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# selective guide to the specification of dimension stone

In this invited paper, Geoff Quick outlines a number of standards and properties by which the architect, designer or specifier of stone can establish appropriate criteria for the selection of stone for specific use.

In the stone industry there are many publications, magazines, trade journals or internet sites that advertise natural stone products through glossy photographic catalogues. The more reputable companies include the physical intrinsic stone properties as ascertained by various standard test methods. However, many architects, specifiers and stone merchants do not understand the importance of the unique properties of natural stone, when selected as a component in a building system. The selection of stone purely on aesthetic grounds is thwart with danger, and it is for this reason that this article has been written. Choosing a stone that has a proven track record in a similar installation (including dimensions and environment) will generally reduce selection problems. However, the need for testing should always be considered, as it should ensure that the stone supplied is equivalent to the original selection criteria, and that it is appropriate for the intended purpose. This article will briefly summarise the most common product standards and specifications presently available, and then, in general terms, outline the major intrinsic properties that should be considered in the selection of natural stone. The test methods discussed are not exhaustive; other test methods may be required for some specialised applications.

In Australia, the only product standards that consider dimension stone are AS/NZS 4455 and AS/NZS 4456 (Masonry Units and Segmented Pavers). The American ASTM Standards for dimension stone (Tables 1 and 2) have been widely used to characterise stone, but the dimensional requirements prevent the adequate testing of tiles. This led to the development of the CSIRO "BEST" standards for stone tiles (Table 3 and references [1-3]). In Europe, EN Standards are evolving that will replace existing national stone standards. This article concentrates on the most common and useful properties that are needed when selecting stone products.

The slip resistance of stone may be specified according to AS/NZS 4586. The slip resistance may change with use, either becoming more slippery as a result of natural polishing, or less slippery as a result of abrasion and roughening of the surface. AS/NZS 4663 is the new standard for determining the slip resistance of existing pedestrian surfaces. The next issue of Discovering Stone will contain a paper that considers the sustainable slip resistance of some stone tiles.

Stone is a product of nature and has its own unique performance characteristics. Its physical properties (including colour, grain and pattern) can vary widely, even within the same batch of stone units. Unlike other building products, this emphasises the nature and originality of each stone unit. Selection of stone should not be based on a single specimen; the complete range of colours and textures should be viewed. A firm understanding on the laying pattern is also required. When the stone arrives at the building site, enough cartons should be opened to allow approval of the colour and textural range. On ordering, an allowance must be made for time and materials lost in extracting unwanted stone units.

Stone testing is used to establish the properties of the stone and their effect on its behaviour when subjected to various loads, moisture, abrasion and/or thermal cycles. However, useful data can only be gained through representative sample selection, and accurate and careful preparation of the specimens. The characteristic variation in stone properties may require additional specimens for some tests (e.g. strength) in order to obtain reliable data. Since some natural and agglomerated stones are dimensionally unstable (they may warp, expand or change colour when exposed to water, heat or UV radiation), exposure tests and dimensional stability tests are also sometimes required. Not all the test procedures are appropriate for every situation. The architect should specify those tests that are appropriate for a particular stone in a specific application. Tests appropriate for different uses of stone are summarised in Table 4.

## STONE FINISHES

Natural stone comes in a varying degree of finishes. These are listed in ascending order, for each stone, from smoothest to roughest:

| | |
|---|---|
| Granite | Polished, honed, rubbed, abrasive, diamond sawn, thermal (flamed, exfoliated). |
| Marble | Polished, honed, abrasive. |
| Limestone | Polished (dense limestones only), honed, cleft, rustic. |
| Slate | Honed, abrasive, cleft. |
| Bluestone (basalt) | Honed, diamond sawn. |
| Sandstone | Abrasive, diamond sawn, cleft. |

A polished surface displays a glossy or mirror finish, which brings out the full character of the stone. However, it will require considerable care in order to maintain its high shine. A honed surface has a superfine

TABLE 1

ASTM DIMENSION STONE STANDARDS COMMONLY REFERENCED OR PRACTICED IN AUSTRALIA

| | |
|---|---|
| C119 | TERMINOLOGY RELATING TO DIMENSION STONE |
| C406 | SPECIFICATION FOR ROOFING SLATE |
| C503 | SPECIFICATION FOR MARBLE DIMENSION STONE (EXTERIOR) |
| C568 | SPECIFICATION FOR LIMESTONE DIMENSION STONE |
| C615 | SPECIFICATION FOR GRANITE DIMENSION STONE |
| C616 | SPECIFICATION FOR QUARTZ-BASED DIMENSION STONE |
| C629 | SPECIFICATION FOR SLATE DIMENSION STONE |
| C97 | ABSORPTION AND BULK SPECIFIC GRAVITY OF DIMENSION STONE |
| C99 | MODULUS OF RUPTURE OF DIMENSION STONE |
| C120 | FLEXURE TESTING OF SLATE (MODULUS OF RUPTURE, MODULUS OF ELASTICITY) |
| C121 | WATER ABSORPTION OF SLATE |
| C170 | COMPRESSIVE STRENGTH OF DIMENSION STONE |
| C217 | WEATHER RESISTANCE OF SLATE |
| C880 | FLEXURAL STRENGTH OF DIMENSION STONE |
| C1352 | FLEXURAL MODULUS OF ELASTICITY OF DIMENSION STONE |
| C1353 | USING THE TABER ABRASER FOR ABRASION RESISTANCE OF DIMENSION STONE SUBJECTED TO FOOT TRAFFIC |
| C1242 | GUIDE FOR DESIGN, SELECTION AND INSTALLATION OF STONE ANCHORS AND ANCHORING SYSTEMS |
| C1354 | STRENGTH OF INDIVIDUAL STONE ANCHORAGES IN DIMENSION STONE |
| C1496 | GUIDE FOR ASSESSMENT AND MAINTENANCE OF EXTERIOR DIMENSION STONE MASONRY WALLS AND FACADES |

## TABLE 2

SUMMARY OF ASTM DIMENSION STONE SPECIFICATIONS

| TYPE OF STONE | ABSORPTION C97 (WT%, MAX). | DENSITY C97 (KG/M³, MIN) | COMPRESSIVE STRENGTH C170 (MPA, MIN) | MODULUS OF RUPTURE C99(MPA, MIN) | FLEXURAL STRENGTH C880 (MPA, MIN) | ABRASION RESISTANCE* C1353, (Ha MIN) | ACID RESISTANCE C217 (MM, MAX) |
|---|---|---|---|---|---|---|---|
| GRANITE C616 | 0.40 | 2560 | 131 | 10.34 | 8.27 | 25 | - |
| MARBLE C503 | 0.20 | | 52 | 7 | 7 | 10 | - |
| I. CALCITE | | 2595 | | | | | |
| II. DOLOMITE | | 2800 | | | | | |
| III. SERPENTINE | | 2690 | | | | | |
| IV. TRAVERTINE | | 2305 | | | | | |
| LIMESTONE C568 | | | | | NS | 10 | - |
| I. LOW-DENSITY | 12 | 1760 | 12 | 2.9 | | | |
| II. MEDIUM-DENSITY | 7.5 | 2160 | 28 | 3.4 | | | |
| III. HIGH-DENSITY | 3 | 2560 | 55 | 6.9 | | | |
| QUARTZ-BASED C616 | | | | | NS | | - |
| I. SANDSTONE | 8 | 2003 | 27.6 | 2.4 | | 2 | |
| II. QUARTZITIC SANDSTONE | 3 | 2400 | 68.9 | 6.9 | | 8 | |
| III. QUARTZITE | 1 | 2560 | 137.9 | 13.9 | | 8 | |
| SLATE C629 | **C121** | NS | NS | **C120** | NS | | |
| I. EXTERIOR | 0.25 | | | | | 8 | 0.38 |
| ACROSS GRAIN | | | | 62.1 | | | |
| ALONG GRAIN | | | | 49.6 | | | |
| II. INTERIOR | 0.45 | | | | | 8 | 0.64 |
| ACROSS GRAIN | | | | 49.6 | | | |
| ALONG GRAIN | | | | 37.9 | | | |

NS = NOT SPECIFIED * LIGHT FOOT TRAFFIC ONLY

machine-ground satin finish with little or no gloss. A rubbed surface is smooth, flat and non-reflective. An abrasive finish is a flat non-reflective surface that has usually been sandblasted with silicon carbide grit, steel shot or fine glass beads. A sawn surface is a raw sawn finish that has not received further treatment. A cleft finish is a natural split finish. A rustic finish is rough or irregular, while a thermal (flamed or exfoliated)

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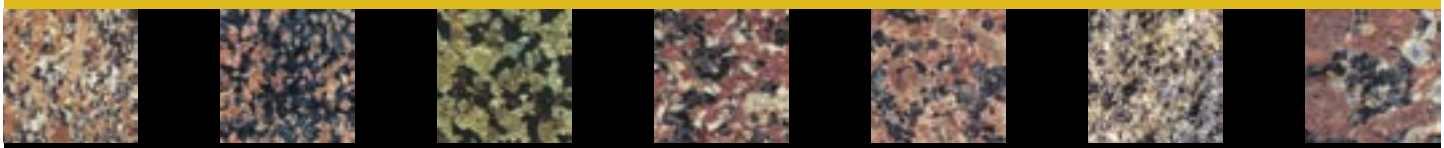

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## TABLE 3

CSIRO 'BEST' TEST METHODS FOR EVALUATING STONE TILES

| | |
|---|---|
| CSIRO METHOD BEST-0 | INTRODUCTION |
| CSIRO METHOD BEST-1 | DETERMINATION OF PETROGRAPHY OF STONE TILES |
| CSIRO METHOD BEST-2 | DETERMINATION OF WATER ABSORPTION, APPARENT POROSITY, AND BULK DENSITY OF STONE TILES |
| CSIRO METHOD BEST-3 | DETERMINATION OF FLEXURAL STRENGTH OF STONE TILES |
| CSIRO METHOD BEST-4 | DETERMINATION OF IMPACT RESISTANCE OF STONE TILES |
| CSIRO METHOD BEST-5 | DETERMINATION OF SCRATCH HARDNESS OF STONE TILES |
| CSIRO METHOD BEST-6 | DETERMINATION OF RESISTANCE TO ABRASION OF STONE TILES (CAPON METHOD) |
| CSIRO METHOD BEST-7 | DETERMINATION OF COEFFICIENT OF THERMAL EXPANSION OF STONE TILES |
| CSIRO METHOD BEST-8 | DETERMINATION OF RESISTANCE TO THERMAL SHOCK OF STONE TILES |
| CSIRO METHOD BEST-9 | DETERMINATION OF DIMENSIONAL STABILITY OF STONE TILES |
| CSIRO METHOD BEST-10 | DETERMINATION OF FROST RESISTANCE OF STONE TILES |
| CSIRO METHOD BEST-11 | DETERMINATION OF CHEMICAL RESISTANCE OF STONE TILES |
| CSIRO METHOD BEST-12 | ACID IMMERSION TEST FOR STONE TILES |
| CSIRO METHOD BEST-13 | DETERMINATION OF STAIN RESISTANCE OF STONE TILES |
| CSIRO METHOD BEST-14 | DETERMINATION OF WEATHERABILITY OF STONE TILES |

## TABLE 4

TEST METHODS APPROPRIATE FOR THEIR INTENDED USE[1]

| TEST METHOD | EXTERNAL CLADDING | LOAD-BEARING MASONRY UNITS | NON LOAD-BEARING MASORY UNITS | COPINGS | SILLS/ LENTILS | ROOFING | INTERNAL FLOORING | EXTERNAL PAVEMENTS | INTERNAL WALLS | COUNTER TOPS (BAR & VANITY TOPS) | FOOD AREAS (RESIDENTIAL/ COMMERCIAL KITCHENS, DINING AREAS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PETROGRAPHY | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| ABSORPTION & DENSITY | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| COMPRESSIVE STRENGTH | | ✔ | | | | | | ✔ | | | |
| BENDING STRENGTH | ✔ | | | | ✔ | ✔ | ✔ | | | | |
| HARDNESS | | | | | | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| ABRASION RESISTANCE | | | | | | | ✔ | ✔ | | | ✔F |
| IMPACT RESISTANCE | | | | | | | ✔ | ✔ | | | |
| THERMAL EXPANSION | ✔ | | | | | | ✔ | | | | |
| THERMAL SHOCK | | | | | | | | | | | ✔ |
| DIMENSIONAL STABILITY | ✔ | ✔ | ✔ | | | ✔ | ✔ | ✔ | ✔W | | ✔ |
| FROST RESISTANCE | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | | ✔ | | | |
| SALT ATTACK | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | | ✔ | | | |
| CHEMICAL RESISTANCE | ✔ | | | | | ✔ | ✔ | ✔ | ✔W | ✔ | ✔ |
| STAIN RESISTANCE[2] | | | | | | | ✔ | | ✔W | ✔ | ✔ |
| SLIP RESISTANCE[2] | | | | | | | ✔ | ✔ | | | ✔F |

1 ADDITIONAL TESTING MAY BE REQUIRED FOR USE IN SPECIALISED APPLICATIONS (E.G. INDUSTRIAL KITCHENS, COLD STORAGE AREAS, HOSPITALS, ETC.).
2 AFTER SEALING (IF APPLICABLE)
F = FLOORING ONLY W = WET AREAS ONLY

surface is a rough surface resulting from passing a fiercely hot flame over the surface of the stone.

The different surface textural finishes may affect the inherent properties of the stone. For example, a honed surface may have a higher slip resistance than a polished surface, but may be harder to keep clean due to its more open pore structure. A thermal finish on granite can reduce the strength of the stone by up to 30%. This is the result of the formation of extensive microcracking in the surface; it will also increase its porosity and water absorbency and decrease its cleanability. Sealing is recommended for thermal granites. Marbles or limestones are relatively soft and may eventually have their polished surfaces worn down, resulting in a shading effect. Although honed surfaces have often been considered to provide slip resistance for external pedestrian areas, some honed stones do not comply with the existing slip resistance standards. It is clear that one must not only understand the inherent properties of the stone, but also how the various finishes affect these properties when specifying natural stone in the built environment.

### PETROGRAPHY

Petrography uses microscopic examination to describe and classify rocks. Where stone is to be used in the built environment, petrographic descriptions must emphasise any deleterious components. Other analytical techniques can also supplement the petrographic data (e.g. X-ray diffraction, scanning electron microscopy and energy-dispersal X-ray analysis).

An accurate description of the mineralogy, texture and other microscopic features of the stone, allows a prediction of its chemical, physical and mechanical performance in service. For example, minerals such as swelling smectite clays (Fig. 1), zeolites (e.g. laumontite) and sulfides (e.g. pyrite) have affected the long-term durability of some stones. Petrography must not be used in isolation to predict the durability of stone; the intended

application will determine what other tests are required to predict its service performance.

### Stone Classification

In the building industry 'stone types' may not reflect their exact geological definition. There are no set naming rules, and definitions may vary from country to country, or in some instances from state to state. For example, many of the stones typically referred to as granite are not granite at all. Geologically, granite is a visible granular, light coloured plutonic igneous rock consisting of quartz, alkali-feldspar and mica minerals. In the trade, however, the term usually encompasses nearly all coarse-grained crystalline igneous and metamorphic rocks despite their origin, and includes such varieties as gabbro (black granite), diorite, syenite and gneiss. Similarly, the geological definition of a marble is a calcareous rock (usually a limestone) that has undergone recrystallisation due to heat and/or pressure (metamorphism). In the building trade many marbles are actually dense limestones, a sedimentary rock composed of calcium carbonate (often fossiliferous) capable of taking a polish. In Victoria, Australia, bluestone is a dark basaltic volcanic rock, while in South Australia and the USA the term is reserved for blue-coloured siltstones or fine-grained sandstones (sedimentary rocks). Stones that have been cleft (i.e. split) are sometimes all referred to as slates (e.g. some split-faced sandstones, limestones).

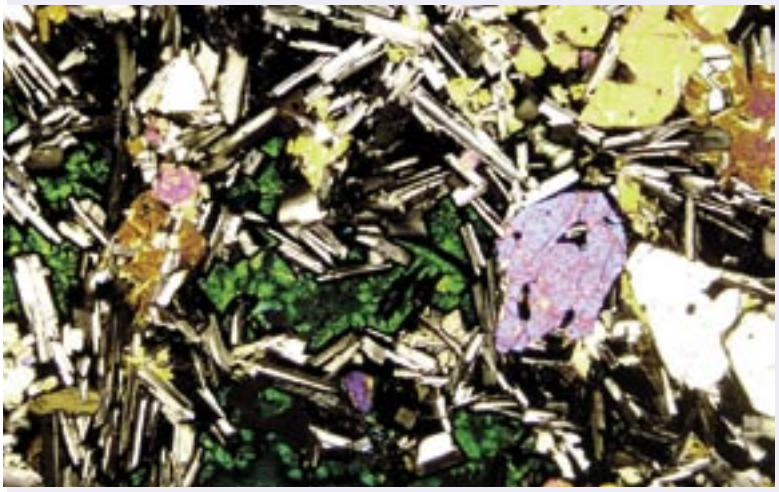

Figure 1 – Petrographic micrograph of basalt in thin section (stained with methylene blue) showing volcanic glass (dark areas) undergoing alteration to deleterious smectite clay (dark green). Crossed-polarised light, width of field: 3.5 mm.

However, a true slate is a fine-grained metamorphic rock, derived from sedimentary shales, and composed mainly of planar micas, chlorite and quartz. True slates can be easily split into thin sheets because of the planar orientation of the minerals. To add to the confusion, some stones are named after their place of origin (e.g. Sydney Blue) or special visual characteristics of the stone (e.g. Desert Lilac) and bear no relationship to any geological names. For the exact definition of many of these terms, please refer to ASTM C119 (Standard Terminology Relating to Dimension Stone).

Geologically, rocks are classified into three major groups based on the fundamental differences in the ways in which rocks are formed, and then into further types based on their mineralogy and textures. The main rock groups and types used for dimension stone include:

**A Igneous** those formed by the cooling and solidification of molten magma.

**Granite** a visibly granular, igneous rock ranging in colour from pink to light or dark grey and consisting mostly of quartz and feldspars, accompanied by one or more dark ferromagnesian minerals. The texture is typically homogeneous but may be gneissic or porphyritic. Some dark granular igneous rocks (e.g. gabbro, dolerite, diorite), though not geologically granite, are included in the definition; these are sometimes referred to as Black Granites (ASTM C119). Likewise some metamorphic rocks (e.g. gneiss, schist) are also included in the commercial definition of granite.

**Basalt (bluestone)** a hard blackish coloured volcanic rock composed of fine-grained plagioclase feldspar and ferromagnesian minerals. The term 'bluestone' is often referred to in Victoria, Australia, as basalt, but elsewhere it has been used to describe other bluish sedimentary rocks such as dense feldspathic sandstones or siltstones.

**Trachyte** usually a pale coloured and porphyritic volcanic rock composed dominantly of alkali-feldspar and minor ferromagnesian minerals.

**B Sedimentary** rocks formed by the accumulation and compaction of: fragments from pre-existing rocks which have been disintegrated by erosion; organic debris such as shell or coral fragments; or materials dissolved in surface waters or groundwater, which is precipitated in conditions of oversaturation.

**Sandstone** a sedimentary rock composed mostly of mineral and rock fragments within the sand size range (from 2 to 0.06 mm) and having a minimum of 60% free silica, cemented or bonded to a greater or lesser degree by various materials including silica, iron oxides, carbonates or clay, and which has a compressive strength over 28 MPa (ASTM C119, Quartz-based Dimension Stone Definition I).

**Quartzitic sandstone** sandstone containing at least 90% free silica (quartz grains plus siliceous cement), which has a compressive strength over 69 MPa (ASTM C119, Quartz-based Dimension Stone Definition II).

**Limestone** a rock of sedimentary origin composed principally of calcium carbonate (the mineral calcite), or the double carbonate of calcium and magnesium (the mineral dolomite), or some combination of these two minerals (ASTM C119). (Recrystallised limestone, compact microcrystalline limestone, and travertine that are capable of taking a polish are also included in the category 'commercial marble' and may be sold as either limestone or marble.)

**C Metamorphic** rocks formed from pre-existing rocks of any type, which have been subjected to increases of temperature or pressure or both, such that the rocks undergo recrystallisation.

**Marble** a true marble is a metamorphosed limestone capable of taking a polish, that exhibits a recrystallised interlocking texture composed principally of the carbonate minerals calcite and/or dolomite. However, some stones in the industry are referred to as green marbles, many of which are composed principally of the mineral serpentine, and by geological definition, should not be included in the marble definition. (It is important to distinguish between these two type of marbles, since some (but not all) green marbles are dimensionally unstable.)

**Slate** a microcrystalline metamorphic rock most commonly derived from shale and composed mostly of micas, chlorite and quartz. The micaceous minerals have a subparallel orientation and thus impart strong cleavage to the rock, which allows the latter to be split into thin but tough sheets (ASTM C119).

**Quartzite** highly indurated, typically metamorphosed sandstone containing at least 95% free silica, which has a compressive strength of over 117 MPa (ASTM C119, Quartz-based Dimension Stone Definition III).

**Greenstone** a general term applied to any altered or metamorphosed igneous rock of low silica composition (e.g. metamorphosed basalts, gabbros, peridotites). The rock is mainly composed of ferromagnesian minerals as well as chlorite, actinolite, epidote, serpentine and talc. It usually has a poorly defined granularity, ranging in colour from dark green to black. It is typically dense, compact and fractures irregularly.

Table 5 lists commonly used but broad generalised commercial stone names, together with a more precise range of geological equivalents. However, the use of such commercial terms may vary somewhat throughout the world. The list is not exhaustive.

TABLE 5

COMMERCIAL STONE TYPES AND THEIR GEOLOGICAL EQUIVALENTS

| COMMERCIAL NAME | EQUIVALENT GEOLOGICAL NAMES |
|---|---|
| GRANITE | GRANITE<br>GRANODIORITE<br>ADAMELLITE<br>PORPHYRY<br>GABBRO<br>DOLERITE<br>DIORITE<br>QUARTZ DIORITE<br>MONZONITE<br>GNEISS<br>SYENITE<br>TONALITE<br>RHYOLITE<br>DACITE |
| SANDSTONE | SANDSTONE<br>GREYWACKE<br>ARKOSIC SANDSTONE<br>FELDSPATHIC SANDSTONE<br>CALCAREOUS SANDSTONE<br>QUARTZ ARENITE<br>LITHARENITE |
| FLAGSTONE | SANDSTONE<br>SILTSTONE<br>SLATE<br>LIMESTONE |
| SLATE | SLATE<br>FINE-GRAINED SILTSTONE OR SANDSTONE<br>QUARTZ SCHIST<br>FINE-GRAINED MICA SCHIST |
| QUARTZITIC SANDSTONE | QUARTZITIC SANDSTONE<br>QUARTZITE |
| BLACK GRANITE | GABBRO<br>NORITE<br>DIORITE<br>PERIDOTITE |
| TRACHYTE | TRACHYTE |
| BLUESTONE | BASALT<br>ANDESITE<br>FELDSPATHIC SANDSTONE<br>BLUISH SILTSTONE |
| LIMESTONE | LIMESTONE<br>CALCARENITE<br>COQUINA<br>OOLITIC LIMESTONE<br>DOLOMITE<br>TRAVERTINE<br>BIOMICRITE<br>BIOSPARITE |
| MARBLE | MARBLE<br>LIMESTONE (ABLE TO TAKE A POLISH)<br>TRAVERTINE<br>DOLOMITE<br>SERPENTINITE<br>CALCSCHIST |
| GREEN MARBLE | SERPENTINITE<br>DIOPSIDIC MARBLE<br>PERIDOTITE |
| GREENSTONE | GREENSTONE<br>META-DOLERITE<br>META-BASALT |

IT IS CLEAR FROM THESE DEFINITIONS THAT THE COMMERCIAL TERMS 'GRANITE' AND 'MARBLE' CAN ENCOMPASS MANY DIFFERENT ROCK TYPES, WHICH THEREFORE CAN EXHIBIT A GREAT VARIATION IN PHYSICAL PROPERTIES. FOR THESE REASONS, IT IS IMPERATIVE THAT ALL STONES BE TESTED. THE PHYSICAL PROPERTIES OF AN AVERAGE GRANITE OR MARBLE MAY NOT SUFFICE.

## WATER ABSORPTION, POROSITY AND DENSITY

Water absorption is the proportion of water able to be absorbed by stone under specific immersion conditions. The value obtained provides some indication of the stone's performance in service, particularly its strength, durability and stain resistance. The water absorption value is also closely related to its inherent apparent porosity, i.e. the volume of open pores accessible to moisture within the stone. The bulk density (mass per unit volume) depends not only on the porosity but also on the mineral density of its components. The bulk density is important in calculating the weight of the stone in a wall or constructional element. According to Spry [4], sandstones with a bulk density of less than 2.2 g/cm$^3$ have been found to be of poor quality.

As a general rule, with higher water absorption and porosity, and lower density, the stone tends to be less durable and less stain resistant, and more susceptible to frost and salt attack. However, the porosity result must be treated with caution as it gives no indication of the way in which the pore space is distributed within the stone: whether there are many fine pores which increases the likelihood of absorption by capillary tension, or a smaller number of coarse pores. A low-density stone with a low water absorption value may indicate the presence of deleterious inclusions. Likewise, in choosing durable stones the composition of the stone is also important. You may have a sandstone or limestone with low porosity, but because of the mineralogy of some of these stones, e.g. sandstone cemented by calcium carbonate, or a limestone made up entirely of calcium carbonate, the stone may be susceptible to attack by acidic rainwater.

Note that stone units produced by thermal or flamed processes (exfoliated surfaces) tend to have extended microcracking and thus have increased absorption properties. Some stones, after absorbing water and alkalis from the mortar bed or cementitious adhesives, may have their volumetric

## TABLE 6

COMMON PROPERTIES FOR DIFFERENT STONE TYPES

| STONE TYPE | ABSORPTION (wt %) | BULK DENSITY ($g/cm^3$) | COMPRESSIVE STRENGTH (MPa, dry) | FLEXURAL STRENGTH (MPa, dry) | *HARDNESS* | | *ABRASION RESISTANCE* | | THERMAL EXPANSION $10^{-6}/°C$ (REF 10) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | MOHS, H | KNOOP MICRO HARDNESS ($Kg/mm^2$) | TABER INDEX, $H_a$ | CSIRO CAPON INDEX | |
| GRANITE | 0.1-3.0 | 2.6-2.7 | 80-310 | 8-18 | 5-7 | 400-620 | 90-160 | 150-260 | 5-11 |
| BLACK GRANITE (GABBRO) | 0.1-1.8 | 2.8-2.9 | 110-300 | 15-28 | 5-6.5 | 380-560 | 60-100 | 90-130 | 4-7 |
| BLUESTONE (BASALT) | 0.3-4.0 | 2.7-2.9 | 50-280 | 11-16 | 4-6.5 | 360-480 | 50-90 | 100-140 | 2-5 |
| MARBLE | 0.1-1.5 | 2.6-2.7 | 40-190 | 7-19 | 2-4 | 80-220 | 8-35 | 35-45 | 3-7 |
| LIMESTONE (MEDIUM-DENSE) | 0.3-20.0 | 2.2-2.6 | 20-230 | 4-20 | 2-3 | 90-230 | 6-28 | 30-50 | 2-6 |
| SANDSTONE (MEDIUM-DENSE) | 2.0-25.0 | 2.0-2.6 | 20-240 | 4-12 | 2-7 | | 5-40 | 15-75 | 2-12 |
| QUARTZITE | 0.1-1.5 | 2.6-2.7 | 110-350 | 10-25 | 5-7 | 450-740 | 20-70 | 40-90 | 8-16 |
| SLATE | 0.1-2.5 | 2.6-2.7 | 50-300 | 35-55 | 3-5 | | 8-20 | 22-28 | 3-9 |

dimensions permanently changed. As a result, these stones may display warping and bowing. Certain serpentines, often called 'green marbles', can display this characteristic.

The requirements for many physical properties, according to ASTM specification standards, are listed in Table 2. Table 6 gives some typical property values for some commonly used stones.

## STRENGTH TESTS

In many cases, strength testing is required in both wet and dry conditions, because many stones are markedly weaker in the saturated state than in the dry condition, either because of a reduction in the integrity of the matrix that binds the stone, or because some clay-like secondary alteration minerals within the stone may be susceptible to wetting. In addition, stone is not isotropic and the strength may vary significantly due to the orientation of the stone on the testing rig. For example, some stones have a preferred orientation of their grain structure (e.g. bedding); the strength parallel to the bedding plane may be significantly lower from that perpendicular to it. It is therefore essential that test results refer to the direction of loading, relative to the orientation of the grain in the specimen. As a consequence, the number of specimens tested should be increased to allow for different loading directions.

Depending on the intended application, there are several test methods available for testing the strength of stone. Only the most common routine tests are included here.

### Compressive Strength

Uniaxial unconfined compressive strength is the measure of the load that a stone can take before it crushes, and as such a measure of the stone's ability to support load-bearing structures. In more specific terms, it is a measure of the applied stress (load per unit area) at failure. Natural stone is generally strong in compression, but it can vary widely. Stones less than 7 MPa are comparatively weak, while those greater than 140 MPa are considered very strong. Compressive strength increases with decreasing grain size in homogeneous rocks. The test is performed on sawn cubes or on core-drilled cylinders usually in both dry and wet states. As most modern stone installations are non- load-bearing, the test has little direct relevance for cladding systems. It can be useful in evaluating different stones for floor applications if density, abrasion and slip resistance are also considered. The strength of the stone is often related to its durability; stones having high strength are generally more durable, although strength may decrease with weathering. In Australia, it has often been used to distinguish durable and less durable sandstone [4—6]. In some sandstones, a low wet to dry compressive strength ratio may indicate potential lower durability.

### Flexural Strength

The flexural strength (bending strength) of the stone is critical in both the design and detailing of building facades, and also for use as a flooring material. It is useful in determining the maximum load a stone panel can withstand in a curtain-wall system with anchors located at the edges of the panel. It also assists in the evaluation of the stone's resistance to wind loads. Flexural strength is a measure of the tensile strength induced by bending; it is highly affected by the stone's surface condition on the face that is in tension. For example, the flexural strength of thermally finished granite is generally 30% lower than a polished granite. In stones displaying preferred grain orientations, the highest results are obtained when the tensile stress is applied parallel to the grain rather than across it.

The test can be used to determine whether a thin stone unit will crack or fracture under externally induced stress conditions. Both the ASTM C880 and CSIRO BEST-3 methods use a four-point loading procedure. Stone with low flexural strength and large surface areas will normally require fairly thick cross-sections. In testing stone for curtain- wall use, it is advisable that it be tested at the same thickness and surface finish as that proposed. The flexural strength of stone generally increases as the water absorption decreases for stones of equal grain size.

### Modulus of Rupture

This is a similar test to the method for flexural strength but with loading at a single point. The modulus of rupture (or transverse strength) measures the combined shear strength and diagonal strength of the stone. The test causes the failure to occur directly under the load (and not at its weakest point), and the specimen sizes bear little relationship to the actual thickness of the stone. It is valuable in determining the strength of the stone at its point of attachment with anchoring devices.

Guidance upon the use of flexural strength or modulus of rupture test results in calculations of loading cladding panels can be found in Lewis [7]. According to Lewis, ASTM C99 modulus of rupture values range from 20—35% higher than C880 flexural test values on the same material. Lewis recommends that thin panels should be tested by the ASTM C880 procedure, while thick and (thermally) flamed specimens should be tested using the ASTM C99 procedure.

## HARDNESS

The perception that stone is extremely hard and long-wearing is incorrect. Some stones are very soft and should not be used in areas of high traffic nor in areas close to external entranceways, where loose grit or sand can be brought in, by shoes or wind, and ground into the stone's surface, unless appropriate measures are taken. Stones with low scratch resistance will require higher levels of maintenance. Testing for both hardness and abrasion resistance should be considered when selecting stone for flooring applications.

The determination of scratch hardness has been frequently used by geologists for many years, and is included in the CSIRO BEST-5 method. Scratch hardness is determined by drawing certain minerals of defined hardness by hand over the test surface. The testing minerals are graded according to Mohs hardness scale (H); 1 (softest) to 10 (hardest). The scale indicates the rank not the absolute value of hardness. Each mineral in the scale will scratch other minerals of lower rank and will be scratched by those higher than it in the scale. The greater hardnesses are spaced further apart than the soft values. The hardness of the stone is expressed by the number immediately preceding that of the first material on the Mohs scale to succeed in scratching the stone. In the case of stones that have a coarse mineralogical texture and/or those with a variable scratch hardness, the lowest Mohs hardness value is recorded.

However, as scratch hardness results are subject to varying interpretation, we would prefer to use a more accurate and controlled hardness method, such as the diamond indenter technique used in determining Knoop microhardness. This technique is used extensively in Europe for classifying limestones, and involves the permanent indentation that results from a stone being subjected to a loaded long, diagonally -shaped diamond indenter. The applied load and the size of indentation produced determines the hardness.

## ABRASION RESISTANCE

Abrasion resistance represents the resistance of the stone's surface to wear, usually caused by pedestrian traffic, the wheels of trolleys and the legs of furniture. There are many different test methods available for evaluating abrasion resistance, the results of which are often not compatible with each other. The ASTM C1353 and CSIRO BEST-6 methods are commonly used in Australia and are suitable for comparing the abrasion resistance of different stones, providing the tested surface is relatively flat. However, both methods cannot predict the in-service behaviour of inclusions, such as the 'soft veins' in some calcareous stones. These small calcitic veins usually occur in limestones and, among a number of deterioration mechanisms, may be preferentially eroded by abrasive traffic because they are softer than the host stone. Both methods only measure the abrasion resistance of the stones near surface zone, which may not reflect the properties at normal wear depth. In selecting stone for pavement materials, one must also allow for appropriate slip resistance, as measured in Australia according to AS 4586 and in its guidance for application use [8].

The ASTM C1353 method utilises the Taber abraser and standardised abrading wheels; it establishes a value of abrasion resistance by determining the loss of weight resulting from abrasion on flat specimens under controlled conditions (Fig. 2a). The index of abrasion resistance (Ha) is calculated from the weight loss and the bulk density of the specimen. It is a number, which is inversely proportional to the volume of the specimen removed during the test. The bulk density value used in the calculation is determined according the ASTM C97 method. The higher the Taber index, the more resistant the stone is to abrasion. The method has been used extensively in Australia, long before it became an ASTM procedure, in characterising the abrasion resistance of many Australian stones for pavement applications. Recommended abrasion limits for the Taber abraser method are listed in Table 7.

TABLE 7

TABER Abrasion limits for recommended applications

| PROPOSED USE | MINIMUM TABER INDEX VALUE (FROM SPRY [4]) |
|---|---|
| LIGHT DUTY, DOMESTIC | 8 |
| MEDIUM DUTY, LIGHT COMMERCIAL | 12 |
| HEAVY DUTY | 15 |

The CSIRO BEST-6 method is based on the European Capon method, which uses abrasive and a steel wheel to grind a chord into the stone (Fig. 2b). Like the Taber method, it establishes a value of abrasion resistance by determining the loss of weight resulting from abrasion. The CSIRO abrasion index is calculated from the weight loss and bulk density (as determined by the CSIRO BEST-2 method), the resulting number being inversely proportional to the volume of specimen removed. The higher the CSIRO Capon abrasion index, the more resistant the stone is to abrasion. For compatibility with the ceramic tile standards, the length of the chord is also determined.

Granites and bluestones (basalt) are highly desirable as flooring materials due to their hardness and uniform wearing qualities. The use of softer

Figure 2 – Determining abrasion resistance of stone using: (a) the Taber abraser method; and, (b) the Capon method.

stones for demanding applications may be difficult to justify in terms of the amount of repair and maintenance required over the expected life of the surface. Polished softer stones in dark colours may also tend to scratch white (e.g. some black marbles). Mixing stones of different abrasion resistance characteristics cannot only cause maintenance problems, but also uneven wear and potential slip hazards.

## THERMAL EXPANSION

Thermal expansion testing determines the extent of the dimensional changes exhibited by a stone unit as a result of changes in temperature. In the CSIRO BEST-7 method, a dilatometer is used to determine the linear thermal expansion coefficient in the temperature range from ambient to 100˚C. More precisely, the linear thermal expansion coefficient is defined as the ratio between the increase in length of the material being tested (corresponding to the increase in temperature $\Delta T$) and the product of its initial length and $\Delta T$. For example, if a stone had a linear thermal coefficient of 5 x $10^{-6}$/˚C, it would expand by 5 units in 1,000,000 when subjected to a temperature increase of 1˚C, or a movement of 100 units per 1,000,000 for a temperature change of 20˚C (i.e. 0.1 mm/m).

The thermal expansion in stone can vary widely. Darker tiles are likely to become hotter on exposure to the sun. Table 6 outlines typical linear thermal expansion coefficients for the major stone types. The manufacturers of some epoxy-based reconstituted stone have indicated that some products have a coefficient as high as 74 x $10^{-6}$/˚C.

Such test results are particularly useful where tiles are to be installed in conditions that are exposed to large temperature differences. It is important to consider this characteristic when planning a project so that one can assess the likely differential movement that may occur within a stone system, taking into account the characteristics of the other materials, which constitute the completed system with respect to thermal exposure. Consideration should be given (if applicable) to measuring the thermal expansion across and parallel to the grain of the specimen. Differential movements caused by temperature (and/or moisture) changes can lead to bond failures, warpage, bowing and cracking. Thermal expansion is usually reversible, however some marbles have been known to retain a residual expansion.

## ACCELERATED WEATHERING TESTS

'What will the stone look like five, ten, or many years from now?' This is a question architects should always ask their suppliers, especially for stone laid in external environments. It is often a very hard question to answer. Local stone products may be abundant, and usually have a recognisable track record in the industry. Imported stone, with possible exceptions such as Italian Carrara Marble, will not have the same local service record. They may have been extensively used overseas for generations, but stone can perform differently in the hotter and maybe more humid environments encountered in Australia. Even within Australia, a particular stone may behave differently whether it is installed in Darwin or in Hobart. Some stones (e.g. limestones, marbles, calcareous sandstones) are susceptible to acid rain and are thus not appropriate for some external applications, unless protected from the elements. If there is no track record of the particular stone, one can use chemical resistance testing (e.g. CSIRO BEST-11 or 12) and/or some form of an artificial accelerated weathering procedure.

### The Weather-o-meter Technique

At CSIRO we have developed a weather-o-meter that simulates weathering processes by using alternate cycles of high temperatures, ultraviolet radiation and humidity levels over a minimum six-week period. This procedure (CSIRO BEST-14) has been used to observe the following properties:

- colour changes (of minerals, veins, stylolites and fillings), general fading and loss of gloss;
- mineral staining (e.g. oxidation of pyrite);
- surface defects such as etching, pitting, swelling, flaking, cracking and chipping;
- dimensional changes and warpage (in combination with CSIRO BEST-9); and
- compatibility of stone sealers to UV radiation.

Such test results must be used with caution when predicting product lifetimes. However, when test results are used for comparative purposes, they can provide a very useful indication of the relative performance of stone products for particular applications and environments. Consideration should also be given to testing the durability of various sealers on specific stones. Although the test method does not address the degree of weathering attributed to (a) atmospheric pollution in urban environments, or (b) salt-laden coastal environments (see below), CSIRO does have facilities for testing stone in both simulated sulfurous atmospheres and various salt spray conditions. CSIRO also has a wide range of other climatically controlled environmental chambers and accelerated weathering facilities.

### Salt Attack

The deterioration of stone can be caused in many different ways. However, the susceptibility of porous stones (such as sandstone) to chemical

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deterioration and crystallisation erosion is of major significance in this country. One of the most fundamental tests on sandstones (and porous limestones) is determining their resistance to salt attack. Known in the industry as the sodium sulfate soundness test, it has now been adopted as an Australian Standard (AS 4456.10: Method A: - Masonry Units and Segmental Pavers; Method 10: - Determining Resistance to Salt Attack). It was initially developed from many years of research mainly by the UK Building Research Station and further refined in Australia by Spry [4, 6]. A good summary of its development and history of use in Australia can be found in West [9]. The test simulates cyclic wetting and drying in the presence of soluble salts and provides a measure of a stone's susceptibility to decay by crystallisation pressure. In general, the more porous and permeable the stone, the less resistant it will be to salt attack.

The Australian method subjects cut samples to 15 cycles of soaking in either 14% sodium sulfate or sodium chloride solutions, oven drying and cooling. The total mass loss of the particles is then determined, and the sample is classified into an exposure category: exposure, general purpose or protected. Spry [4] proposed the following durability classification system for sandstones based on the sodium sulfate soundness method.

| | |
|---|---|
| A CLASS (MOST DURABLE) | < 1% MASS LOSS |
| B CLASS | 1 - 5% |
| C CLASS | 6 - 10% |
| D CLASS (LEAST DURABLE) | > 10% |

Spry's classification system is still widely used in the Australian stone industry.

**CONCLUSION**

Dimension stone forms an attractive range of unique natural products that vary in their inherent characteristics. This article has shown that a sound understanding of these unique properties is essential when selecting stone and determining the maintenance requirements for any particular application. However, it must be emphasised that stones meeting the best performance characteristics can still fail in service if the stone is not properly installed or maintained. ⁎

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