the stone.

5.4 Preliminary tests

Preliminary tests are only carried out when specifying exterior stone for large projects, or where the unique design of the building necessitates, and should be completed prior to the start of production. Stone provided for preliminary tests should be taken from different locations within areas intended for quarrying during the production phase of the project, and as indicated on the submitted map of the quarry. A sample of stone produced for testing purposes should include 20 specimens and the minimum number of specimens required should be 20 per cent greater than the number of tests specified to account for breakages.

Stone tests are specific to a particular bed within a quarry, therefore it is important to establish that the specimens submitted for testing are part of the same sample block from a particular level of quarry from which the contract supply will be produced. The range of tests to be performed on the specimens of stone are listed below and full details of durability and strength tests are covered in detail in Sections 2 and 3 respectively.

5.4.1 Test regime

The schedule of preliminary tests are based on North American practice and relate to testing of stone that will be mechanically fixed as part of a rainscreen or curtain wall construction. The schedule to adopt for any project will depend on the scale of the project, historic test data available and the likely stress the stone will be subjected to during the life of the building.

The full schedule of tests are outlined in steps (a - h). For preliminary testing it is necessary to test from (a - d) inclusive together with test (e or f) depending on the orientation of the stone on the building. Where durability of the stone is an issue because of the large volume of stone being used or the environmental conditions the stone will be subjected to, then aged-strength test (g) may need to be specified. Fixing tests (h) should not be performed until the strength of the stone has been reviewed and appropriate factors of safety at the anchorage points are accounted for.

a) Petrographic analysis

Number of specimens: 1

b) Absorption

Number of specimens: 3

c) Bulk specific gravity

Number of specimens: 3

d) Compressive strength tests

Number of specimens: 20. From these, ten will be taken perpendicular to the rift and ten parallel to the rift. Each of the ten samples will be divided into two batches from which five samples will be tested wet and five tested dry or sufficient tests will be carried out to establish which tests give the weaker results. The remaining tests, up to ten in total will be carried out wet or dry accordingly to show the weakest results.

e) Modulus of rupture

Number of specimens: 20. These tests are to be carried out as specified in Clause (d).

f) Flexural strength

Number of specimens: 40. The specimens should be of the same thickness as the stone proposed for use on the project and if the production stone is textured the samples should preferably be textured with that surface tested in tension. Of the forty samples twenty will be taken perpendicular to the rift and twenty parallel to the rift. Each of the twenty samples will be divided into two batches from which both wet and dry samples will be tested. If the modulus of rupture tests (e) show the wet conditions to be weakest then tests should be carried out on wet samples only, otherwise it will be necessary to test an equal number of wet and dry samples.

g) Aged strength testing

Number of specimens: 20. The specimens should be of the same thickness as used for the flexural strength test (f). Samples shall be taken parallel to the rift, from which ten samples will be tested wet and ten samples tested dry or as determined by the modulus of rupture test (e).

Flexural strength tests should be conducted prior to aged strength testing and after 50, 100, 200 and 300 thermal cycles between 20 - 70 C. If the surface of the samples are flame-textured it is necessary that this face is placed in tension during the testing.

h) Fixing tests

The purpose of the anchor tests is to assess the load carrying capacity of any existing wall or new wall to which it is intended to fix the cladding panels and should be included as part of a site test. The panel-to-support structure connections also need to be tested either during production, to reduce the number of site tests, or as part of a panel test.

Number of tests 10: This number of tests should be performed on each type of anchor proposed for use on the building, with five tests conducted in each loading direction simulating positive and negative wind loading. Tests shall be performed with the stone in either wet or dry condition at the discretion of the constructional professional after review of the preliminary stone test results. Anchors to be used as gravity plus direct load shall have the gravity load simulated in the test. Where adhesives are used in conjunction with mechanical anchorage assemblies, testing shall be performed without the benefit of the proposed adhesive component to simulate the worst situation.

The specimens of stone shall be the thickness and finish of stone proposed for use on the structure. The test should be performed using the following procedure:

1) Gradually load the anchor with the gravity load as required simulating the gravity design load of the anchor plus 20 per cent.

2) Apply the direct load in equal increments, holding the load at each increment for 10 seconds, up to three times the design load.

3) Gradually increase the direct load to failure.

4) Record the load at failure and the type of failure (stone failure, fixing pull/push out failure).

5) Record displacement during loading.

Further details of the site testing procedure are given in the CFA guidance document.

The stone fixing test data can be assessed either by:

- Considering if the load at failure of a single test is less than the stone flexural safety factor (F.S.F) x design load, or if the average results of all the tests are less than the stone anchorage safety factor (A.S.F) x design load. (If either is the case the construction professional may require that the fixing assembly be modified and re-tested.) Or

- Considering if the load at failure of a single test is less than the factored design load. If this is the case then the construction professional may require that the fixing assembly be modified and re-tested.

5.5 Panel tests

These are often performed as part of a comprehensive rainscreen or curtain wall test at NAMAS accredited test houses and can cover a broad range of tests as specified in the *Standard and guide to good practice for curtain walling* (CWCT, 1996). Testing of the anchor assemblies and panels may not be possible on a complete wall specimen and it may be more suitable to test them separately.

a) Pull out tests

These may be tested separately as described in section 5.4(h) or as a combination as described in 5.5(b)

Provide three panel test samples from the first quarry block and one panel from every 15 m^3 of stone thereafter. On each sample perform three pull out tests for each fixing type to be used.

b) Full scale tests (optional)

Panel and fixing assemblies shall be accurately configured for testing to simulate project conditions and details. Each assembly will be tested to 4.0 x the design load, with both positive and negative cycles of load, the cyclic load is to be incremented in steps of 500 N/m². The test pressure at failure should be recorded together with the type of failure.

5.6 Production tests

Production tests should be performed on every 15 m³ of stone throughout the quarrying operation, unless otherwise agreed.

The production tests are an on-going process carried out during the quarrying phase. The water absorption test (a) or bulk specific gravity test (b) are early indicators and are a useful guide to the ease with which natural stone can be worked into thin panels. If the preliminary test data show a wide variation of results then it would be appropriate to carry out either of the tests (c, d or e), whichever are considered most appropriate in the orientation and thickness that the stone is to be used.

a) Water absorption

Number of specimens: 3

OR

b) Bulk specific gravity

Number of specimens: 3 from first block only.

Where the preliminary test data shows a wide variation of results it would be appropriate to conduct an additional test (c, d or e) depending on how the stone is to be loaded when installed on the building.

Strength tests

c) Flexural Strength

Number of specimens: 20

The tests will include 20 specimens to be taken from every fifth block; the specimens are to be tested 5 wet and 5 dry both perpendicular and parallel to the rift. These should be the thickness of the stone proposed for use on the project and where flame finished panels are required the samples shall be provided with the specified finish and tested with that side in tension.

OR

d) Compressive strength

Number of specimens: 20

The tests will include testing 5 specimens each wet and dry, perpendicular and parallel to the rift, from the first block only.

OR

e) Modulus of rupture (MoR)

Number of specimens: 20

The tests will include testing 5 specimens each wet and dry, perpendicular and parallel to rift, from first block only.

GLOSSARY

This is not a full glossary of terms used within the stone and facade industry, it is only a reference to the terms used within this document:

Anistropic	This is the display of unequal physical properties in different directions.
Bed	Sheet or layer of sedimentary material.
Bedding plane	The surface between successive beds of sedimentary rock.
Breccia	A form of rock composed of large angular fragments that have been cemented together in a combined matrix.
Cleavage	The tendency of stones to split along definite planes so as to yield smooth surfaces.
Construction professional	The architect, designer, engineer or specifier.
Creep	Gradual increase in deformation of a material under load.
Curtain wall	A form of vertical building enclosure which supports no load other than its own weight and the environmental forces which act upon it.
Facade	A series of components and/or prefabricated sub-assemblies which only become a finished product (rainscreen or curtain wall) when assembled together on site.
Fissure	An open crack within the rock.
Fixing bracket	A main component metal fixing device, engineered to transmit all the load forces acting on the facade to the building structure.
Fracture	A break with an uneven or irregular surface.
Frame construction	A technique adopted for the pre-assembly of inter-linking storey height or multi-storey height frame modules, complete with infill panels.
Hardness	The resistance by a substance to actions which tend to modify its surface by scratching, abrasion and penetration.
Igneous rock	These are formed by cooling and consolidation of magma. It contains a high proportion of minerals of which granite is the most common.
Inclusions	Substances within a mineral including other minerals, gas bubbles, liquids, or other foreign objects.
Isotropic	Materials in which all characteristics are the same in all directions.
Kerf	A slot cut into the cladding panel to accept fixings (can be continuous or partial).
Oolite	Sedimentary stone, usually limestone and sandstone, characterised by small spherical grains.

BS 2846: Part 3:1975 (1985), *Determination of a statistical tolerance interval,* British Standards Institution, London

BS 5628, three parts, *Code of practice for the use of masonry,* British Standards Institution, London

BS 5642: Part 1: 1978, *Specification for window sills of precast concrete, cast stone, clayware, slate and natural stone,* British Standards Institution, London

BS 5930: 1981, *Code of practice for site investigation,* British Standards Institution, London

BS 8298: 1994, *Code of practice for design and installation of natural stone cladding and lining,* British Standards Institution, London

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APPENDIX A

A1 Stone acceptance criteria

Stone Types	**Reference Standard ASTM**	**Test properties**				
		Density (C 97) Mg/m³ min	**Absorption (C 97) % min**	**Modulus of rupture (C 99) MPa min**	**Compressive strength (C 170) MPa min**	**Flexural Strength (C 880) MPa min**
Granite	C 615-85	2.560	0.40	10.34	113	8.27
Limestone						
Low density	C 568-89 *	1.760	12	2.9	12	NA
Medium density	C 568-89 *	2.160	7.5	3.4	28	NA
High density	C 568-89 *	2.560	3	6.9	55	NA
Marble					52	7
Calcite Class I	C 503-89 *	2.595	0.20	7	52	7
Dolomite Class II	C 503-89 *	2.800	0.20	7	52	7
Serpentine Class III	C 503-89 *	2.690	0.20	7	52	7
Travertine Class IV	C 503-89 *	2.305	0.20	7	52	7
Sandstone						
Sandstone	C 616-89 *	2.160	20	2.1	13.8	NA
Quartzitic sandstone	C 616-89 *	2.400	3	6.9	68.9	NA
Quartzite	C 616-89 *	2.560	1	13.9	137.9	NA

* These ASTM Standards were re-approved in 1996.

This table is for guidance only and should not be used as a substitute for a specification. The current test used to measure the flexural strength of a stone is the four point loading test and it is the preferred test for assessing strength of the cladding panels.

CENTRE FOR WINDOW AND CLADDING TECHNOLOGY

The Centre for Window & Cladding Technology is an industry sponsored research and education organisation based at the University of Bath. It provides training and education for those involved in the design, fabrication and installation of cladding, curtain walling and windows. The Centre undertakes research funded by industry and by Government and gives technical advice to its members. Membership of the Centre is open to all who have an interest in the building envelope.

CENTRE FOR WINDOW AND CLADDING TECHNOLOGY

Published by

Centre for Window & Cladding Technology
University of Bath
Claverton Down
Bath BA2 7AY

Telephone (01225) 826541
http://www.cwct.co.uk

ISBN 1 874003 09 2