ORNAMENTAL STONES NETWORK

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STONE CHARACTERISATION SECTOR

STATE OF THE ART

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Forward

To be written by the OSNET coordinator (Ioannis Paspaliaris)

Preface

ROBERTO BRUNO (+), MODESTO MONTOTO (*)

The State of the Art Edition on Ornamental and Dimensional Stones Characterisation points out and synthesises, for the first time in a unique presentation, all aspects concerning general and fundamental problems of the stone product qualification. The present Edition focuses on the three main aspects of characterisation, as the several and different "objects" of interest to be characterised, the modern technology available and the environmental standards. A complete list of references supports each of those three main topics.

OSNET Network and particularly the Stone Characterisation Sector have to be acknowledged for their effort to recall the stone world attention on an activity as stone characterisation that constitutes the base for further decision making, all of economic relevance and solidly based on the industrial point of view.

The main economic decision concerns in fact the existence of a stone deposit that is technically and economically exploitable. Any rock mass can be considered as a potential deposit, but only a feasibility study will allow the evaluation of the rock mass exploitation viability, by means of defining a final cash flow. In order to design a quarry it is necessary to know as many properties of the rock mass as possible. Indeed, any parameter to be used in a feasibility study is linked to many factors, some of which factors refer to the rock mass: recovery depends on joints spatial distribution; the intermediate and finished product type and value depend on aesthetical and physical-mechanical properties of the stone and their natural variability must be seriously taken into account; any exploitation design choice depends on morphological and geological properties; etc. It is evident that neglecting a complete rock mass characterisation is actually a non-industrial approach and it leads to investments of high risk. On the other hand, the transition from an attitude based on the personal knowledge and experience of each producer, to another one based on universal knowledge and experience and a continuous technical innovation, is an important goal for the E.U Stone industry and the OSNET.

The need for detailed stone properties knowledge grows when moving from the rock mass to the quarry. In that case the problem is more focused on the exploitation optimisation than on the exploitation viability. Again, any economic results depend on the interaction between the quarrying project choices (i.e. stope height, exploitation direction) and aesthetical and physical-mechanical properties of the stone (i.e. cut plane orientation, block dimensions, recovery). When ignoring the above factors, it is difficult to get the best exploitation results, from an economic and environmental point of view. Again it is a Characterisation Sector duty to point out the fact and deepen in the most important properties to be controlled at this stage.

In the stone industry, even for the same raw material, the possible products are several, and call for specific processing lines. A semi-finished product can be sold as it is (i.e. slates) or can be sold to a processing industry for the production of finished products. The properties of semi-finished and finished products determine the product value and usability, therefore the need of knowing as many of the product properties as possible is evident. For a producer, a wrong use of a stone product by the buyer is worse, from a marketing point of view, than a price discount. In addition, the product prices comparison can no longer be based just on subjective evaluations. The current commercial offer is many times based just on the image of one sample and without a numerical representation, will soon become an old practice. In fact, the market should be able to evaluate the validity of the advertised data. In short, stone products characterisation, either semi-finished or finished, will become the discriminating factor among the commercial offers. This fact is essential for the E.U stone products competitiveness.

Stone world is so traditional, that instruments for stone characterisation have remained unchanged for a long-time. However, this characterisation can be improved nowadays by the use of many effective technologies and by obtaining meaningful results at reasonable cost. Nevertheless, the new characterisation practice is still not much diffused and in some cases the technologies are unknown. Moreover, specific advanced technology was developed during the last years; specific on stone problems, advanced in terms of tools and results. Furthermore, the relevance of a proper qualification and its economic impact allows a correct evaluation and choice of the technology and of the sampling plans to be adopted. Things are different in case of plant or laboratory or field testing. Attention must be paid to the availability and significance of non-destructive testing, that allows the characterisation of actual selling elements (tiles, slabs, etc.) and not only of samples taken by somewhere and with their own geometric characteristics. The availability of technologies allowing reduction of subjective evaluation is becoming important, especially when such subjective evaluation can heavily affect product prices.

All the presented considerations can be materialised through the development and introduction of standards into the stone market. A first action of standardisation is testing, for getting meaningful data and for comparing the characterising figures. Then, the subsequent natural action is the products qualification, for guaranteeing the product quality to the buyer and for allowing him to compare alternative products. E.U, by the CEN Technical Committees and in particular by TC246, is playing a key role in the stone product valorisation. However, there are still different standards in the world and some of them must be known, given their importance in terms of market for E.U production. Certainly, the standardisation process related to civil works speeded up and in some cases started up the standardisation process in the stone world; the take off of this process has been initiated, but it requires a deeper evolution. Most of all, it requires continuous updating given the rapid and continuous evolution of the characterisation technology.

The Stone Characterisation Sector hopes that this Edition will help the E.U Stone industry to face the world competition; with such a final purpose in mind all the Members of this Sector contributed to this Edition; based on their complementary professional qualification, they tried to guarantee the best subjects development. The following paragraphs summarise the contents of the three main Chapters of the Edition, aiming to answer key questions of the Stone Sector and in particular on stone characterisation aspects.

Chapter 1, “Stone Characterisation and Targets”, covers a wide range of preliminary topics. These topics range from the properties that have to be characterised in terms of further productivity, recovery and costs of production, to more detailed geological and engineering characteristics of the exploitable rock mass and, also, to a classification of stone resources/reserves based on market economy criteria. In addition to that, the quarry characteristics, the objectives of the different stages of characterisation (focused on the evaluation of the optimised stone production level), the extractable block size, the long-term reliability of supply and the stability of the stone quality are discussed. Finally, the properties of the finished products are presented from a market requirements approach.

The second Chapter refers to "Stone Characterisation and Methodologies". Laboratory and in-situ methods, following destructive and non-destructive techniques, are described. The main characterisation topics covered are related to: petrography, following EN 12407, and chemical and physical characteristics, according to the Ornamental Stone Industry requirements. The Chapter ends with the description of image analysis technology, new in the Stone Sector, for inspection and classification of finished products, as another stage in the factory production line; this technique is able to detect stone defects and measure stone properties and characteristics that people consider as a basis for aesthetical evaluation, further industrial classification and, consequently, marketed price.

The edition ends with a fundamental Chapter on "Stone Characterisation and Standards"; a very valuable document on Standards from the different E.U members is compiled here; their necessary European harmonisation in the Stone Sector, the organisation of European Commission in this field, the existing Working Groups on the subject, the stone properties to be evaluated for each specific stone use and the test methods to be applied are exhaustively discussed for a practical day-by-day use by professionals in this Industry.

Finally, the authors believe that the present Edition will contribute in keeping the professionals in the Stone Sector informed about the procedures and techniques that are nowadays available for characterising stone deposits and stone finished products; the authors also believe that this effort should be continued in the future for a persistent updating of information and for contributing to the competitiveness of the European Stone Industry.

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Stone characterisation and targets

KLAUS GERMANN, KOSTAS LASKARIDIS, MODESTO MONTOTO, PAOLA MARINI, ROBERTO BRUNO, ANGELICA FRISA MORANDINI

1.1. Rock Mass Characterisation in a deposit

The present chapter describes those inherent properties of a Dimensional Stone deposit, which influence productivity, recovery and costs of production in relation to the rock properties essential for the deposit and product value. As demonstrated by Selonen et al. (2000) and Luodes et al. (2000), who present examples from Southern Finland, Dimensional Stones exploration is a systematic and stepwise procedure including desk studies, field mapping, detailed examination, geophysical (e.g. geo-radar) survey and core drilling. According to Selonen et al. (2000) the factors to be considered in the evaluation of a Dimensional Stone deposit are summarised in Table 1.

The study group "Natural Stone" of the Engineering Geology Section of the German Society for Geotechnics and German Geological Society, which acts as the National study group of Commission No. 10 "Building Stones and Ornamental Rocks" of the International Association of Engineering Geology, has published *general recommendations for geotechnical investigations with respect to the development or expansion of natural stone quarries* (Arbeitskreis Naturstein 1997). The following basic methods of investigation are useful in characterising Dimensional Stone deposits (Table 2):

- Compilation of topographic and geological information from all available maps and documentation.
- Detailed geological mapping in scales from 1:10.000 to 1:1.000 using natural and artificial outcrops.

- Opening of shallow test pits.
- Drilling (preferably core drilling).
- Surface geophysical methods (seismic, geoelectric, geomagnetic, radar measurements).
- Borehole geophysics (resistance, γ-ray, self-potential logging).

Table 1. Factors to be considered in the evaluation of a Dimensional Stone deposit (Selonen et al., 2000)

1\. Geology-based factors
1.1. Geological factors
1.1.1. Macroscopic factors
- Rock appearance (colour, structure, inclusions, stripes etc.)
- Soundness of the deposit (faults, fractures, shear planes, veins)
- Area, shape, depth/thickness of the deposit

1.1.2. Microscopic factors
- Mineral composition
- Grain size, shape, orientation, contacts
- Deformation and weathering state of minerals

1.2. Technical factors
- Density
- Porosity and water absorption capacity
- Modulus of rupture
- Compressive strength
- Flexural strength
- Hardness/abrasion resistance
- Workability
- Weathering resistance

2\. Non-geological factors
2.1. Economic factors
- Market demand
- Fashion and cultural value (colour/stone types)
- Price
- Product selection

2.2. Infrastructural factors
- Legislation
- Environmental aspects
- Storage of excess blocks
- Logistics
- Availability of labour

Based on the above methods, the following characteristics of the deposit and the enclosed rock mass have to be determined:

- Delimitation (boundaries) of the deposit/rock mass
- Thickness of the overburden
- Thickness of the mineable rock mass
- Discontinuity pattern

- Hydro geological situation
- Homogeneity of the rock mass

Table 2. Main methods of investigation used in the characterisation of Dimensional Stone deposits (modified from Arbeitskreis Naturstein, 1997)

Methods of investigation	**Characteristics of a Dimensional stone deposit**						
	Delimitation of the deposit	**Thickness / type of overburden**	**Thickness of the deposit**	**Discontinuity pattern**	**Hydro geological situation**	**Homogeneity**	**Suitability for sampling**
Detailed geological mapping	(+)	-	(+)	(+)	(+)	(+)	+
Test pit	+	+	-	+	(+)	(+)	+
Drill cuttings	(+)	+	(+)	-	(+)	(+)	(+)
Drill core	+	+	+	(+)	+	+	+
Surface geophysics	(+)	(+)	(+)	-	-	(+)	-
Borehole logging	(+)	(+)	(+)	-	(+)	(+)	-

Legend: + useful (+) partly useful - not useful

A much simpler but more market-oriented approach was used in a *Dimensional Stone feasibility study* of Michigan's Upper Peninsula by Borque et al. (1999) for the selection of locations with the best potential for quarry development. A rating system was set up to determine, which sites were the best candidates. Four criteria were used and rated on a 1 to 5 scale basis (with 5 being a good rating):

- *Location*: evaluation of the site's accessibility, the proximity to residential/business area and the availability of existing infrastructure.
- *Colour*: Evaluation of the stone colour based on current market trends and the stone potential to satisfy these trends.
- *Texture*: Evaluation of the stone texture and its applicability to popular uses of Dimensional Stones.
- *Stone deposit*: Evaluation of how extensive the deposit is, how fractured it is believed to be, how consistent it is believed to be, etc.

In many industrialised countries, guidelines and codes for reporting mineral exploration results, mineral resources and mineral/ore reserves, including industrial minerals in their widest sense, are available. In Europe for example, the *Code for Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves (The Reporting Code*) is effective since October 2001 and is available at the website of the European Federation of Geologists (www.eurogeologists.de). The Code was published by the Institution of Mining and Metallurgy (Working Group on Resources and Reserves) in conjunction with the European Federation of Geologists, the Geological Society of London and the Institute of Geologists of Ireland.

The *European Code of 2001* sets out minimum standards, recommendations and guidelines for public reporting of mineral exploration results, mineral resources and mineral reserves in the United Kingdom, Ireland and Europe. The Code is applicable to all solid minerals, including metals, gemstones and bulk commodities, such as coal and iron ore, industrial minerals, stone or aggregates. In the case of industrial minerals, stones and aggregates factors such as quality and marketability are important and should be carefully considered before declaring mineral reserves.

1.1.1. Deposit types

Rough block extraction from a Dimensional stone deposit strongly depends on the deposit type. Regarding the degree of disintegration and weathering of the initial rock mass, the following types can be distinguished:

- *Boulder formations*. They are unconsolidated (loose) deposits of residual core-stones mainly of magmatic rocks (often in a clayey-sandy matrix) which have resisted deep weathering. Boulder quarrying is still widespread in the third-world countries. According to Nelles (1996), the majority of granite blocks production results from boulder formations, which are exploited by the simplest technical means (Figure 1a).
- *Semi-consolidated formations* represent near-surface transitions between the strongly weathered boulder zone, which may already be eroded, and the non-weathered fresh rock. In this case, the fracture system is partly opened and oxidation of Fe^{2+} minerals and kaolinisation of feldspar has started. Quarrying and block extraction follow mainly the open discontinuity system (Figure 1b).
- *Massive formations* of fresh, non-weathered rocks which can be mined in surface and underground quarries with a wide variety of cutting and extraction technologies (Figure 1c).

Weathering related to mineral alteration and the accompanying discolouration effects are more likely to occur in the stones produced from both boulder and semi-consolidated formations than from massive formations. In weathered deposits it is much more difficult to estimate the reserves of fresh rock available for quarrying, and consequently, the reliability of long-term supply of constant stone quality can be strongly reduced.

1.1.2. Characterisation of the overall geological situation

Regional geological reconnaissance programs for Dimensional Stones should be designed to identify prospective geological units through a general geological mapping survey (Harben & Purdy 1991). This must include mapping of the rock units together with collecting observations and data concerning the geological history of the area, particularly regarding deposition or intrusion and tectonic situation. This is followed by core drilling on a wide pattern designed in such a way that helps in determining the geological structure, continuity, and soundness of the rocks.

Field investigations in a deposit area are also the basis for identification of the stratigraphic sequence, possible trends of lithologic variation, extension and shape of the stone mass, deformation patterns and especially for the detailed measurement of the existing discontinuity system.

a) b) c)

Figure 1. a) Boulder quarrying of a deeply weathered granodiorite massif (Western Anatolia, Turkey), b) Quarrying in a semi-consolidated weathered zone of a granodiorite (Saxony, Germany), c) Quarry in fresh, massive granite (Northern Bavaria, Germany).

Figure 2 shows a geological map from an area in Greece with different marble types. Figure 3 gives an impression of the lithologic variability of a metacarbonate-bearing series intruded by granite. The section was constructed from observations in quarries and from drill holes. Figure 4 exhibits the distribution of marble types, characterised by different degrees of fracturing, in a geological map.

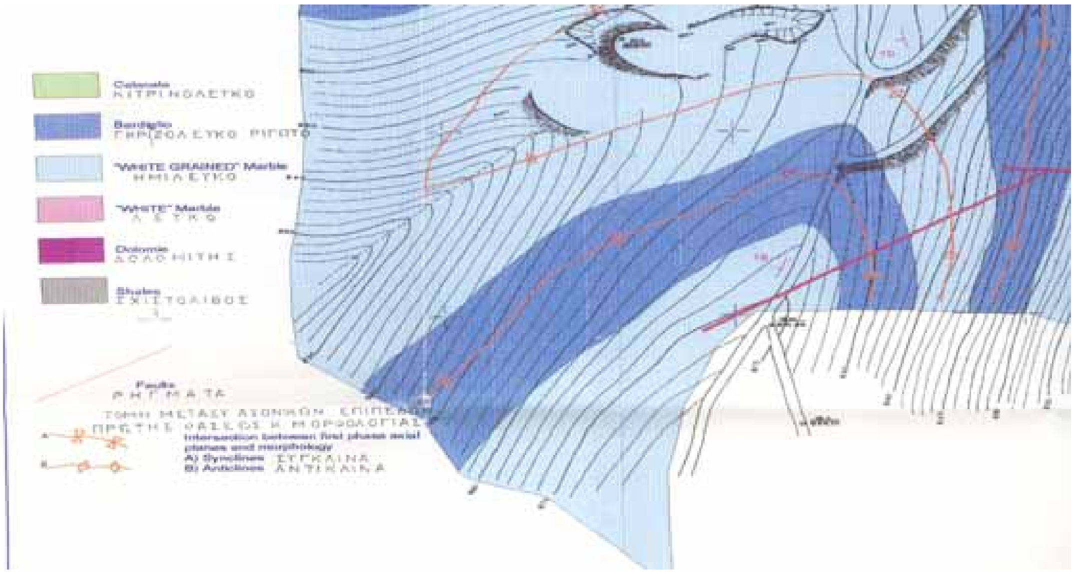


Figure 2. Geological map

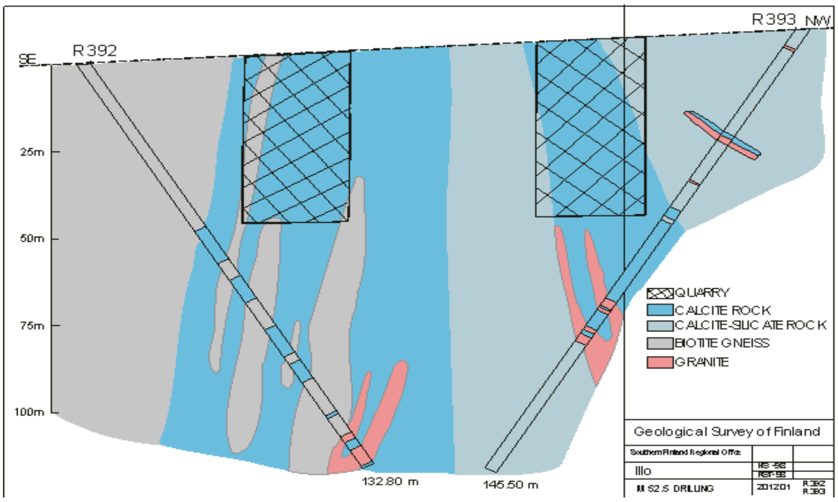


Figure 3. Geological profile containing drill holes

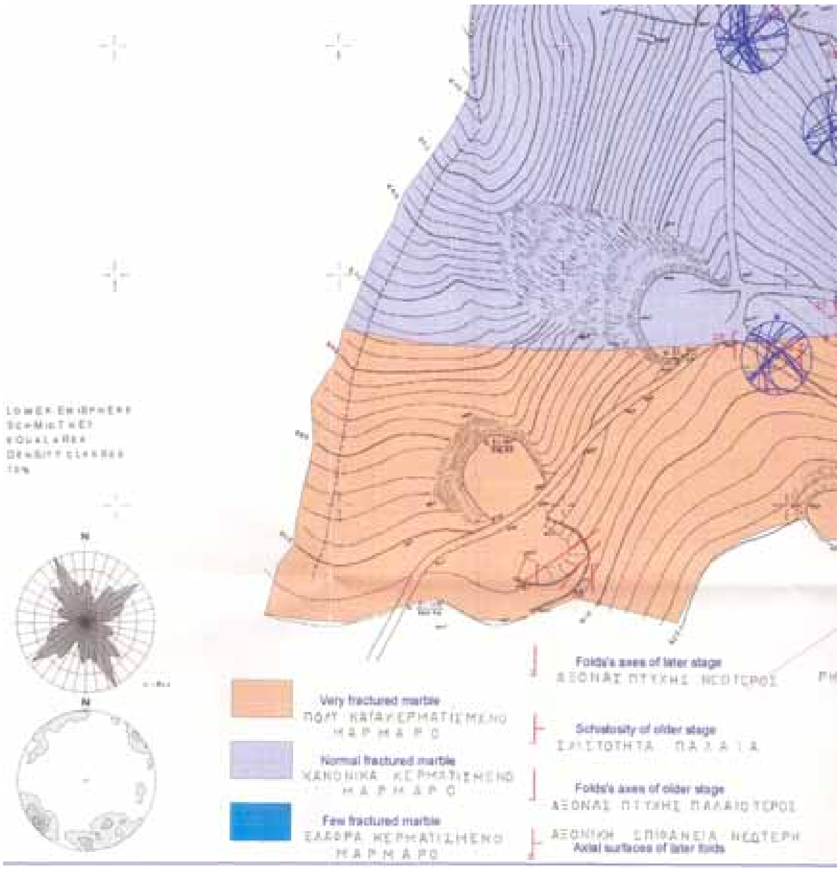


Figure 4. Marble fractures map

1.1.3. Preliminary petrologic classification: magmatic, metamorphic, sedimentary

Earth, under the combined effect of thermal and gravitational energy, is classically considered as a gigantic machine that, since its origin, is creating and destroying lithosphere; tremendous stresses deform and elevate some parts of the Earth's crust, and the oceanic lithosphere is carried down at depths of hundreds of kilometres into the upper mantle.

Those highly dynamic processes are clearly manifested in both the Earth's interior and in the rocks, met at her surface. At surface, mountain ranges uplifted, later they were weathered, eroded, transported, and sedimentary rocks were thus formed; at depth, the existing rocks, under very high pressure, temperature and volatiles, underwent deep mineralogical and textural changes and metamorphic rocks were formed or, even, locally melted and later crystallised forming igneous rocks. Those genetic and post-genetic geological events constitute the rock cycle and its products, which are the Dimensional Stones (Figure 5). A geological cross section of an idealised zone, where different rock formations – as a consequence of the aforementioned processes - coexist, is shown in Figure 6.

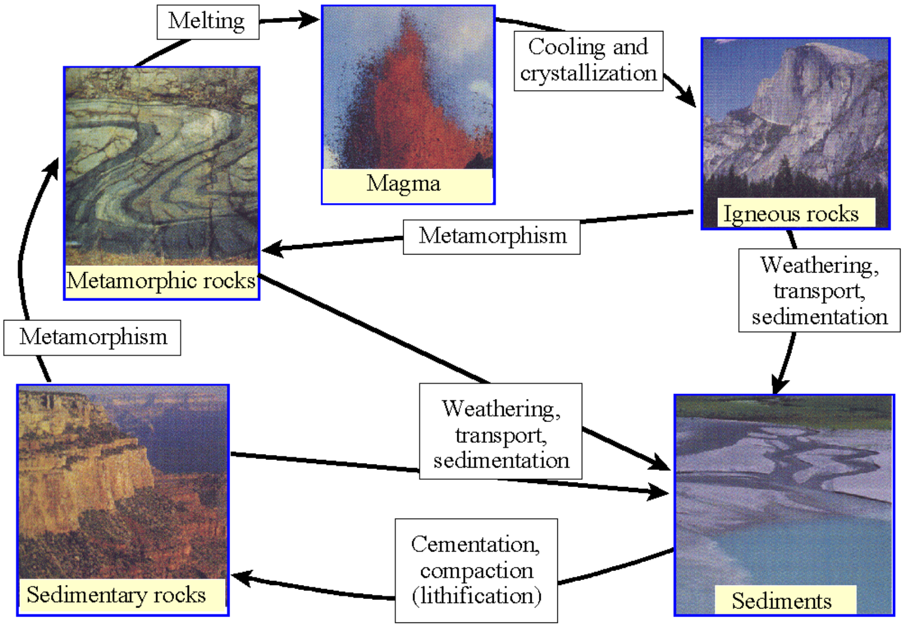


Figure 5. Rock cycle; scheme of the main geological processes for rock transformations (Lutgens and Tarbuck, 1996).

Rocks, as observed with the naked eye or microscopically, show distinctive characteristics due to the kind of genesis and transformations that they went through along their geological history. In general, sedimentary rocks are typically layered, volcanic rocks show evidence of flow and fast cooling plutonic rocks are massive and sometimes with signs of movement and crystallization, and metamorphic rocks are largely deformed with folded structures that reflect their plastic flow behaviour. In addition, they commonly show an alignment of grains that gives a flaky, banded or layered appearance.

In the field, it is advisable to map the rock mass and draw cross sections, mainly along the zones of contact between different rock types; in these sections all the available structural, lithological and other information must be recorded. When sampling, it is very important to draw the orientation of samples in relation to the main local structures and to take notes about some general petrographic characteristics of the sampled rock-mass: structure, texture, granulometry, weathering degree, identified rock-forming minerals, colour and so on. The petrographic classification is a laboratory test that requires a textural and mineralogical analysis under a petrographic microscope; in the field only a preliminary rock classification can be established.

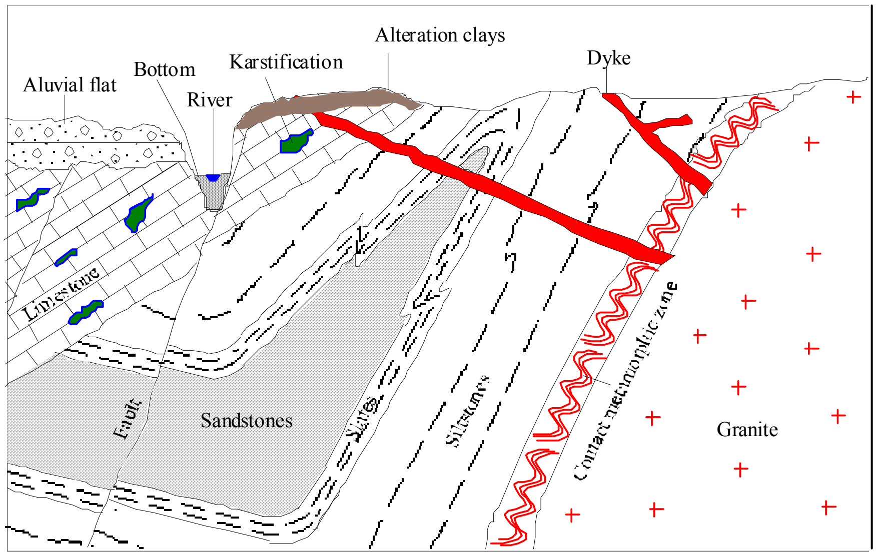


Figure 6. Cross section of an idealised geological zone with sedimentary, metamorphic and igneous rocks.

Almost every variety of rock can or has been used as a Dimensional Stone. The suitability of a particular rock for use as Dimensional Stone is determined primarily by aesthetic and physical properties, whereas mineralogy and chemistry mainly affect the resistance of a rock to weathering. Mineralogy- and chemistry-based petrologic classification, using the standard geologic nomenclature and classification of rocks, is needlessly cumbersome for an industry which is denominated by non-scientific, sales-oriented people and architects (Power, 1994). CEN (prEN 12670) and ASTM (C119-90) have adopted standard scientific and commercial definitions for large stone groups and their varieties. A preliminary classification of Dimensional Stones should use the three large genetic groups, such as igneous, sedimentary, and metamorphic, or the main market-oriented groups of granite, limestone, marble, greenstone, sandstone, and slate.

Sedimentary rocks have been formed on Earth surface through very different geological processes; weathering and erosion destroyed, both physically and chemically, the exposed rocks; the particles so liberated are solid fragments of clay, quartz, feldspar, mica, and aqueous solutions of ions such as Ca, Na, K, Fe, Mg, HCO^{3-}, etc., as well as molecules, mainly of dissolved silica. All these weathering products have been transported by water, wind and mass flow and deposited into areas of lower relief, either within the continental landmass or at the continental-oceanic boundary. There, they have been lithified through processes of cementation, recrystallisation and compaction. Therefore, sedimentary rocks consist of accumulations of clastic and non-clastic materials: fragments of rocks, minerals and fossils, chemical and biochemical precipitates and combinations of these materials. The resulting products are rocks extremely different in texture, mineralogy and chemical composition, such as conglomerates, breccias, sandstones, limestones, dolomites, mudstones, cherts, evaporites, etc.

Metamorphic rocks are formed at variable depths into the Earth's crust, through mineralogical and textural transformation of previous sedimentary, igneous and, even metamorphic rocks (Figure 7). These transformations and deformations represent the response of the rock, which cannot support the new thermodynamic conditions: temperatures in the range of 100 - 800^{o}C, hydrostatic pressures of about 200 – 900 MNm^{-2}, as well as oriented stresses and chemically active fluids or gases. The main types of metamorphism are presented in Table 3.

Table 3. Main types of metamorphisms.

Type	Mapping characteristics	Agent	Representative rocks
Contact	Aureole between the intrusive igneous mass and the non-metamorphised country rock	Heat transfer and fluids from the intrusion	Hornfels Skarns
Regional	Largely extended zones in mountain belts	Increasing P and T	Slates, Schists Gneisses, Marbles
Dynamic	Localised along shearing zones	Very high shearing stresses and temperature	Mylonites

Igneous rocks are formed by crystallisation of magma. Magma is easily defined as a molten rock; in fact it can be formed by three different phases: solid (minerals or rock fragments), liquid (the melt) and volatile (gases, such as H_2O, CO_2, O, H, S). According to the way magma was crystallised of the Earth's surface or in its interior intruding at variable depths in the Earth's crust into other rock formations, igneous rocks can be classified into extrusive (volcanic) and intrusive (plutonic) rocks. As a consequence, they differ in their field characteristics, relationships with the country rock, textures, presence or absence of gas-bearing vesicles or amygdules. The textures are generally glassy to fine-grained in the volcanic rocks, due to their rapid cooling and fine- to coarse-grained in the plutonic, where crystallisation was extremely slower, and therefore glass can never be found in them; besides, the flow textures in some volcanic rocks clearly evidence the low viscosity of the flowing magma.

Concluding, such a classification although petrological, points out that there are natural differences between characteristics of the various lithological types, coming from their mineralogical composition, their genetic conditions, etc., as it is demonstrated in Table 4.

Table 4. Basic characteristics of the main lithological types

Stone type	Water absorption (%)	Open porosity (%)	Apparent density (kg/m3)	Compressive Strength (Mpa)
Granites	0.2 to 0.5	0.4 to 1.5	2600 to 2800	110 to 240
Diorites and Gabbros	0.1 to 0.4	0.2 to 1.0	2800 to 3000	150 to 300
Basalts	0.1 to 0.3	0.2 to 0.8	2900 to 3100	170 to 350
Marbles	0.2 to 0.8	0.3 to 1.8	2600 to 2900	60 to 180
Limestones	0.1(5) to 1.7	0.2(5) to 2.5	2200 to 2700	40 to 220
Sandstones	0.6 to 13.8	1.6 to 26.0	1900 to 2600	30 to 150
Schists	0.4 to 1.5	1.2 to 3.5	2600 to 2800	30 to 70

1.1.4. Geometry of Dimensional Stone deposits

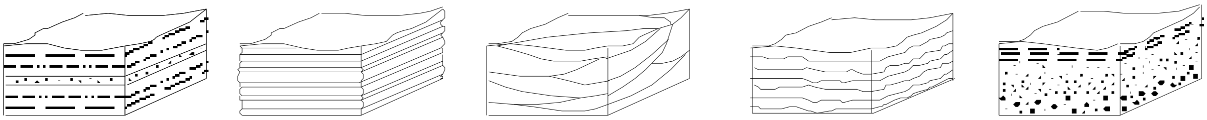
The field characteristics of any rock deduced from geological mapping, its surface and internal structures, its geometry, the character of its contacts with other surrounding rocks, resume its most outstanding genetic and historical features; accordingly, it is possible to resume the main distinctive characteristics of the three main genetic groups: sedimentary, metamorphic and igneous.

Layering is the most common feature in *sedimentary rocks* (Figure 8); their particular genetic conditions during transport and deposition are shown in their structure such as flat, tabular, planar. The most common bedding characteristics of sedimentary rocks are shown in Figure 9.

Metamorphic rocks, according to their field characteristics deduced after geological mapping, can be classified into contact, regional and dynamic; the agent responsible for the metamorphism is thus deduced. Table 5 summarises all these aspects as well as their main geometrical characteristics. There are two main *igneous rock types:* the volcanic (or extrusive) and the plutonic (or intrusive); they show different field characteristics (Figures 10-13). The first type, depending on its viscosity, which in fact reflects the SiO_2 content, has been flowed on the surface, forming very large deposits, or has consolidated very close to the outer surface; therefore, layering, as in sedimentary rocks, can also be found in igneous rocks, such as basalts flows, but their field, textural and mineralogical characteristics are completely different.

Figure 7. Isolated slate sheet along its well defined cleavage planes

Figure 8. Dipping of planar bedding in limestone.



Flat tabular sheet Planar bedding Lenticular bedding Irregular (nodular) bedding Graded bedding

Figure 9. Different types of bedding characteristics of sedimentary rocks

Among the extrusive structures, the largest are the lava plateaus and the basaltic plains; the first sometimes constitutes enormous deposits of many millions of square kilometers of basaltic lavas, covering a surface larger than one million square kilometres and several kilometres thick. Other volcanic structures such as pyroclastic sheet deposits, shield and composite cones and calderas have a wide variety of extension and thickness.

The intrusion of magma through the surrounding rocks and the way it is emplaced to zones closer to the surface largely depends on the country rock structure and its mechanical behaviour (which in fact depends on the intrusion depth). Based on their size and geometry, the most common forms or bodies of igneous intrusive rocks are summarised in Table 5.

Table 5. Main igneous intrusive bodies

Plutons	Generic name for large bodies of igneous rocks emplaced and crystallised in depth. Usually heterogeneous; concordant or discordant contacts with the structure of the surrounding country rocks. In general, considered to be of “indefinite” vertical extent. Plutons include batholits, stocks and plugs; dykes and sills from the main pluton are often named “offshoot”.
Batholits	Large volumes of plutonic rocks, generally discordant, the outcrop area of which is larger than 100 km^2. Some have been detached from their source pluton by a diapiric intrusion.
Stocks	Small volumes of plutonic rocks, with an area of less than 100 km^2.
Dykes	Tabular or wall-like intrusions, which cut across the structures of the country rocks.
Sills	Tabular intrusions parallel to the planar structures in the surrounding rock; generally injected between bedded rock formations.
Lopoliths	Large volumes of plutonic rocks; generally concordant and with a plano-convex or lenticular shape depressed in the centre.
Cone sheets	Conical dykes that converge towards a central point. On the map they are usually represented as concentric sets of dykes dipping towards a centre of igneous activity
Ring dykes	When mapped they show arc forms dipping away from a central zone of igneous activity.

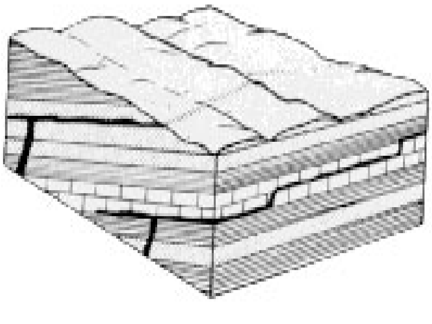


Figure 10. Tabular intrusion of igneous rocks: sills (concordant) and dykes (discordant)

Figure 11. Dykes of basic igneous rocks lamprophyres (spessartite, vertical), cutting the camptonite (sub horizontal) intruded into the granitic country rock

Figure 12. Overlying basaltic lava flows

Figure 13. Veins of aplite intruded in the country granitic rock along the fractures

1.1.5. Estimation of rock volume and deposit size

Apart from the quality characterisation of the rock mass, the estimation of its volume is of decisive importance in the economic evaluation of a Dimensional Stone deposit. For the calculation of the volume of deposits there is a variety of available standard **geometrical methods** (Wellmer, 1998). These methods fall mainly into two categories: volume/reserve calculation on the basis of cross sections and on the basis of longitudinal planar sections or level plans, respectively. Only the order of magnitude will be available in this early phase of deposit characterisation, but evaluation does not yet aims at accurate economic assessment and should rather contribute to an estimation of the possible lifetime of a deposit.

However, in this early phase of deposit characterisation, **geostatistical methods** (Goovaerts (1997), Houlding (2000)) can be usefully applied for the assessment of the mine able rock volume – provided that sufficient information about the overall geological situation, the lithological and structural pattern of the rock mass and the rock quality attributes is available.

The typical sequence of a geostatistical study comprises exploratory data analysis, quantitative modelling of spatial continuity, prediction of attribute values at unvisited locations by a linear regression estimation method (kriging) and assessment of the local and spatial uncertainty. In the case of Dimensional Stones, measurements of primary attributes are inevitably supplemented by secondary information originating from other related categorical (for instance lithotype, colour) or continuous (petrophysical variables) attributes. To incorporate secondary data a wide variety of kriging algorithms is available: the “cokriging” and especially the “collocated cokriging” approach and “kriging with external drift” are improved estimators designed to incorporate exhaustively sampled secondary information (Goovaerts, 1997).

With the help of multivariate statistical techniques indexes, may be obtained as a function of the multitude of factors or attributes determining quality and recovery of a Dimensional

Stone. These indexes can be taken as regionalised variables, which allow the estimation of the quality of a Dimensional Stone in hidden parts of a deposit (examples for granite and slate deposits in Taboada et al. 1997, 1998, 1999). In a regional study of a marble region, Albuquerque et al. (1999) have demonstrated the usefulness of defining a multivariate recovery index for the stone as a regionalised variable and using geostatistical methods such as kriging with external drift and soft kriging. Geostatistical methods reach their maximum importance in the evaluation of resources in a later stage of exploration when information from drillings and quarry faces is accessible. Definition and derivation of combined quality factors or indexes and geostatistical characterisation of the quality distribution within the stone deposit will then be achieved with improved evaluation approaches (see Chapter 1.2.2).

1.1.6. Rock Mass Structures

Rock mass structures are of outmost importance in the development of quarry plans and the assessment of the stability of surface and underground quarrying operations. Deformation structures and patterns may also belong to positive or negative quality factors, and they influence stone production from blocks cutting until the final processing steps. There are 3 major aspects to be considered in a structural geological study of a deformed rock body. These aspects are interdependent and none of them can be ignored:

- *Geometric*: a three-dimension quantification of the positions and orientations of lithological and structural features. These data are derived from mapping, geophysical interpretation, thin section study, and any other technique which can yield such data.
- *Kinematics*: a quantification of the history of motion of parts of the deformed rock mass (movement senses, directions, amounts, rates relative to one another).
- *Mechanical*: an understanding of the forces that have been applied to the deformed rock mass, and of the physical and chemical response and rheology of various parts of the rock mass to those forces under determined or assumed conditions of pressure, temperature, deviatory stress, fluid pressure and activity, and so on. There may be foliations, schistosities, cleavages and bedding planes presented locally or throughout the material (Figures 14-17).

This information is used in order to understand the *processes* of rock deformation (Figure 14), and then can make *predictions* about the likely behaviour of parts of a rock mass during quarrying (where and in which orientations fault zones might influence the extension of a useable rock mass, which pre-existing faults and joints might influence the stability of the rock mass) and also during the preparation of the finished product (e.g. the influence of schistosity on the mechanical behaviour of a stone). Such an understanding of structures is extremely important in the early phases of exploration of a Dimensional Stone deposit.

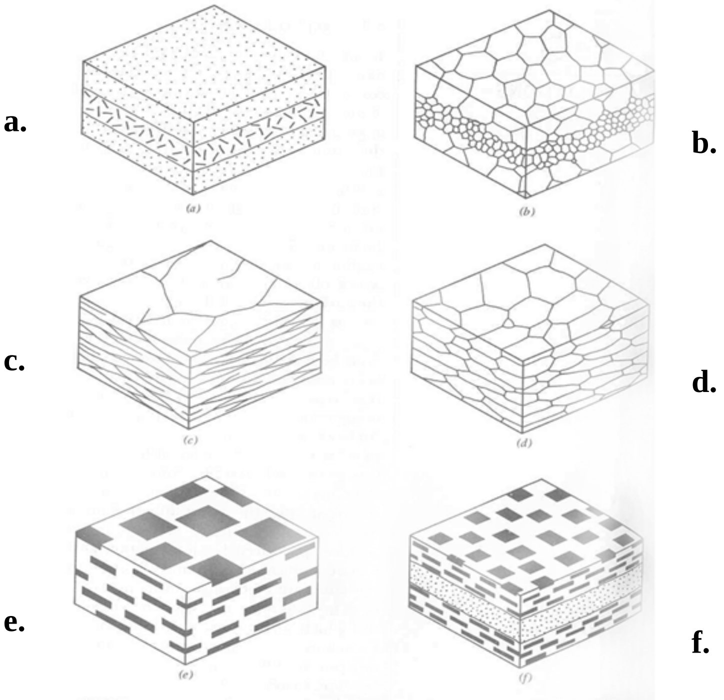


Figure 14. Various types of foliation. The foliations are defined by: (a) compositional layering; (b) grain- size variation; (c) closely spaced, approximately parallel discontinuities such as microfaults or fractures; (d) preferred orientation of grain boundaries; and (e) preferred orientation of platy minerals or ventricular mineral aggregates. These various microstructures may be combines and (f) shows a combination (a+e) that is very common in both sedimentary and metamorphic rocks.

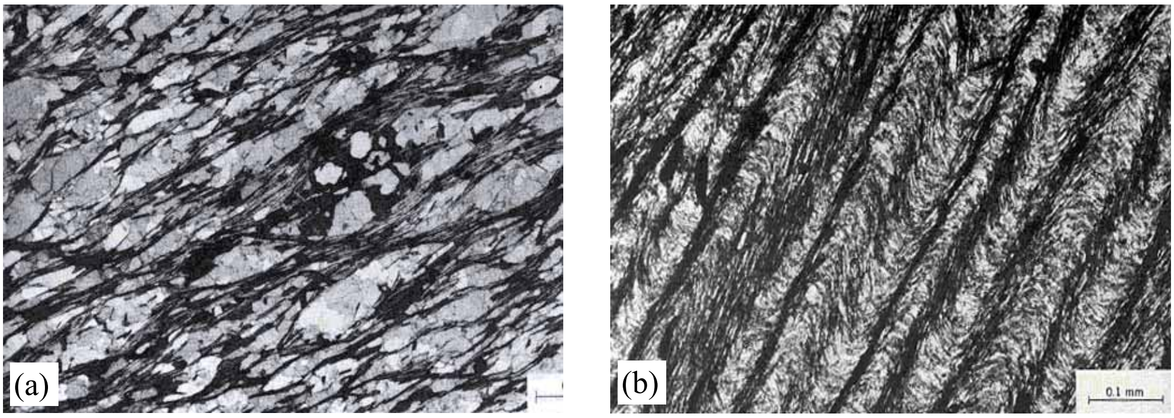


Figure 15. Crenulations cleavage parallel to the axial plane of a small fold in quartz mica phylite. (a) Cleavage seen in hinge of fold. Here the crenulations are symmetrical and the cleavage is defined principally by the limbs of the tighter crenulations. This is logically defined by microfaults developed within the limbs of the crenulations and oriented parallel to their axial planes. Plane-polarised light (Photograph by W.C. Laurijssen). (b) Cleavage seen in limb of fold. Here the crenulations are asymmetrical and the cleavage is defined principally by microfaults, which are particularly well developed at the left-hand side of the photograph. Plane-polarised light (Photograph by W.C: Laurijssen).

Figure 16. Transposition of carbonate-rich layers in slate near Duchtown, Tennesee. Isolation of the fold hinges may have been achieved in part by metamorphic differentiation. (R.J. Holcombe, personal communication). Note that bedding in the slate is much less folded at the left of the transposed layer and shortening has apparently been achieved by a more homogeneous flattening

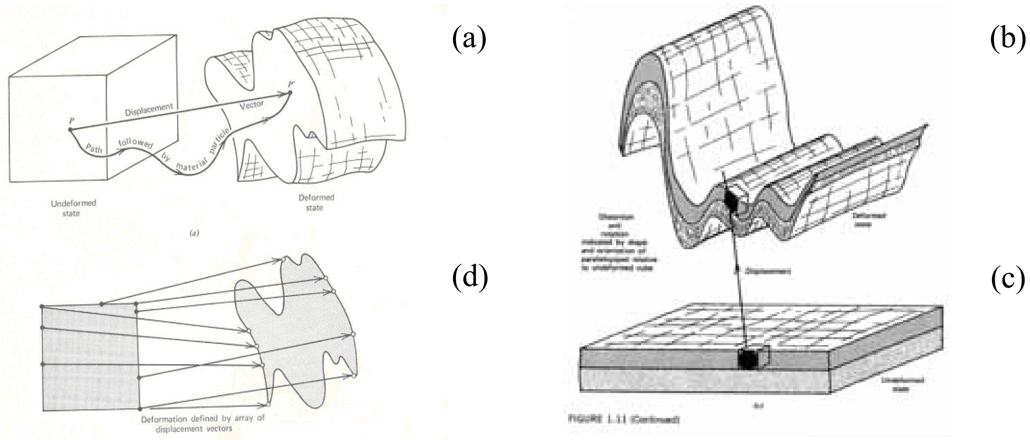


Figure 17. (a) An inhomogeneous deformation where point P in the non-deformed state becomes point P' in the deformed state. The actual path followed by P' during the deformation is the curved line. The vector PP' is the displacement vector that defines the displacement of P. (b) the array of displacement vectors that defines a deformation. (c) An inhomogeneous deformation in which flat sheets in the deformed state become folded in the deformed state. A small cube with a circle inscribed in the non-deformed state becomes a parallelepiped with an inscribed ellipse in the deformed state. The deformation of this cube may be expressed as a displacement together with a distortion and a rotation. (d) Displacement vectors for an inhomogeneous deformation. AB and CD are equal and parallel in the non-deformed state but this is not true for A'B' and C'D' in the deformed state

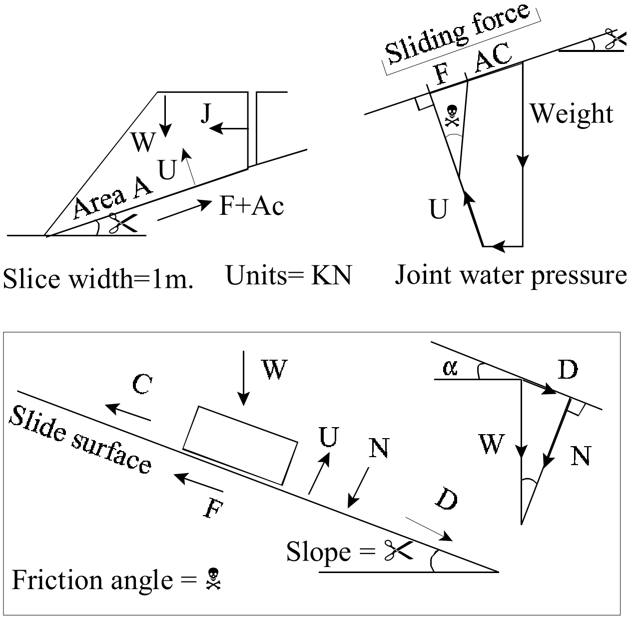
1.1.7. Rock mass stability: pre-assessment based on structural situation

As it is already mentioned in the preceding paragraphs, the structural situation of a Dimensional Stone deposit is an important factor of the stability of surface and underground excavations and, thus, exerts strong influence on productivity and safety in stone quarrying.

The analysis of the stability of a rock massif implies the evaluation of all the gravitational and non-gravitational forces acting there (Figure 18).

Stability is basically controlled by the geological structure (mainly discontinuities), groundwater, lithology, in-situ stresses and topography. Discontinuities, such as faults, joints, cleavage, sheeting ("onion skin" joints in granite), schistosity, bedding planes etc., represent the weakness planes capable for structural breaks in the rock massif, conditioning slope failures and landsliding. Consequently, they deeply affect the engineering properties and behaviour of the rock massif. Another adverse agent for stability is water; its presence not only modifies the weight and the gravitational stresses exerted by a rock mass, but also reduces the shearing strength of discontinuities, generates internal forces against their walls (Figure 18), develops seepage forces due to the groundwater flow along slope faces, promotes weathering destabilizing slopes etc.; drainage is the most appropriate solution to remedy this adverse water influence. The different geological and engineering aspects related to stability have been studied extensively (Blyth and de Freitas, 1986; Hudson, 1989; Grandjean and Gourry, 1996; Hoek, 2000; Agliardi et al, 2001).

Heterogeneity and anisotropy of structure and lithology which is one of the most outstanding geological and geotechnical features, has to be given special consideration here; as, rock massifs and their components (discontinuities and intact rock) show different properties in different locations and directions.



Legend:
W = weight of block, with two components (D and N) F = frictional resistance on slip plane = N tanΦ
D = driving force = W.sin α R = resistance to shear = c + (W cosα – u) tanΦ
N = normal stress on slip plane = W.cosα – u J = Joint water pressure
u = uplift force due to pore water pressure Safety factor = R/D = resistance/driving force
C and F = resistances in reaction to D C and Φ are properties of the rock material

Figure 18. Basic forces in a two-dimensional slope stability analysis (Waltham, 1994, modified).

Pre-assessment of the rock mass stability basically lays to the following elements:

a) Geometrical configuration of discontinuities: orientation, spacing, persistence, roughness and aperture (Brown, 1981) (Figure 19) has to be measured; also, some other characteristics, such as their filling and seepage, have to be rated. Faults have to be described in terms of their relative movement and throw. For the estimation of roughness, a graphic representation of standard profiles and corresponding JRC (Joint Roughness Coefficient) values can be found in Barton and Choubey, 1977. The accurate measurement of the orientation and inclination angle and dip of all the studied discontinuities is a key aspect here; in cases where the direct measurement of the true dip is difficult, it will be evaluated through the measurement of apparent dips (Blyth and de Freitas, 1986).

b) For the structural analysis of discontinuities, they have to be stereographically plotted, along with the geometry of the local topography (Figure 20). Many software programs (Dips, Stereonett, etc.) facilitate this tedious plotting of structural data. From these plottings, discontinuities can be structurally grouped into different sets or families and the characteristics of each of them can be better documented in the geotechnical map.

c) All the geological features that are mechanically significant in the deposit, such as structure (bedding, unconformities, folding, intrusions), discontinuities, lithology (including their different degrees of weathering and potential cavities), and hydrogeology, have to be represented in a geotechnical map, which in the most conflictive zones, have to be complemented with well documented structural and lithological cross sections.

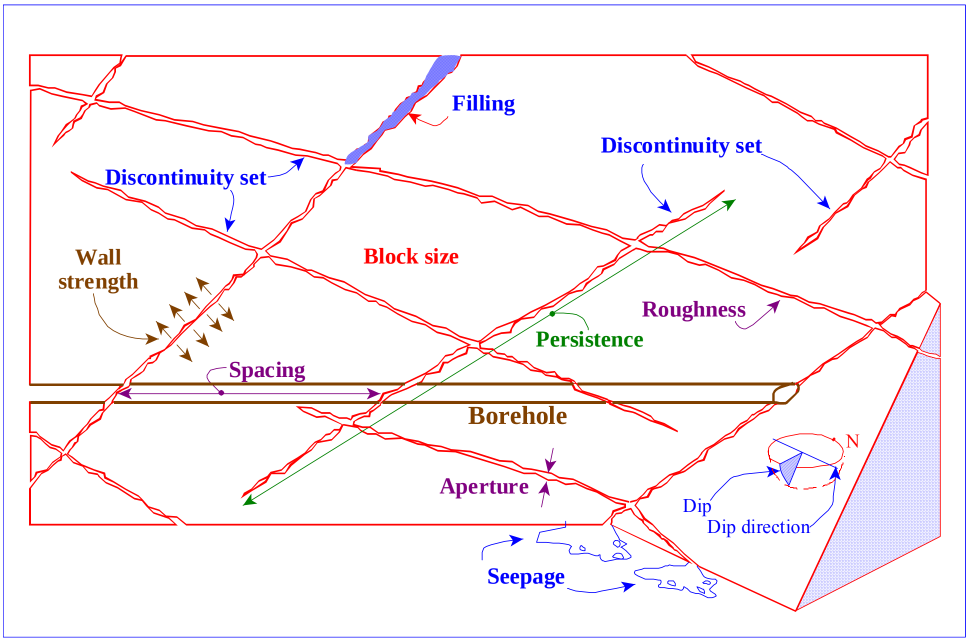


Figure 19. Main geometrical characteristics of discontinuities (Hudson, 1989, modified)

All the geological information obtained up to here, will allow a first identification of the favourable and unfavourable orientation of discontinuities, the location of potential weakness planes and the evaluation of the rock volume they limit. Many software programs have been developed for helping in this type of rock mechanical problems; they provide information about block size and weight, stability, (STEREOBLOCK, Hadjigeorgiou et al., 1995; Hobrslp, Sonmez et al., 1998; UNWEDGE, Rocscience, 2002). A pre-assessment of stability is thus established. For a more complete pre-assessment, a “Rock Mass Classification” can be applied. For this classification and for the structural analysis just described, many helpful documented tables exist in literature; among them “Typical problems, critical geological parameters, methods of analysis and acceptability criteria for slopes and for hard rock mining excavations” in Coggan et al. (1998) and in Hoek (2002) stand out. In addition, the shear strength parameters along sliding surfaces (c, cohesive strength and Φ, friction angle) could be estimated for very different refilling materials and for rock masses of different character (Hoek and Bray, 1974; Barton, 1974; Hoek, 2000); therefore, the shear strength of those joints or fractures, which the previous structural exercise anticipated as potentially unstable, can be estimated.

Finally, instability is manifested by different types of movement (rolling and turning of blocks, slow down-slope gravitational movement, etc.) or failure (detachment of rock as rock falls and topples, shear failure on long-range discontinuities, fall of roof wedges in underground cavities, etc.); some of them are illustrated in Figure 21. Those movements and failures confirm that the strength of the affected discontinuity has been overcome; therefore, the estimated values of shear strength parameters can be revaluated more precisely.

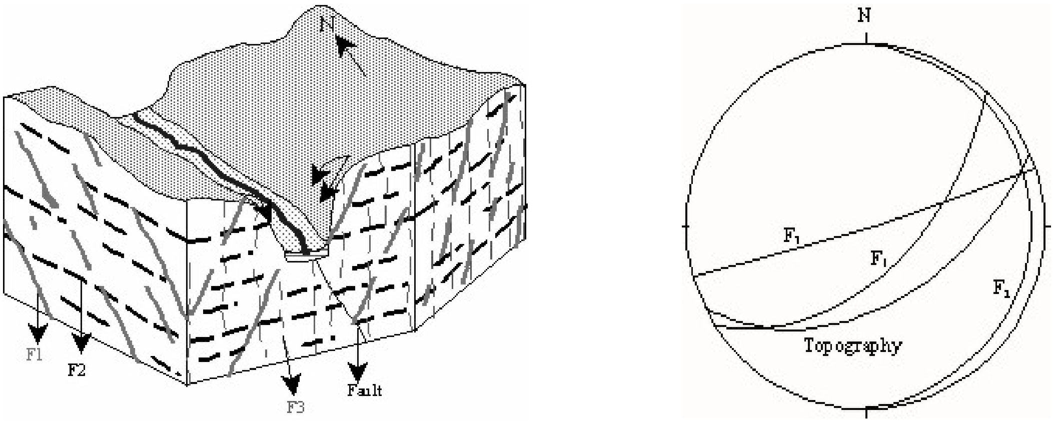


Figure 20. A block diagram of a rock mass and the stereographic projection of its main joint planes are two basic tools for analyzing the influence of a simple geological structure upon the stability of slopes in a cutting.

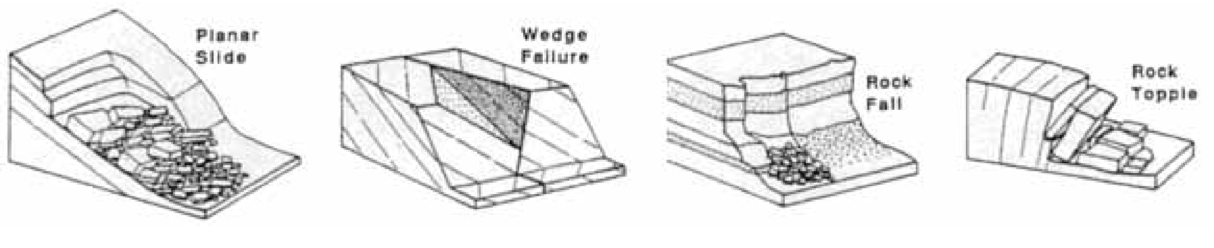


Figure 21. Main types of rock mass failure, discontinuities and topography relationship (Waltham, 1994, modified).

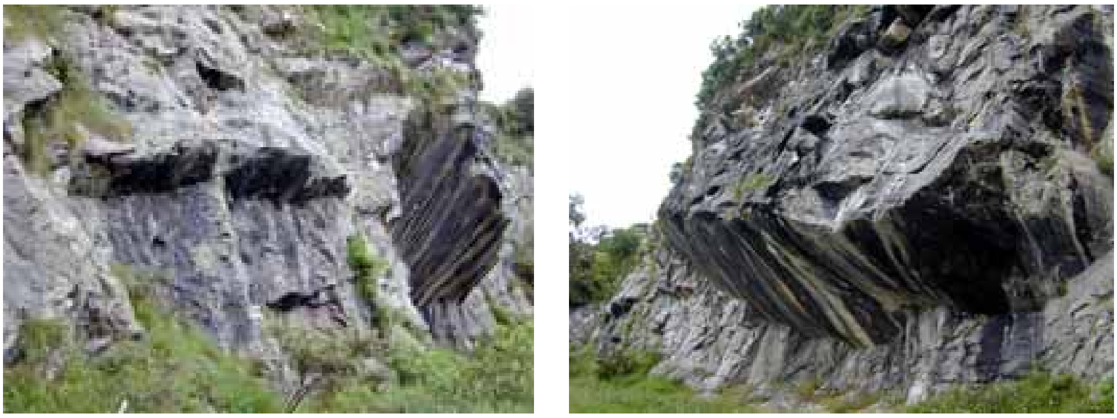


Figure 22. Well defined joint sets controlling the stability/instability conditions in this slope.

1.1.8. Lithologic consistency

The following general facts have to be considered when evaluating a Dimensional Stone deposit or mass:

- Dimensional Stone masses or deposits in most cases are **heterogeneous** in respect to lithologic and consequently to aesthetic properties, like colour or textural pattern.
- Stone masses are often **anisotropic** in respect to other physical/mechanical properties, not only in the case of metamorphic rocks.
- Heterogeneities and anisotropies may occur from the mm- to the m-scale in respect to the application-related properties of the stone.

Lithologic consistency of a rock mass is a prerequisite for a long-term and economically successful operation of Dimensional Stone quarries. Together with geometric characteristics and the degree of fracturing, lithologic consistency is a major feature in the evaluation of stone deposits. Lithology determines the aesthetic factors of a stone, including colour, pattern, and texture, and thus its marketability. As Swenson (1991) has pointed out, stone may continually change during the life of a quarry. Therefore, from the early stages of geological reconnaissance and evaluation of a Dimensional Stone deposit, its lithologic uniformity or irregularity has to be assessed, at least in a preliminary way. For those methods of detailed examination, which require more intensive investigations and the availability of extensive quarry exposures and drill cores, see Chapter 1.2.2. The lateral and vertical continuity of the stone mass or deposit of aesthetic properties has to be understood in as much detail as possible. Geological mapping and profiling of the rock types together with representative sampling is required.

In general, primary and secondary factors influence the lithologic uniformity of a rock mass. Primary factors are those, which determine the lithologic character and association during the original formational stages, e.g. the deposition (and diagenesis) of a marine or fluvial sediment, the crystallization of a magma or the metamorphic overprint of any parent rock. Secondary effects change the original lithologic character during later stages of the stone history.

In **sedimentary rocks** and their metamorphic descendants a wide variety of primary vertical and lateral lithofacies differentiations can be expected (for details see e.g. Walker 1984, Reading 1996, Selley 2000). In sandstones (quartzites) for example, grain size distribution may vary laterally and horizontally in short distances from medium to fine grained, depending on the depositional environment. Facies models for fluvial and Aeolian sediments should be consulted in the prediction of the variability of sandstones. In addition, the varying degree of diagenetic (or metamorphic) cementation of sandstones should be considered. In limestones – and marbles as their metamorphic equivalents – facial changes from pure carbonate sediments to siliciclastic ones are common. In many marble deposits vertical transitions from pure marbles to quartz- and mica-bearing ones and to mica-schists are observed (Figure 23). Additionally, marble lenses of only some hundred meters of lateral extension may occur intercalated in thick metapelitic rock sequences.

Figure 23. Transition from a marble horizon into a mica-schist (Marble quarry in Greece).

In limestones and marbles originating from shallow-marine carbonate platforms the intensity of early diagenetic stratiform or late diagenetic massive dolomitisation may vary strongly. Examples of calcite marbles grading laterally into fine-grained dolomites are well-known. Conditions of sedimentation, diagenesis and metamorphism, in addition, have a strong influence on the colour of sediments. Limestones, in places originating from reducing depositional conditions, may contain relics of organic carbon, which typically appear as graphitic pigment also in many marbles. Paleokarst fillings in the form of karst metabauxites represent another type of common lithofacies variation in marble deposits.

In **igneous rocks,** primary vertical and lateral lithologic variations can be produced by the different speed of cooling/crystallization of magma in core and marginal parts of the intrusive body, affecting size and shape of the mineral grains. Diapiric intrusion may also result in increasing foliation of granite towards its margin and the number and progressive flattening of xenoliths in the outer part of the intrusion (Figure 24). Many intrusive complexes are large batholiths, typically composed of a number of separate intrusions. These generations of e.g. granites, may strongly differ in crystal size, mineralogical composition, and colour. Another lithologic feature characterising many igneous rocks is the occurrence of late-intrusive pegmatites, aplites and lamprophyrs filling pockets, veins and dykes, which cut through granite and wall rocks. Basics of igneous petrology, useable in the prediction of lithofacies variations in igneous rocks, are well described in Hall (1996). Structurally controlled hydrothermal alteration may contribute to chloritisation, kaolinisation or partial sulfidisation of igneous rocks.

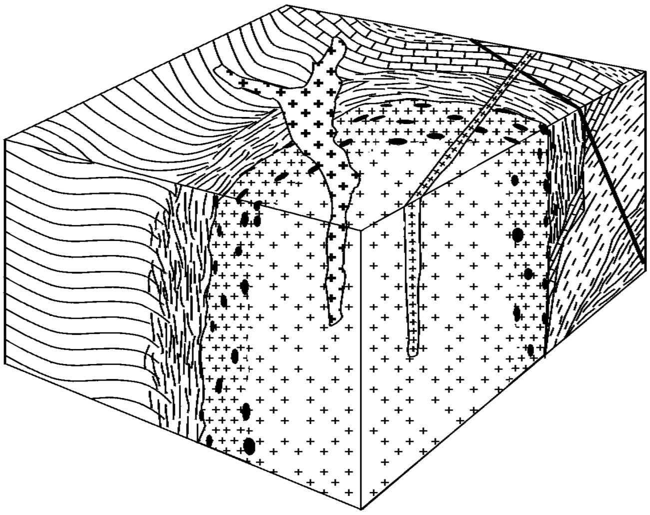


Figure 24. Block model of a granite intrusion (Hall, 1996)

Sedimentary and igneous rocks, subjected to increased pressure and temperature by burial or contact with intrusive bodies, adjust to their new environment by re-crystallisation to more stable minerals and structures. The resulting **metamorphic rocks** are characterised by textures, structures, and mineral compositions, which reflect the character and degree of metamorphism. Thus, in areas with steep metamorphic temperature gradient, metamorphic rocks with different textural, structural and mineralogical character may lithologically merge at short distances. Depending on the mineralogical composition and the degree of tectonic deformation, metamorphic rocks can be structurally characterised by foliation, lineation, and slaty cleavage and folding, properties which partly result in reduced rock strength.

Patterns in metamorphic (and also in sedimentary) rocks may display a kind of regularity or periodicity in different scales. Müller (2001) proposes a terminology to quantify the minimum size of a sample, which must be used in describing and determining a particular type of such a multicoloured or textured stone (Figure 25).

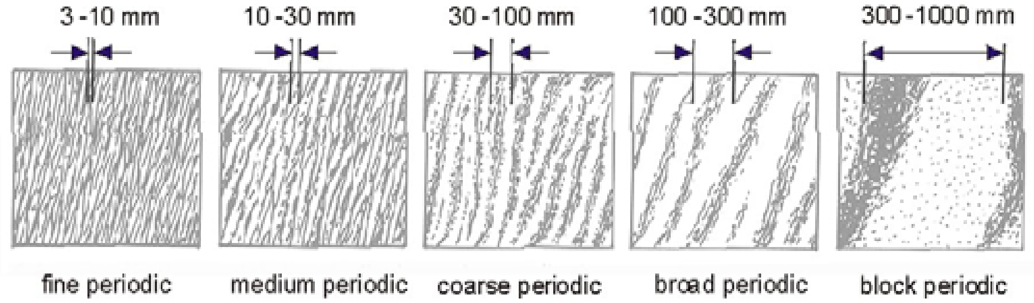


Figure 25. Periodicity of patterns in metamorphic rocks (migmatite, gneiss, marble etc.) (Müller, 2001)

In such extreme cases as migmatites (Figure 26), even a series of different types of stone could be produced from one block. Mononen et al. (1998) have pointed out, that the quarrying method in a multicolour migmatite deposit should be more selective than the method in homogeneous granite deposits, and that a migmatite deposit needs to be investigated (and sampled) much more thoroughly than granite deposits in order to exploit it successfully.

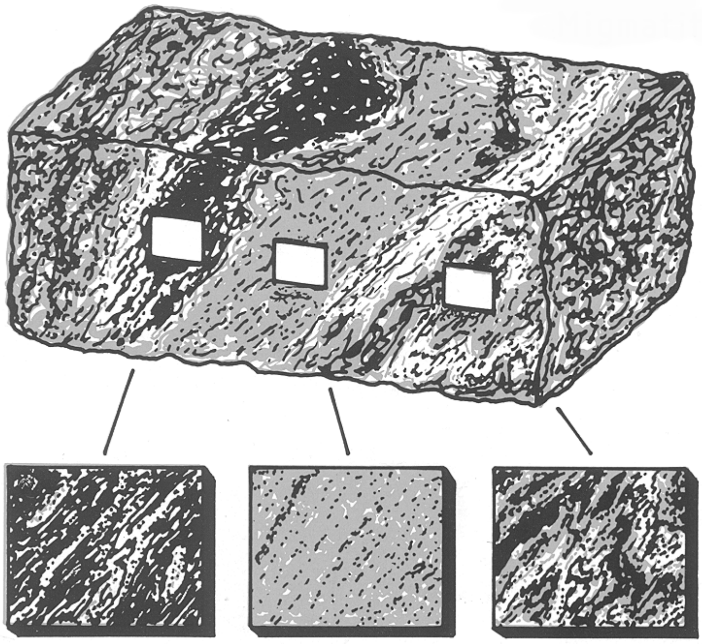


Figure 26. "Block periodicity": three different rock types from only one block of migmatite (Müller, 2001)

In deposits of industrial minerals and rocks a large number of characteristics have to be determined in samples of standardised dimensions in order to describe the average quality of the mineral deposit, and these inherent properties that are decisive for the quality and marketability of the finished product. These facts make sampling of industrial rocks a particularly difficult and responsible task, for which rules or norms are hardly available. The sampling strategy that should be followed for the characterization of a rock deposit is presented in detail in Chapter 3.

1.1.9. Weathering: general situation

Rocks have been formed under very different conditions on the Earth's surface; as a consequence, when they are exposed to environmental conditions (atmospheric agents such as air, rain, water, frost, etc.) undergo deep transformations, which degrade and disintegrate their original characteristics. This geological process is named weathering and it implies a variable combination of chemical, physical and biological mechanisms that take place in surface or near surface conditions. The final consequence is that rocks and their rock-forming minerals are converted, at the end of the process, into soils and the liberated chemical elements, being dissolved in water, can migrate far away.

Rocks are thus modified in texture, mineralogy, chemical composition, and as a consequence, in physical properties as colour, cohesion, hardness, mechanical strength (Figure 27). The rate of weathering is very variable, depending on the weathering agents and the rock characteristics (discontinuities, hydrogeological conditions at the rock-massif scale, and mineralogical composition, texture, porosity at the intact-rock scale), in places resulting in complete decay of the rock.

As weathering proceeds, a weathered layer is formed, which can be continuously removed by the erosion agents (rivers, wind, and waves). Therefore, any geological scenario is continuously modified by weathering, erosion (denudation) and transport. This is part of the destructive processes on the Earth's surface, and holds true also for Dimensional Stone deposits.

Figure 27. Effects of weathering on a granite outcrop; the decay in the physical properties of both the rock massif and the intact rock is visually perceptible.

The two most basic weathering processes that can be identified along the field geology studies can be grouped into mechanical and chemical. The mechanical weathering, also named physical weathering or rock disintegration, is a simple geological process which only requires that stresses of any natural origin will be applied or released to rocks (Table 6). It merely induces continuous physical fragmentation to rocks without any modification in their chemical composition. A very significant result is the increase in the rock specific surface, S_v. For instance, a squared rock block of 1m side length has: $V=1m^3$, $S=6\ m^2$ and $S_v= 6m^{-1}$, but if fragmented into 64 equal cubic fragments it has: $V=1m^3$, $S=24\ m^2$ and $S_v= 24m^{-1}$. In consequence, much more rock surface is now exposed to chemical reactions and its chemical weatherability should be greater.

Chemical weathering, also named rock decomposition, implies many different and more complex chemical processes than mechanical weathering, basically dissolution, leaching, oxidation and hydrolysis. Water, as well as wet and hot climatic conditions, greatly increases the chemical weathering rate. Rock-forming minerals, as a result of chemical reactions, can reach exaggerated transformations and many of their chemical components are removed dissolved in water; they greatly differ in the type, intensity and rate of chemical reactions they can suffer. Table 7 summarises the most common processes involved in chemical weathering.

Figure 28. Effects of weathering on a marble. Left: underground mining situation in Carrara (Italy) with small karst caves and strongly weathered discontinuities. Right: open pit marble mine situation near Pentelikon (Greece) with strongly weathered marble layers.

Table 6. Mechanical weathering processes.

Process	Description
Mechanical unloading	Vertical expansion due to reduction of vertical load by erosion. This will open existing fractures and may permit the creation of new fractures.
Mechanical loading	Impact on rock, and abrasion, by sand and silt size windborne particles in desert. Impact on soil and weak rocks by rain drops during intense rainfall storms.
Thermal loading	Expansion due to water freezing in pores and fractures in cold regions, or due to rock heating in hot regions. Contraction due to cooling of rocks and soils in cold regions.
Wetting and drying	Expansion and contraction associated with repeated absorption and loss of water molecules from minerals surface and structure.
Crystallisation	Expansion of pores and fissures by crystallisation within them of minerals that were originally in solution. Note: expansion is only severe when crystallisation occurs within a confined space.
Pneumatic loading	Repeated loading by waves of air trapped at the head of fractures exposed in the wave zone of a sea cliff.

Table 7. Commonly occurring processes in chemical weathering (Blyth and de Freitas, 1984).

Process	Description
Solution	Dissociation of minerals into ions, greatly aided by the presence of CO_2 in the soil profile, which forms carbonic acid (H_2CO_3) with percolating rainwater.
Oxidation	Combination of oxygen with a mineral to form oxides and hydroxides.
Reduction	Release of oxygen from a mineral to its surrounding environment.
Hydration	Absorption of water molecules into the mineral structure. Note: this normally results in expansion; some clays expand as much as 60%.
Hydrolysis	Hydrogen ions in percolating water replace mineral captions: no oxidation – reduction occurs.
Leaching	The migration of ions produced by the above processes. Note Ca, Mg, Na, K are easily leached by moving water. Fe is more resistant. Si is not easily leached and Al is almost immobile.
Cation exchange	Absorption onto the surface of negatively charged clay of positively charged dissolved cations, especially Ca, H, H, Mg.

Concerning the characterisation and evaluation of Dimensional Stones on the deposits scale, a thorough collection of observations on weathering-related alterations is necessary. Unfortunately, the procedure for getting the necessary information is not standardised and the description of the weathering state is mostly based on a more or less subjective appreciation of the geological events. This is the reason why weathering indexes are very useful as they link to objective physical data (as explained in paragraph 1.2.3). Processes and products of physical and chemical weathering of stones are described in detail by Winkler (1994).

In igneous and metamorphic rocks, mainly the dark ("mafic") components and plagioclase should be checked for their weathering degree. Iron is rapidly leached from e.g. sulfides, biotite, and hornblende and readily oxidised to insoluble yellowish to brownish ironoxihydroxide, producing a kind of thin rusty coating on stone surfaces. Yellowing of originally grey granite, produced by this process, is an indication of initial weathering. Feldspars decompose to the clay mineral kaolinite during chemical weathering, and in initial phases their surfaces become coated with dull grey clay films. The degree of kaolinisation of igneous rocks strongly determines the rock strength and durability.

Limestone and marble are strongly affected by carbonate dissolution, producing typical surface karst structures, opening of fractures, caves and discolouration of the stone. As a result of open fractures, often filled with clay material, the stability of the karstified marble mass is strongly reduced and water inflow in quarries and subsurface excavations is made easier.

1.1.10. Other cost- and recovery-effective properties

Morphological situation strongly influences productivity and production costs inasmuch as the quarry plan, removal and transport routes of the blocks are determined by the accessibility of the deposit area. In mountainous regions steep-sided valleys may restrict the size of roads or cableways and as a result, the size of transported blocks. In addition, climatic conditions may result in seasonal interruption of stone production.

The quarry plan itself is determined by the geometry of the deposit, type and amount of overburden, and the necessity of handling large blocks (Power, 1994). Most quarries are of the open pit type with relatively small surface area and they are worked downwards below the general surface level. Removing the stone blocks from such quarries is traditionally achieved by fixed derricks or via ramps with mobile equipment. Flat-lying layered deposits may be worked as open shelf quarries in a hillside. If the deposit is thick, the quarry may change into an open pit as deeper layers are removed. The quarry may also be extended under the hill as an underground room and pillar mine if the overburden is too thick for removal.

In quarries of the open pit type and in underground quarries, the *hydrogeological situation* and in particular the position of the ground water level is of importance for stone production. In many cases costly measures for water drainage must be taken. During underground mining of marble, karst water inflow may occur. In order to evaluate a potential Dimensional Stone deposit, type and thickness of the *overburden* must be also determined. The overburden may consist of:

- alluvial sediments (e.g. sand and gravel);
- residual products of weathering (e.g. kaolin or kaolinitic saprolite on top of a granite);
- strongly exfoliated near-surface parts of the deposit;
- hard rocks of the host rock sequence (e.g. micaschist on top of a marble series).

Obviously, the complete lack of any overburden is the most favourable situation from the point of view of costs. In some cases, some clay residual weathering products might even find potential uses. In most cases, however, loose overburden has to be removed and stored at suitable places outside the deposit or in mined-out quarries. Thick overburden, consisting of hard rocks of the host rock sequence must remain in place; in this case, underground quarrying, typically of higher cost and lower recovery, is the only solution.

1.1.11. Classification and reporting of resources/reserves

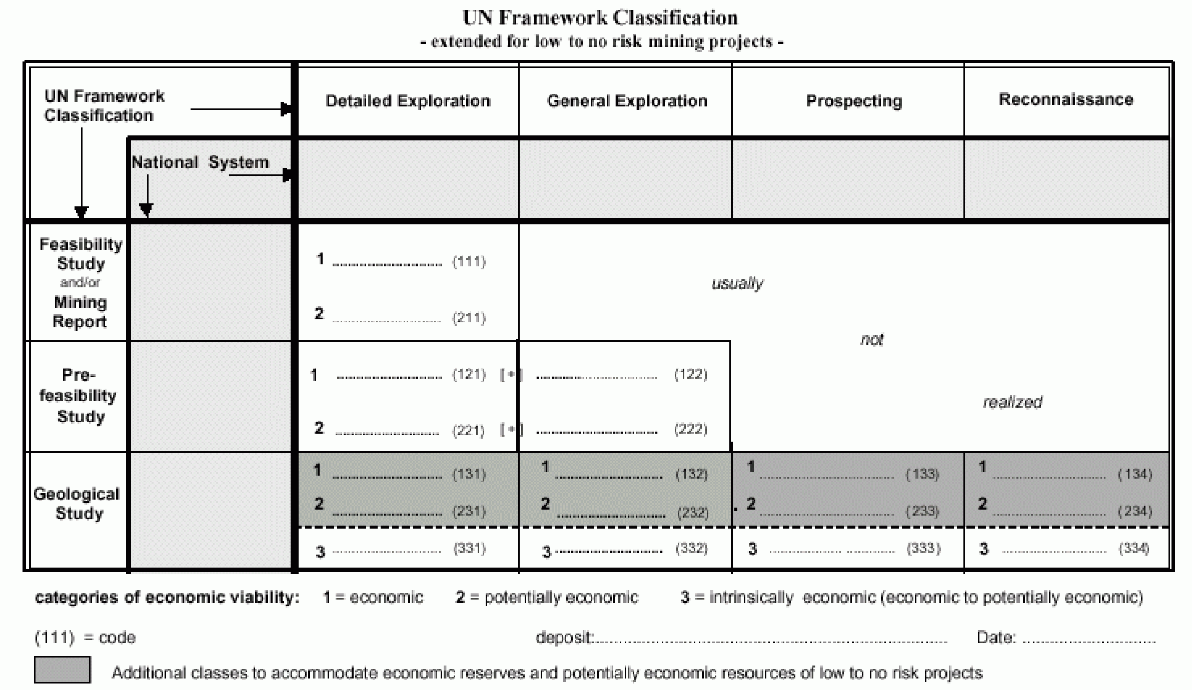
Framework classification

In principle, the **United Nations International Framework Classification for Reserves/Resources** (UN-ECE, 1997), which is valid for solid fuels and mineral commodities in general, can be also used for the classification of the reserves/resources. The main objective of the UN Framework Classification (UNFC), designed as an umbrella system, was to create an instrument that permits reserves/resources of solid fuels and mineral commodities to be classified using an internationally uniform system based on market economy criteria.

It has been emphasised (UN-ECE, 2001, p. 3) that UNFC is not intended as a means of regulating the methods by which Mineral Resources and Mineral Reserves are estimated or of controlling national and in-house procedures for estimating and accounting them. Its purpose is to provide a standard international framework within which important information on Mineral Reserves and Mineral Resources is reported to all interested parties. The UN Classification provides information about the following:

- Stage of Geological Assessment
- Stage of Feasibility Assessment
- Degree of Economic Viability

The principle behind the UN Framework Classification and methodology of classifying reserves and resources is revealed in its matrix form (Figure 29).



UN Framework Classification
- extended for low to no risk mining projects -

UN Framework Classification	National System	Detailed Exploration	General Exploration	Prospecting	Reconnaissance
Feasibility Study and/or Mining Report		1 .... (111) 2 .... (211)	usually not realized		
Pre-feasibility Study		1 .... (121) [+] 2 .... (221) [+]	.... (122) .... (222)		
Geological Study		1 .... (131) 2 .... (231)	1 .... (132) 2 .... (232)	1 .... (133) 2 .... (233)	1 .... (134) 2 .... (234)
		3 .... (331)	3 .... (332)	3 .... (333)	3 .... (334)

categories of economic viability: 1 = economic 2 = potentially economic 3 = intrinsically economic (economic to potentially economic)

(111) = code deposit:.................................... Date: ....

▨ Additional classes to accommodate economic reserves and potentially economic resources of low to no risk projects

Figure 29. UN Framework Classification matrix for low to no risk projects.

Geological Study is subdivided into four consecutive stages of Geological Assessment which are, in order of increasing detail and increasing degree of geological insurance, the following:

- Reconnaissance
- Prospecting
- General Exploration
- Detailed Exploration

Feasibility Assessment is divided into three consecutive stages which, in order of increasing detail, are:

- Geological Study
- Pre-feasibility Study
- Feasibility Study/Mining Report

Economic Viability, corresponding to the reserve/resource figures as obtained from the Feasibility Assessment, is reported as the third dimension, using the following categories, which are only quoted in the stages of Mining Report/Feasibility Study and Pre-feasibility Study:

- Economic (normal, exceptional)
- Potentially economic (marginal, sub marginal economic)

In the geological study of a deposit, the Economic Viability is only roughly estimated, e.g. by comparison with mining or quarrying activities carried out in similar deposits. The resource figures, thus, are quoted as being in the range of economic to potentially economic, and the viability category is:

- Intrinsically economic

A three-digit codification scheme is used to designate the different classes in the three-dimensional diagram with the axes Economic Viability, Feasibility Assessment and Geological Study.

Lorenz et al. (2000) critically noted that using the UN Framework Classification, reserves can only be assessed as economic if a feasibility study or at least a pre-feasibility study has been carried out. However, low-value, bulk commodities such as sand, gravel, common clay, limestone, and quarried stone are hardly ever assessed by carrying out pre-feasibility or feasibility studies; often extraction is simply started. In many cases not even in-depth geological studies are available, mainly because there is little financial risk involved. This holds true also for many Dimensional Stone deposits and not only for mining operations of developing countries. Therefore, they suggested that the Geological Study category, which on an international basis contains only one class ("intrinsically economic"), could be amended by two extra economic viability classes (1 = "economic", 2 = "potentially economic"), if one country wishes to do so.

For those users who do not deal daily with the classification of reserves/resources, a **Key for the Classification of Reserves/Resources** has been prepared (United Nations-ECE, 2001 a). This Classification Key provides an easy to use tool to the user for classifying reserves/resources of solid fuels and mineral commodities according to the UN Framework Classification. Following the recommendation of Lorenz et al. (2000), the Key now presents a UNFC diagram that permits a more realistic classification for many mineral deposits, especially those of construction raw materials as sand and gravel, brick clay, limestone, and Dimensional Stones. This is made possible by the addition of two further subcategories to category 3 ("intrinsically economic"): "economic" and "potentially economic". Thus, in the bottom row ("geological study") of the UNFC diagram the following three categories appear for low to no risk mining projects:

Category 1 ("economic") for all reserves in deposits exploited by low to no risk operations that have been described in a geological study and have been profitably mined/quarried on a regular basis for a relatively long time. In this case, the existence of an operation is viewed as proof of economic viability, and thus a pre-feasibility or feasibility study is not necessary. This category can also be assigned to reserves of a future operation whose economic viability has been concluded by an experienced specialist in economic geology on the basis of comparison with active operations in the region.

Category 2 ("potentially economic") for all resources in a deposit that have been described in a geological study and, by analogy to other deposits in the region, have been classified as not economically viable at the present time, but could become so in the foreseeable future if certain economic, technological, ecological, legal, and other conditions change in a positive way.

Category 3 ("intrinsically economic") for all resources of low to no risk operations that cannot be classified as "economic" or "potentially economic" because of the lack of information on their economic viability.

It has been objected that the "intrinsically economic" category should not be accepted in Europe, because it gives to justify a government or an employer the needed justification not to invest in geological studies (e.g. mapping, sampling, data collection) of a deposit. The proposed extended classification for low risk projects, however, now restricts the category "intrinsically economic" to those resources where Economic Viability is not described in a Geological Study and is not derived from a previous production period or from analogy to other deposits in the region. In order to be classified among the economic reserves and potentially economic resources, the rock mass has to be characterised in the course of a Geological Study by quality, continuity and quantity as basis for Feasibility Assessment and initial evaluation of Economic Viability so as to define an investment opportunity.

As the most recent activity of the UN Task Force on Reserves/Resources for Solid Fuels and Mineral Commodities, "**Guidelines to the United Nations International Framework Classification for Reserves/Resources"** has been published (United Nations-ECE, 2001 b). These Guidelines concern both technical and non-technical persons and are designed to assist in the use and application of UNFC. The main objective of the Guidelines is to assist in incorporating the numerous conventional classifications into the UNFC in order to make them comparable. This harmonization will finally allow mineral statistics to be communicated internationally using a uniform system based on market economy criteria. These Guidelines can be adopted on a national basis, taking into account country specific features. The Guidelines are of particular practical usefulness as they comprise the following extensive **Appendices**:

I. Definition of Terms
II. List of the more important items to be addressed in a Geological Study
III. List of the more important items to be addressed by Feasibility Assessment
IV. Codification

Appendix II of the Guidelines (United Nations-ECE, 2001 b) lists the following important items of a Geological Study:

- Property description; location and access
- History
- Geology
- Investigation methods
- Features of the deposit
- Sampling details
- Analysis details
- Quality/Grade
- Resource estimation
- Economic viability estimation.

Codes for reporting

For about 20 years, mining organisations in many industrialised countries have been continuously developing and increasingly harmonizing guides, guidelines and *codes for reporting of mineral exploration results*, *mineral resources and mineral/ore reserves*, including industrial minerals in their widest sense. Some recent examples are among others:

- A Guide for Reporting Exploration Information, Mineral Resources, and Mineral Reserves. The Society for Mining, Metallurgy and Exploration, Inc. Colorado, U.S.A. March 01, 1999.
- CIM Standards on Mineral Resources and Reserves, Definitions and Guidelines. Canadian Institute of Mining, Metallurgy and Petroleum. October 28, 1999.

- The 1999 Australasian Code for Reporting Mineral Resources and Ore Reserves (JORC Code). Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, the Australian Institute of Geoscientists and the Minerals Council of Australia, 1999.
- South African Code for Reporting of Mineral Resources and Mineral Reserves (The SAMREC Code). South African Mineral Resource Committee (SAMREC) under the Auspices of the South African Institute of Mining and Metallurgy, March 2000.
- Code for Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves (The Reporting Code). Institution of Mining and Metallurgy Working Group on Resources and Reserves in Conjunction with the European Federation of Geologists, the Geological Society of London and the Institute of Geologists of Ireland. Effective from October 2001, this Reporting Code has been published by the organisations involved (e.g. at the website of the European Federation of Geologists: www.eurogeologists.de).

The European Code for Reporting of Mineral Resources and Mineral Reserves of 2001 sets out minimum standards, recommendations and guidelines for Public Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves in the United Kingdom, Ireland and Europe. The Code is applicable to all solid minerals including metals, gemstones, and bulk commodities, such as coal and iron ores, industrial minerals, stone or aggregates. In the case of industrial minerals, stones and aggregates, such factors as quality and marketability are important and should be carefully considered before declaring mineral reserves.

With regard to the Resource/Reserve Classification, the Reporting Code is consistent with the UNFC. The UNFC categories “Reconnaissance Mineral Resource”, “Pre-feasibility Mineral Resource”, and “Feasibility Mineral Resource” which are of particular interest for government planning purposes (including further land use or strategic mineral inventories), are not part of the Code, as these categories are not intended to be used for non-governmental investment and financing decisions.

1.2. Rocks characterisation in a quarry

The main objectives for rock characterisation in already existing quarries are to guarantee:

- optimised stone production level,
- long-term reliability of supply,
- stability of stone quality.

Therefore, in this phase of exploration and rock characterisation, the assessment of block-size (Chapter 1.2.1) and stone quality (Chapters1.2.2, 1.2.3) distribution patterns together with geomechanical investigations (Chapter 1.2.4) will be of prime importance. Also, additional sampling and laboratory testing has to be carried out with these aims in view.

Main features of the characterisation of rocks in already existing quarries will be exemplarily demonstrated in the case of a marble quarrying project. Starting from surface quarrying, the CAD-PUMA project (Crassoulis et al. 1999, 2000, Germann et al. 2001) has developed a computer-aided design and planning methodology for underground marble quarries. This project was addressed both to already operating underground marble quarries and to quarry operators that intend to go underground, and it aimed to provide improved design and planning techniques for underground quarry exploitation. These techniques supports the prediction of cost effective and safe quarry layouts for maximum block recovery of such sizes and qualities that the market demands. Based on geological marble deposit models, derived mainly from the surface quarry situation, and combined with computer simulation methods, a geometric model of the available and recoverable rock blocks can be achieved. Thus, the methodology in most of its aspects is also valid for surface quarries.

1.2.1. Discontinuity pattern and related block size distribution: methods of assessment

Presence, nature, size, spacing, frequency, orientation and persistence of geological discontinuities (bedding planes, fractures and joints) determine the extractable block size and the in-situ block size distribution of a rock mass and are decisive for its geomechanical behaviour in surface cuttings and underground openings. Data on block size and shape have applications in the design and exploitation of surface and underground quarries, in the prediction of block recovery, and in a wide variety of other rock engineering branches using rock mass classification systems. The in-situ block size is a major factor in assessing the economic and technical viability of a new quarry source of large blocks for dimension and armourstone production. Recent developments in the assessment of in-situ block size distributions of rock masses have been compiled by Lu and Latham (1999).

The discontinuities found in a rock mass in preferred directions (sets, families) are forming the discontinuity pattern. The discontinuities define blocks, the dimensions and shapes of which are determined by the number of discontinuity sets, the orientation and spacing of the discontinuities. The most common methods (for a detailed discussion see e.g. Palmström, 2000) to obtain the information needed for assessing the block volume are the following:

- Observations and logging of drill cores
- Observations and measurements in outcrops, quarry surfaces, underground openings
- Assessments from geophysical measurements.

Under favourable conditions, for instance in quarries with open faces in different directions, the *direct measurement of block volume* can be achieved by selecting representative blocks and measuring their average dimensions. In most cases, however, it will be necessary to measure and calculate block volumes from the joint (discontinuity) sets and spacing. From the main joint sets the *block volume Vb* can be measured as:

$$V_b = S_1 \times S_2 \times S_3 \times (\sin a \times \sin \beta \times \sin \gamma)$$

Where: S_1, S_2, S_3 are joint spacing for each joint set and α, β, γ are the angles between the joint sets. Joint (discontinuity) spacing is the distance between individual joints within a set. From joint frequency measurements it is also possible to find the block volume directly.

The *volumetric joint count Jv*, which is the number of joints within a unit volume of rock mass has been described by Palmström (1982) and is defined as follows:

$$J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots\ldots \frac{1}{S_v}$$

where: S_1, S_2, S_3, S_v are the joint spacing. J_v can easily be calculated from common joint observations, since it is based on measurements of joint spacing and frequencies.

Block size – and sometimes shape - is an essential component of engineering rock mass classification systems, as e.g. the widely used *Rock Quality Designation Index (RQD)*, developed by Deere et al. 1967 (see Deere & Deere 1988). RQD is defined as the percentage of intact drill core pieces longer than 100 mm in the total length of core (Figure 30). RQD gives at least a qualitative impression of the degree of jointing in a rock mass. If properly oriented cores are used, strike and dip of the discontinuities can be measured, too. The ratio RQD/Jn (where Jn is a rating that depends on the number of joint sets present), as used in the Norwegian Geotechnical Institute (NGI) Tunneling Index (Barton et al. 1974), is used to define block size. There is no clear evidence, however, that this dimensionless parameter is indeed representative of the actual block size.

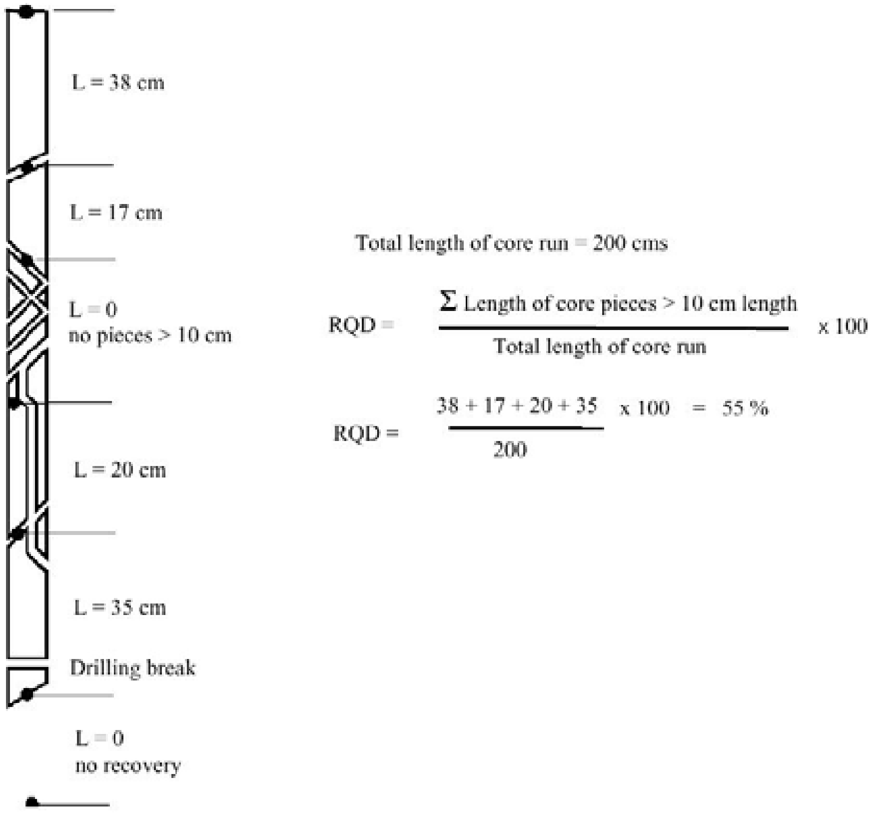


Figure 30. Procedure for measurement and calculation of RQD (Deere & Deere 1988).

An image-analysis methodology was proposed for automatic core logging and determining the Rock Quality Designation RQD by Lemy et al. (2001). Recently, a rock mass characterisation based on fractal geometry, using simple photographic techniques and computer-aided analyses of rock mass fracturing features was introduced by Badge et al. (2002). There is still need, however, for extensive field studies to find a correlation between fractal dimension and parameters like RQD, joint frequency and joint number. Based on the RQD Index, Singewald (1992) has developed a method of *discontinuity* or *fracture system analysis* which produces average (mean) values for joint spacing in three directions, an average (mean) block volume, and an estimate of *block prospectivity*. In contrast to the RQD method, Singewald uses measurements of all types of discontinuities from surface (e.g. quarry) *scan lines* in the X-, Y- and Z-direction.

Based on the Singewald method, Weber et al. (2001) recently presented a practice-oriented method for the economic evaluation of Dimensional Stone deposits with regard to the block volumes. This method is suitable for Dimensional Stone deposits with a predominantly orthogonal fracture pattern and uses the following parameters: minimum block volume, fracture spacing, mean block volume and block prospectivity. The parameter “block prospectivity” is defined here as the percentage of blocks that can be extracted with a minimum volume of 0.4 m^3 and, additionally, a minimum length of 0.4 m on all three sides. According to Weber et al., “block prospectivity” is a direct measure of the yield that can be expected from a Dimensional Stone deposit. A numerical computer program to calculate the values for block prospectivity and a list of required equipment and appropriate forms that facilitate necessary field work are provided by the authors.

Hadjigeorgiou et al. (1998) successfully determined *in-situ block size distributions* by using traditional scan line mapping of:

- joint orientation,
- average number of discontinuities intersected by unit length of sampling lines,
- average of all trace lengths of sampling lines for a discontinuity set, and
- set spacing measured along a line that is parallel to the mean normal to the joint set, and applying a variety of computer models (*Simblock*, *Blocks*, *Stereoblock*).

RESOBLOK is a tool for the 3D-representation of a fractured rock mass (Heliot 1988), developed by INERIS – Institut National de l`Environment et des Risques, Nancy, France. It was intensively used for block stability analysis and prediction of block size and shape in developing a design and planning methodology for underground marble quarries (Crassoulis et al. 1999, 2000, Germann et al. 2001). RESOBLOK assumes that the rock mass can be compared with an aggregate of blocks cut out by the discontinuity network. The described zone – the zone of interest – is defined by its dimensions length, width and height.

In a first step (Table 8), discontinuities have to be measured in an exhaustive way (that means to measure all discontinuities), preferably by a scan line method, determining orientation, spacing, persistence and a variety of other characteristics which are of importance for the geomechanical behaviour of the blocky rock mass (aperture, roughness, filling). The second step includes a statistical analysis of the discontinuities with the help of spherical projection techniques, and definition of the number and average orientation of discontinuity sets. 3D-representation of the fractured rock mass is achieved by RESOBLOK “block generator” either in a statistic or in a deterministic way, in which the blocks correspond exactly to those measured in situ. With the help of BSA (Block Stability Analysis), a software package included in RESOBLOK, the stability of blocks near an excavation can be analysed. Statistical analysis of the pillar behaviour is carried out with 3DEC, a software based on the distinct element method. Again, the rock mass is represented as a block assembly cut out by discontinuities which are depicted by RESOBLOK. Regarding the quarry design and exploitation (surface or underground) the prediction of block size and shape with the help of RESOBLOK is of outstanding importance.

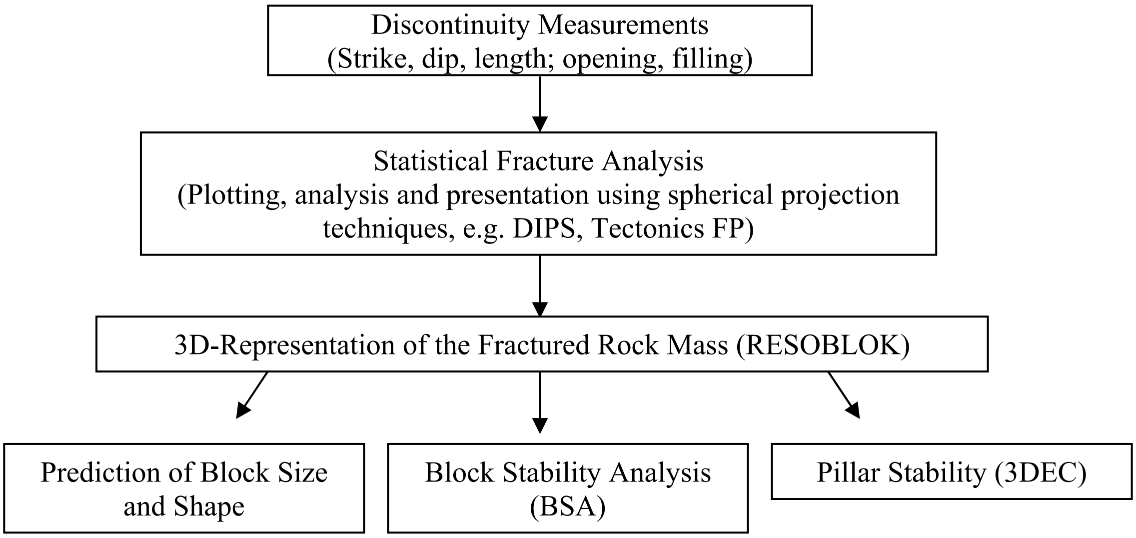
With the help of RESOBLOK discontinuity modelling and prediction of the discontinuity-optimised gallery orientation for underground quarrying of marble has been performed for a variety of test sites (Crassoulis et al. 1999, 2000, Germann et al. 2001). Two types of planning situations have been distinguished:

- Design of a completely new underground quarry regarding the optimum orientation and size for rooms and pillars with respect to the discontinuity pattern. Statistical information about the main sets of fractures is derived from measurements in neighbouring open quarries.

- Optimisation of the extraction process of existing underground marble quarries for a given discontinuity pattern. In this case, in addition to the statistical discontinuity data, deterministic measurements had to be made in close vicinity to the future quarrying space.

In a RESOBLOK model, the zone of interest was defined by the existing or planned excavation size (Figure 31). In each case it was assumed that the best choice would be the one that gave the best block recovery.

Table 8. The INERIS methodology to build a 3D representation of a fractured rock mass.



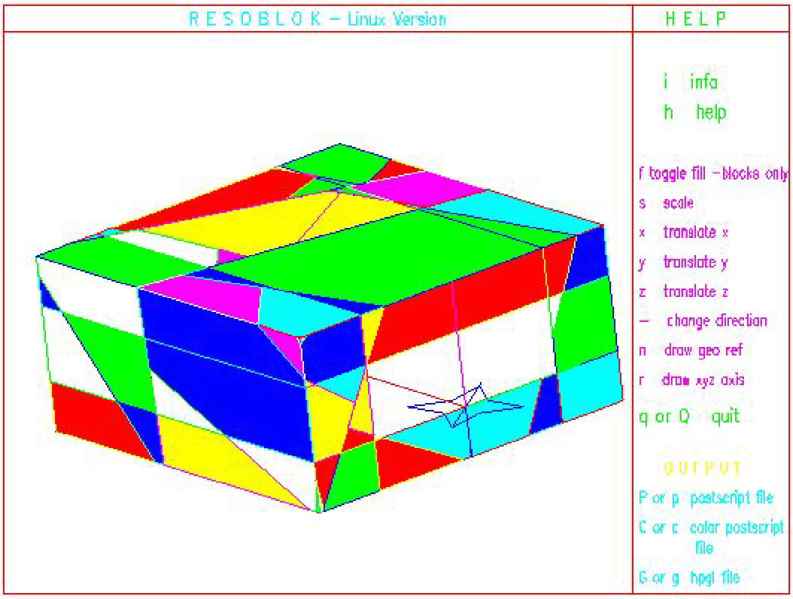


Figure 31. Visualisation of an excavation in the zone of interest in a RESOBLOK model (Germann et al. 2001).

In order to evaluate the block recovery, a histogram was calculated that shows the distribution of marble blocks in the zone of interest in 5 classes of volume (Figure 32).

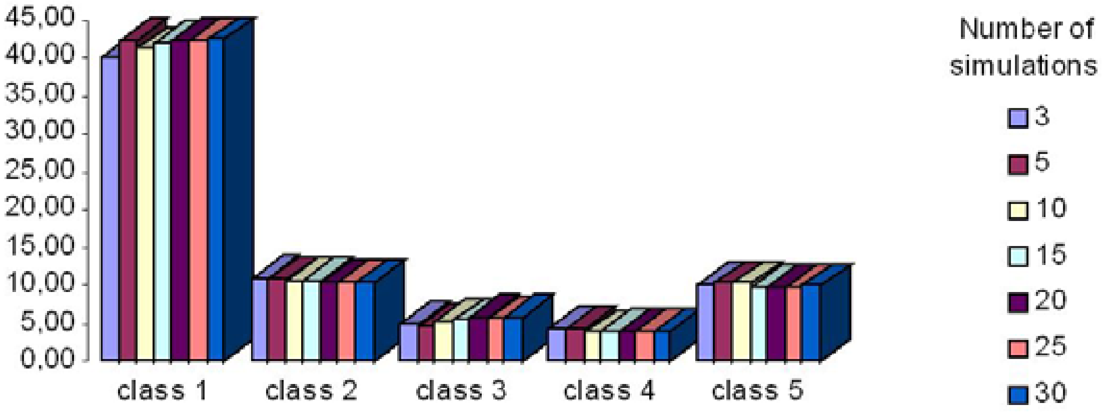


Figure 32. Distribution of the average number of blocks for classes of volume for different numbers of simulation with RESOBLOK (Germann et al., 2001).

In addition, a RESOBLOK simulation has been carried out with regard to the existing and planned orientation of the underground opening. Figure 33 shows the average number of blocks by classes of volume for two different orientations between discontinuity sets and excavation.

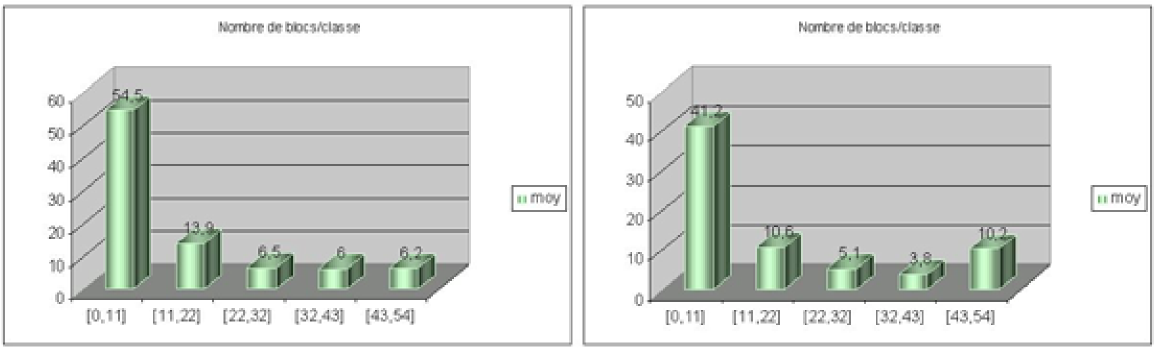


Figure 33. Average number of blocks by class of volume for two different orientations between discontinuity sets and excavation (Germann et al. 2001).

The block size and recovery can be predicted successfully with RESOBLOK simulation. The optimisation of gallery orientation with respect to the discontinuity pattern can also be achieved with this tool. This holds true also for the discontinuity-related simulation of the extension of existing quarries. A practical classification system for granite deposits based on the spacing of discontinuities and related recovery of top quality blocks was proposed by Nelles (1996):

- Deposits with a narrow-spaced discontinuity system and a maximum top-quality-block recovery of 8%.
- Deposits with a widely spaced discontinuity system and a maximum top-quality-block recovery of 20%.

- Deposits without subordinate (secondary) discontinuities and a maximum top-quality-block recovery of 40%.
- Deposits without subordinate (secondary) discontinuities and a widely spaced main discontinuity system making possible a recovery of up to 50%.

Geostatistical methods have been also successfully applied for discontinuity and quality assessment. Tavchandian et al. (1993) used indicator kriging maps to analyse spatial relations between fracture sets and fracture or deformation density. By including fracture geometry Pereira et al. (1993) calculated a summary index reflecting marble quality, which was used as a regionalised variable. Validated by real production data, which match the kriged values, the index can be used in exploitation planning of marble quarries. Geostatistical modeling was applied by Chilés and Gentier (1993) to the morphology or topography of single fracture surfaces. For estimating the quality of a slate deposit, Taboada et al. (1998) selected, among others, the following variables obtained from borehole exploration: RQD (Rock Quality Designation), number of faults and joints, and number of microfractures. Through multivariate statistical techniques they defined a quality index, which was considered as regional variable, allowing the estimation of slate quality in hidden parts of the deposit. A similar approach, including fracture characteristics, was proposed by Taboada et al. (1999) for the evaluation of the quality of a granite quarry. Geostatistical extrapolation (kriging), based on surface quality data, can be applied to the extent permitted by the semivariogram.

1.2.2. Stone quality properties and characterisation of quality distribution

Quality properties

Quality features comprise of those stone or rock mass properties that influence quarrying, processing, marketability, applicability and durability of a stone. In Tables 9 to 11, the quality-related properties of stones are listed in groups, with reference to their dependency and influence on other properties and their technical and economic importance. The list is mainly based on data reported by Peschel (1977) and Winkler (1994) and the available norms and standards for the characterisation of natural stones. Recently, the Commonwealth Scientific & Research Organisation (CSIRO) of Australia has published a "Guide to the Speciation of Dimensional Stone" (QUICK 2002) which refers to standards and properties for architects or stone designers, to help them establish criteria for the selection of stone for specific use.

Table 9. Petrographic properties of Dimensional Stones

Property	Dependency on	Influence on	Technical & Economic Importance
Petrographic rock type	Formation conditions	All petrographic and physical properties	Specific use of stone
Mineral composition	Formation conditions	Physical properties Weathering behaviour	Aesthetic value Workability Durability
Rock textures: Grain size Grain orientation	Formation conditions Mineral composition	Strength Hardness Weathering behaviour	Workability Durability aesthetic value

Grain boundaries Cements			
Rock structures/patterns: Banding Folding Brecciation etc.	Rock type Degree and type of deformation	Strength Hardness	Aesthetic value
Rock colour: Munsell colour Uniformity Stability	Mineral composition	Thermal properties	Aesthetic value Durability

Table 10. Physical properties of Dimensional Stones

Property	Dependency on	Influence on	Technical & Economic Importance
Density: Real density Apparent density	Mineral composition Porosity	Strength	Specific use
Rock pores: Type/shape Volume: Open porosity Total porosity Pore size distribution Permeability	Petrographic rock type Formation conditions	Water absorption Strength Weatherability Stain resistance	Durability Workability
Strength: Compressive strength Tensile strength E-module: Dynamic Static	Rock textures Structure Water absorption	Hardness	Specific use Workability Durability
Hardness: Scratch hardness Indentation hardness Abrasion hardness	Mineral composition Rock textures Strength	Tool wear Abrasion Slip resistance	Specific use Workability Durability
Thermal properties: Conductivity Expansion	Mineral composition Porosity Texture Colour	Dimensional stability	Specific use
Light transmission	Mineral composition Texture		Aesthetic value Specific use
Radioactivity	Mineral composition		Specific use

Table 11. Properties of Dimensional Stones with regard to their applications

Property	Dependency on	Influence on	Technical & Economic Importance
Water absorption: Coefficient capillarity At atmospheric. pressure	Porosity Permeability	Weatherability Resistance to frost and salt attack, Stain resistance	Specific use, Durability
Weatherability	Mineral composition Porosity, Permeability	Hardness, Strength, Colour	Specific use, Durability
Frost resistance	Water absorption Strength	Hardness, Strength	Specific use Durability
Resistance to salt crystallisation	Porosity, Strength	Hardness, Strength	Specific use Durability
Resistance to SO_2 action	Mineral composition Texture	Hardness, Strength	Specific use Durability
Resistance to thermal shock	Mineral composition Texture	Strength, Rock colour	Specific use Durability
Stain resistance	Porosity, Texture	Rock colour	Specific use Aesthetic value, Durability
Abrasion resistance	Mineral composition Texture, Hardness	Slip resistance	Specific use, Workability, Durability
Slip resistance	Mineral composition Texture, Hardness	Abrasion resistance	Specific use, Durability
Impact resistance	Mineral composition Texture, Hardness		Specific use, Durability
Tool wear	Mineral composition Hardness, Texture Strength		Workability
Dry-to-wet strength ratio	Porosity, Texture	Strength	Specific use, Durability
Dimensional stability	Mineral composition	Strength	Specific use, Durability
Soundness: Physical damage Ultrasound travel Chemical damage	Texture, Porosity, Mineral composition Weatherability	Strength	Workability Durability

Spatial distribution of quality features

Vertical and lateral distribution of quality features of stones, as an expression of geological continuity or discontinuity within the rock mass, is one of the deciding factors in assessing the economic efficiency of a Dimensional Stone deposit. It has strong influence both on the costs of extraction and processing. Development strategies of a quarry site have to rely on the consistency of supply of those stone qualities with the market demands. In the early stages of exploration, lithologic continuity can be delimited by large-scale rock type mapping in outcrops and eventually by core drilling. Technologies for quantitative quality control of rock, prior to extraction or excavation, and for extraction planning require the definition and derivation of a combined stone quality factor or index and the geostatistical characterisation of the quality distribution within the stone deposit. In general, such methods require the availability of free faces in already existing quarries.

Improved geostatistical methods applicable for the characterisation of Dimensional Stone bodies or quarries (and also for instance in reservoir characterisation and petroleum engineering) stem from the more or less exhaustive availability of secondary information, which allows the estimation of a primary target variable that is less densely sampled. Calculating quality indexes or combined quality factors derived from the multivariate statistical analysis of stone quality variables is another way to estimate quality distribution in Dimensional Stone masses. Among others kriging algorithms, like "kriging with external drift" (see for instance Albuquerque et al., 1999) or "collocated co-kriging" (e.g. co-simulation of categorical (e.g. lithofacies) and continuous (e.g. petrophysical) variables) can be applied.

Taboada et al. (1999) have demonstrated quality evaluation can be achieved in the case of a *granite quarry*, applying statistical and geostatistical methods. They used previously defined quality parameters, tested them on free quarry faces, and subsequently obtained – with the help of discriminate analysis – a single factor that is a linear combination of the quality parameters in question. This quality index or factor of granite mass is equivalent to the metal grade of a metallic ore and can be treated in a similar way with geostatistical techniques. Taboada et al. (1999) have extended the surface quality data of the granite using geostatistical extrapolation to the extent permitted by the range of the semivariogram (in the studied case: 6 meters). Previously, geostatistical techniques have also been applied to exploitation planning in *slate quarries* (Taboada et al., 1997, 1998). The following quality classification parameters have been identified by Taboada et al. (1999) in constructing a combined quality index for a granite rock:

- **Lithological factors** (intrinsic properties of a block indicating its suitability as a specific kind of construction material), such as:
  - Textural characteristics
  - Composition
  - Colour
  - Mechanical characteristics
  - Alteration
  - Transformability
- **Structural factors** (elements that define both the geometry of a geological body and its internal structure), such as:
  - Microgranular enclaves (number, size and shape)
  - Primary fractures (number and continuity)
  - Secondary fractures (number, continuity or extent, spacing, inclination)

The methodology developed by Taboada et al. (1999) can be extended to other Dimensional Stone quarries. The particular quality factors determining the exploitation potential of the quarry and the quality of the final product, however, have to be determined for every different type of stone.

A basically similar but methodologically extended approach was applied by Tercan & Özçelik (2000) in their geostatistical study of an *andesite quarry*. In constructing the single quality variable they used those rock properties, which control the economics of the extraction process, mainly influenced by the wear on the diamond of the wire saw. In the test quarry, as the hardness and strength of andesite increase, the wear on the diamond increases, and when the wear exceeds 0.0086 mm/m^2, the extraction is not considered economical because of the high operating costs. Equally, the bead wear defines the minimum quality of the rock: when the wear is less than 0.0049 mm/m^2, the andesite exhibits poor mechanical characteristics and does not meet the specifications of economically exploitable material. The following mechanical characteristics, which show a high linear correlation with diamond bead wear, have been selected as combination variables:

- Böhme surface abrasiveness
- Cone indenter hardness
- Uniaxial compressive strength
- Modulus of elasticity
- Tensile strength
- Density

In estimating the single quality variable, the multivariate spatial relations of the above variables have been defined by variogram matrices. For blocks classification, a decision analysis approach has been used by Tercan & Özçelik (2000), which rests on two key concepts: cumulative conditional distribution function and loss function. In this way, the blocks of the andesite deposit have been classified as exploitable or non-exploitable on the basis of economic losses minimisation. The advantage of this approach over traditional classification algorithms is that it does not depend on a single estimation of the quality index and is based on financial costs. Concerning "soft" Dimensional Stones as *marble*, where mechanical properties are less important than quality factors, the aesthetic characteristics, such as colour and design, together with the block dimension could be used in estimating single quality variables. Pereira et al. (1992) have estimated a summary recovery index for marble quarries with geostatistical methods, and Albuquerque et al. (1999) have applied a similar technique to characterise a marble region in Portugal.

1.2.3. Weathering: type, intensity and range

Weathering degrades rocks, both chemically and physically, as the first visual estimation in field suggests; the most practical consequence is the decay of their properties, as well as their original aesthetical appearance, so important in Ornamental Stones. Therefore, in any rock engineering activity, the evaluation of weathering, as well as the establishment of weathering indexes between particular rock types and rock properties is of prime interest. In this chapter, the main types of weathering affecting rocks, the profiles of successive intensities and depths of weathering and some rock engineering indexes and procedures for an engineering classification of weathering are summarised. Due to the very different factors controlling the weathering rate such as mineral solubility, rainfall, temperature, vegetation and soil cover, many different weathering types, under very different intensities, can be identified not only in rock massifs but also in Ornamental and Dimensional Stones. Nowadays, the study of these stones in Historic Buildings constitutes an important subject, Stone Conservation, with a very fundamental objective in Cultural Heritage. Table 12 summarises the main types of weathering as well as their typical names, morphological characteristics, genetic processes, and the most common rocks where they can be found. Figures 34 to 40 illustrate those weathering types.

Table 12. Main types of weathering

Name	Characteristics	Process	Main rocks
Scales Flakes Exfoliation Spheroid weathering Desquamation	Curved slabs of rock stripped from the rock mass, similar to the layers of an onion; slabs range from some few cm thick near the rock surface to several meters deeper inside the rock massif	Physical /mechanical Generated by: - Release of lithostatic pressure as the rock is exhumed by erosion of the overlying rock - Salt crystallization just beneath the rock surface - Heating and cooling cycles of rock surface (insulation weathering)	Igneous rocks Granites Basalts Compact sandstones
Arenisation or granular disaggregation Decohesion	Loss of granular cohesion on the rock surface: grains can be easily removed by hand	Physical: Decay of grain interlocking. Chemical: Solution in carbonate rocks; hydrolysis in silicate rocks	Limestones Sandstones Mudstones Granites
Alveoles (honeycomb weathering) Tafoni	Pits and hollows on the surface of rock outcrops and boulders	Physical/chemical Physical- Disaggregation Chemical-Solution	Sandstones
Crust	Coherent and hard outer layer formed on the rock surface	Chemical: Outer transformation of the rock under combined solution – crystallisation processes. Local stresses induced by salt crystallisation, hydration etc.	Limestones Sandstones Marbles Granites
Efflorescence	Whitish deposits of crystal salts on porous rock surfaces	Chemical: Flow of water with solute salts and water evaporation	Limestones Sandstones Granites, etc.
Organic weathering Biogenic crust	Organic substances settled on the rock surface.	Chemical / Physical: Rock disintegration and decomposition, under the action of microorganisms, plants, animals and decaying organic matter.	All stones

Figure 34. Spheroidal

Figure 35. Scaling

Figure 36. Efflorescence

Figure 37. Disaggregation

Figure 38. Alveoles

Figure 39. Very advanced alveolisation

Limestones and Ca-rich rocks show very distinctive weathering characteristics; when they are exposed to acidic rainwater, they can be partially or totally dissolved. In such cases, the formation of caves of different sizes and shapes, as well as wide open fractures, uneven ground etc., are the most important rock engineering consequences (Figure 40). At the intact rock scale, of fundamental interest in Ornamental Stones, the phenomenon is quite similar and controlled by the pore space geometry (Esbert et al., 1997). At the rock-massif scale, the position and geometry of the rockhead, surface between overlying unconsolidated material and solid bedrock below, is a problem of prime interest in Ornamental Stones quarrying that can not be always easily solved.

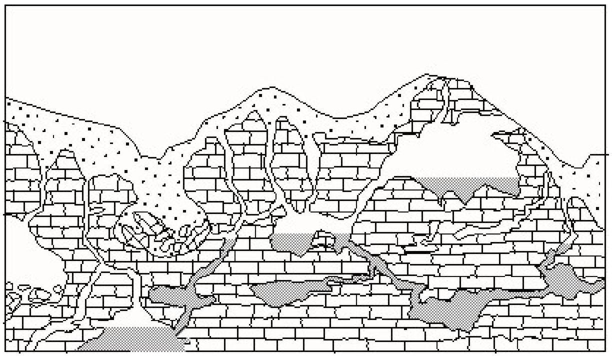


Figure 40. Limestone Weathering

Weathering has not always negative effects; on the contrary, sometimes it has a clear positive effect on building stones: as scanning electron microscopy observations prove, the external part of porous limestone can be dissolved and its carbonate composition is recrystallised on its surface; this process decreases locally the porosity and, consequently, the surface gets a better hydric behaviour. For very precise weatherability studies the environmental conditions and the state of the rock surface have to be evaluated; among them, the rock-surface moisture content is of prime interest and for its local evaluation, non- destructive testing procedures have been developed (Matsukura and Takahashi, 1999). In order to characterise the different levels of weathering intensity presented in a rock mass, weathering profiles are a very useful tool (Figure 41, Waltham, 1994).

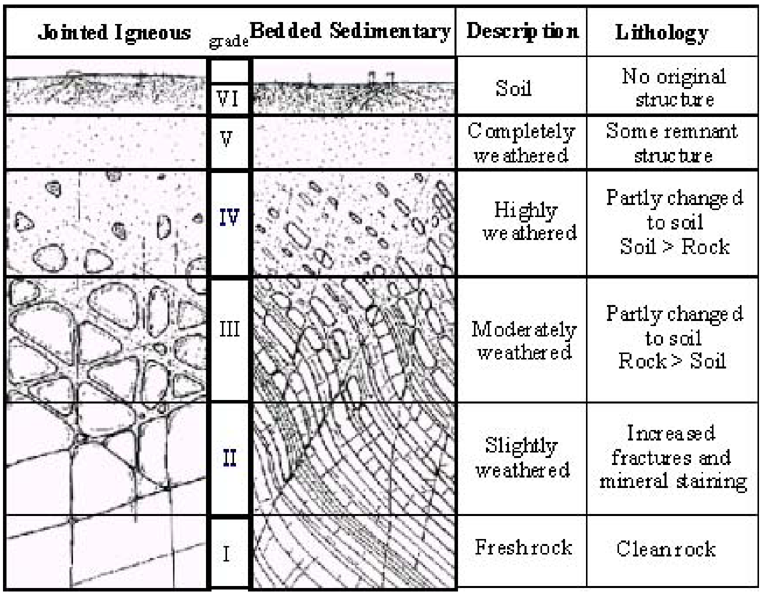


Figure 41. Weathering profiles in jointed igneous rocks and in bedded sedimentary rocks (Waltham, 1994, modified)

Many indexes have been developed for establishing an engineering classification for weathered rock; as an example, the very simple weathering coefficient, $K = (V_f - V_w) / V_f$, developed by Iliev (1967) based on the ultrasonic velocities in fresh, V_f, and weathered rock, V_w, shown in Table 13 can be mentioned. The advantage of ultrasonic measurements is that they can be easily obtained on site.

Table 13. Ultrasonic velocity and grade of weathering (Iliev, 1967).

Weathering Grade	Ultrasonic velocity (m/s)	Weathering Coefficient
Fresh	5000 >	0
Slightly weathered	4000 – 5000	0.0 – 0.2
Moderately weathered	3000 – 4000	0.2 – 0.4
Strongly weathered	2000 – 3000	0.4 – 0.6
Very strongly weathered	< 2000	0.6 – 1.0

In addition, different rates of weathering based on some simple physical properties have been obtained; as an example, the weathering indices for granites, established by Irfan and Dearman (1978) according to their values for water absorption, bulk density and point-load strength are mentioned in Table 14.

Table 14. Weathering indices for granite (Irfan and Dearman, 1978).

Weathering type	Quick absorption (%)	Bulk density (t/m^3)	Point-load strength (MPa)	Unconfined compressive strength (MPa)
Fresh	Less than 0.2	Over 2.61	Over 10	Over 250
Partially stained	0.2 – 1.0	2.56 – 2.61	6 – 10	150 – 250
Completely stained	1.0 – 2.0	2.51 – 2.56	4 – 6	100 – 150
Moderately weathered	2.0 – 10.0	2.05 – 2.51	0.1 – 4	2.5 – 100
Highly/completely weathered	Over 10	Less than 2.05	Less than 0.1	Less than 2.5

The seasonal and daily climatic cycles of temperature induce on rocks cyclic state variations, such as: heating-cooling, wetting-drying and freezing-thawing. Although their short-term mechanical effects (some few days or months) can be negligible, they can seriously affect the rock mechanical strength in the long run (years, centuries). Besides, these effects can be very different on different rocks. Therefore, fractures can be developed on rocks when the thermal fatigue limit is reached and an important reduction in the rock mechanical strength can be obtained (Haimson, 1974); the reduction reported by this author in sandstones is about 30%; capillary tension, surface tension, disjoining pressure, movement of interlayer water and movement of chemically combined water, as the main mechanisms causing expansion and contraction of stone due to moisture availability, are summarised by the author. One of the most important rock mechanical properties, ultimate compressive strength, obviously is highly influenced by weathering, as shown in Table 15.

Table 15. Weathering grade and rock properties for selected rocks (Waltham, 1994)

Weathering grade		I	II	II	IV	V
Granite: unconfined compressive strength	MPa	250	150	5-100	2-15	
Triassic sandstone: unconfined compressive strength	MPa	30	15	5	2	<1
Carboniferous sandstone: rock quality designation	%	80	70	50	20	0
Chalk: standard penetration test	N value	>35	30	22	17	<15
Chalk: safe bearing pressure	kPa	1000	750	400	200	75
Triassic mudstone: safe	kPa	400	250	150	50	
Triassic mudstone: clay particle fraction	%	10-35		10-35	30-50	

Rock weatherability can be evaluated through “durability”, a very interesting engineering parameter. The well known and simple slake-durability test provides a very valuable durability index. The test makes a combined estimation of the rock resistance to abrasion and to cycles of wetting and drying; the test evaluates the weight loss of rock pieces immersed in water and subjected to rotation and expresses it as a percentage (Table 16).

Table 16. Slake durability index.

Durability	Index
Very low	>25%
Low	25 – 50%
Medium	50 – 75%
High	75 – 90%
Very high	90 – 95%
Extremely high	95%>

A very practical weathering index (WI) for any rock mass has been proposed (Hill and Rosebaum, 1994) which takes into account the following significant factors in any rock weathering system: climate, biological activity, mineralogy, texture, discontinuities, permeability, geomorphology and time. Nevertheless, the most commonly used weathering indices avoid considering the rock-massif scale and, therefore the analysis of the geologic aspects that clearly influence the rock-massif properties, that is, discontinuities such as bedding lanes, joints, faults, etc. Most indices are just focused on the rock matrix or “intact rock” scale (volume of rock free of rock-massif discontinuities, as defined by the International Society of Rock Mechanics). As a consequence, it is clear that the work of the so-far mentioned authors requires a further development for a more appropriate characterisation of weathering in Dimensional Stone deposits.

1.2.4. Geotechnical characterisation

One of the most important tasks in the characterisation of a rock mass in quarries is the geotechnical characterisation. This is needed in order to optimise an existing quarry operations plan or to design an underground exploitation of a natural stone deposit. Thus, the purpose of this section is to summarise the main empirical rock mass classification systems in use:

- Norwegian Geotechnical Institute rock quality system (Q) (Barton et al., 1974)
- Geomechanics Rock Mass Rating system (RMR) (Bieniawski, 1989). These rock mass classification systems were developed in response to the demand for numerical design tools.

Kirkaldie (1987) suggests that the rock material field classification procedure should consist primarily of two steps: the classification process and the performance assessment. The classification process includes:

- Identification of the *rock unit*
- Description of the rock in terms of *classification elements*. Classification elements describe the physical properties of the rock units that are most relevant to engineering

activities. This geotechnical characterisation reports rock mass properties in terms of the classification elements of the Q and RMR systems.

In the following paragraphs data collection procedures are described for both Q and RMR systems. These systems are classification methods which aim to characterise the rock mass based on the main geological factors affecting the stability of an underground opening. Both systems have been widely used and adapted for many applications. However, their use continually expands in situations they were not intended to. The output of both, although quantitative in nature, is basically intended to provide the engineer with a 'feel' for the rock mass.

Rock Quality Designation (RQD)

The RQD index is a rating parameter of both the Q and RMR systems for drill core. It was introduced as a quantitative measure of rock quality (Deere, 1989). The total length of core pieces, which have 4 inches (about 10 cm) or greater length, is divided by the length of the core run, which in this case is 5 m. RQD is calculated as follows (eq.1):

$$RQD\% = \frac{\sum Length\, of\ Core\, Pieces > 10cm}{Core\, Run\,(5m)} \times 100 \qquad \text{(eq.1)}$$

Lengths of intact rock adjacent to the detailed line survey tape (DLS) are estimated or calculated as the percentage of core pieces with lengths 10 cm or greater, which would be recovered in an imaginary horizontal drill hole along the left rib of the excavation. The fundamental assumption for RQD calculation is that the length of rock between recorded fractures is intact rock. Apparent man-made or mechanical fractures are excluded. The total of intact rock pieces longer than 10 cm are determined from the fracture spacing. That length, expressed as a percentage of the total length, is the 5 m RQD rating. Where an RQD value within a 5 m section is less than or equal to a rating of 10 or less (including 0), a nominal value of 10 is assigned to it. As described in paragraph 1.2.1, the RQD index can also be used with some restrictions in the assessment of block sizes. Table 17 shows the qualitative description associated with ranges of RQD percentages.

Table 17. RQD ranges and descriptions.

RQD (%)	Rock Quality Description
<25	Very Poor
25 – 50	Poor
51 – 75	Fair
76 – 90	Good
91 – 100	Excellent

Lithophysae encountered in core drilling samples produce a length of drill hole with no core recovery. Similarly, lithophysae zones are treated as void spaces, with no core recovery, and therefore excluded from the theoretical length of intact rock. This procedure of “zeroing out” lithophysal cavities reduces the computed RQD. Therefore, a rock mass with a high concentration of lithophysal cavities is not characterised well by the empirical systems.

Rock Mass Rating (RMR)

The RMR system, also known as the Geomechanics Classification, is an empirical rating system based on the sum of six rock mass parameters. Bieniawski developed the system in 1973 and revised it to the present form (Bieniawski, 1989). RMR was developed for tunnels but has been adapted also for slope stability, foundations, coal mining, and hard rock mining. Output includes stand-up times, support pressures, maximum spans, elastic modulus, cohesion and friction angle of the rock mass. The numerical rock mass rating, RMR is calculated according to the following equation (eq.2):

$$RMR = C + RQD + J_s + J_{cd} + J_w \cdot R + AJO \qquad \text{(eq.2)}$$

where:
C = numerical value associated with the intact rock compressive strength,
RQD = numerical value associated with the rock mass RQD (this rating is not equal to the RQD value),
J_s = numerical value associated with the fracture spacing of a given joint set,
J_{cd} = numerical value associated with the discontinuities condition,
J_wR = numerical value dependent on groundwater or inflow conditions. The “R” is used to distinguish this rating from the Q system joint water rating,
AJO = numerical value associated with the discontinuities orientation

The parameters of compressive strength, joint spacing, joint condition and groundwater are divided into five value ranges. The rating numbers reflect the importance of each parameter. In this procedure, the joint set with the lowest total rating for spacing, joint condition and orientation is used to calculate the RMR. Table 18 provides the qualitative descriptions associated with ranges of RMR percentages.

Table 18. RMR ranges and descriptions

Rock Mass Rating	Rock Quality Description
0 – 20	Very Poor
21 – 40	Poor
41 – 60	Fair
61 – 80	Good
81 – 100	Very good

Norwegian Geotechnical Institute Rock Quality (Q – System)

The Norwegian Geotechnical Institute Q rock mass classification system establishes a numerical value for rock quality for engineering purposes. The Q-SYSTEM, developed at the Norwegian Geotechnical Institute in 1974, includes six parameters: RQD, Jn, Jr, Ja, Jw and SRF that describe block size, interblock shear strength, and active stresses in the particular Geotechnical Mapping Unit. The user must first determine the areas in which rock mass conditions are reasonably homogeneous before proceeding in the evaluation of the aforementioned parameters (i.e. the boundaries of the Geotechnical Mapping Unit should be mapped). A Q rating is calculated as the product of six parameters according to the following equation (eq.3):

$$Q = (RQD / J_n) \times (J_r / J_a) \times (J_w Q / SRF) \qquad \text{(eq.3)}$$

where:
RQD = integer number equal to RQD percentage,
J_n = index number based on the assessment of joint sets number in the considered rating length,
J_r = index number representing the roughness of the joint set,
J_a = index number based on the alteration or filling of a given joint set,
J_wQ = index number based on groundwater conditions. “Q” is used to distinguish this index from the RMR rating system,
SRF = Stress Reduction Factor based on *in situ* conditions that influence the excavation stability.

Qualitative rock descriptions associated with numerical Q values are shown in Table 19. The rock quality (Q) can range from 0.001 to 1000.

Table 19. Q ranges and descriptions.

Q value	Description
0.001 – 0.01	Exceptionally Poor
0.01 – 0.1	Extremely Poor
0.1 – 1	Very Poor
1 – 4	Poor
4 – 10	Fair
10 – 40	Good
40 – 100	Very Good
100 – 400	Extremely Good
400 – 1000	Exceptionally Good

The values of the six parameters along with the assigned lowest Q rating are reported here. The parameters *Jr* and *Ja* (representing shear strength) should be relevant to the weakest significant joint set or clay-filled discontinuity in the 5 m interval. However, if the joint set or discontinuity with the minimum value of *Jr/Ja* is favorably oriented in terms of stability, then a second, less favorably oriented joint set or discontinuity may sometimes be more significant, and its higher value *Jr/Ja* should be (and is) used when evaluating Q. The value of *Jr/Ja* should in fact be related to the surface most likely not to allow failure to initiate.

Theoretically, the application of Barton’s stress reduction factor (SRF) guidelines is open to interpretation and is, therefore, a significant contributor of potential errors in the Q estimation. Kirsten (1988) has recognised the difficulty in assessing SRF and developed an alternative approach to quantify the SRF rating process and remove the subjectivity in applying Barton’s guidelines. Kirsten observes that for the case of non-homogeneous, incompetent rock, SRF is related to the overall quality of the rock, as follows (eq.4):

$$SRF_n = 1.809 \cdot Q^{-0.329} \qquad \text{(eq. 4)}$$

where:
SRF_n = Stress Reduction Factor for non-homogeneous rock

On the other hand, Q is defined as follows (eq.5):

$$Q = (RQD / J_n) \times (J_r / J_a) \times (J_w Q / SRF) \qquad \text{(eq.5)}$$

Combining equations 4 and 5 for non-homogeneous rock results in the following equation (eq.6):

$$Q = [(RQD / J_n) \times (J_r / J_a) \times (J_w Q / 1.809)]^{\frac{1}{1-0.329}} \qquad \text{(eq.6)}$$

In the case of homogeneous, competent rock, SRF is related to the field stress state relative to the rock strength as follows (eq.7):

$$SRF_h = SRF_{h1} + SRF_{h2} \qquad \text{(eq.7)}$$

where:
SRF_h = SRF for homogeneous rock,
SRF_{h1} = SRF for stress-controlled behavior of homogeneous rock,
SRF_{h2} = SRF for geologic-structure controlled behavior of homogeneous rock.

The terms SRF_{h1} and SRF_{h2} are defined as follows (eqs. 8, 9):

$$SRF_{h1} = 0.244 K^{0.346} \times (H / UCS)^{1.322} \qquad \text{(eq.8)}$$

$$SRF_{h2} = 0.176 \times (UCS / H)^{1.413} \qquad \text{(eq.9)}$$

where:
K = maximum-to-minimum principal field stress ratio,
H = thickness of overburden above excavation (m),
UCS = unconfined compressive strength of rock (MPa).

If SRF_{h1} is greater than SRF_{h2}, then the behavior of the competent rock mass will be controlled by stress conditions. On the contrary, if SRF_{h2} is greater, then the behavior of the competent rock will be controlled by geologic structure. Rock mass for homogeneous rock (Q_h) is expressed as follows (eq.10):

$$Q_h = [(RQD / J_n) \times (J_r / J_a) \times (J_w Q / 0.244 K^{0.746} (H / UCS)^{1.322} + 0.176 (UCS / H)^{1.413})]$$

The Q value for a given rock mass region is determined as the minimum of Q_n and Q_h.

The field stress state was determined based on hydraulic fracturing, in situ-stress measurements in the Thermal Test Facility Alcove in the ESF (Sandia, 1997), and found the principal stresses to be: σ_h = 1.7 MPa, σ_H = 2.9 MPa and σ_v = 4.7 MPa. The average horizontal and vertical stress are typically used to calculate the field stress ratio (Hoek, 1998) therefore, Kirsten's parameter (K) can be determined as follows (eq.11):

$$K = \frac{S_v}{0.5 \cdot (\sigma_h + \sigma_H)} = \frac{4.7}{0.5(1.7 + 2.9)} = 2 \qquad \text{(eq.11)}$$

A stress ratio (K) value of 2 will be assumed to be constant throughout future excavations. The head of rock H is equal to the thickness of the overburden above the tunnel alignment.

A. Classification Parameters and Their Ratings	
Parameter	Range of values
A1. Strength of Intact Rock Material (**see field estimates**)	

Uniaxial Compressive Strength (MPa)	> 250	100 - 250	50 - 100	25 - 50	5 - 25	1 - 5	< 1
Rating C	15	12	7	4	2	1	0

A2. Drill Core quality

RQD (%)	90 – 100	75 – 90	50 – 75	25 – 50	< 25
Rating - RQD	20	17	13	8	3

A3. Spacing of discontinuities

	> 2 m	0.6 – 2 m	200 - 600 mm	60 – 200 mm	< 60 mm
Rating J_s	20	15	10	8	5

A4. Condition of discontinuities (see B)

	Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickenside surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5mm thick or Separation > 5mm Continuous
Rating J_{cd}	30	25	20	10	0

A5. Groundwater

Inflow per 10 m tunnel length (L/min)	None	< 10	10 - 25	25 - 125	> 125
Joint water pressure/ Major principal σ	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5
General Conditions	Completely dry	Damp	Wet	Dripping	Flowing
Rating JwR	15	10	7	4	0

B. Guidelines for Classification of Discontinuity Conditions**

Discontinuity Length (persistence)	< 1 m	1 - 3 m	3 - 10 m	10 - 20 m	> 20 m
Rating	6	4	2	1	0
Separation (aperture)	None	< 0.1 mm	0.1 - 1.0 mm	1 - 5 mm	> 5 mm
Rating	6	5	4	1	0
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickenside
Rating	6	5	3	1	0
Infilling (gouge)	None	Hard Filling < 5 mm	Hard Filling > 5 mm	Soft Filling < 5 mm	Soft Filling > 5 mm
Rating	6	4	2	2	0
Weathering	Unweathered	Slightly	Moderately	Highly	Decomposed

		weathered	weathered	weathered	
Rating	6	5	3	1	0

*Bieniawski 1989

**Some conditions are mutually exclusive. For example if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly.

Field Estimates of Uniaxial Compressive Strength

Term	Uniaxial Compressive Strength (MPa)	Point Load Index (MPa)	Schmidt Hardness (Type L - hammer)	Field Estimate of Strength	Examples*
R5 Extremely Strong	> 250	> 10	50 - 60	Rock material only chipped under repeated hammer blows	fresh basalt, chert, diabase, gneiss, granite, quartzite
R4 Very Strong	100 - 250	4 - 10	40 - 50	Requires many blows of a geological hammer to break intact rock specimens	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble rhyolite, tuff
R3 Strong	50 - 100	2 - 4	30 - 40	Hand held specimens broken by a single blow of a geological hammer	Limestone, marble, phyllite, sandstone, schist, shale
R2 Medium Strong	25 - 50	1 - 2	15 - 30	Firm blow with geological pick indents rock to 5mm, knife just scrapes surface	Claystone, coal, concrete, schist. shale, siltstone
R1 Weak	5 - 25	**	< 15	Knife cuts material but too hard to shape into triaxial specimens	chalk, rock salt, potash
R0 Very Weak	1-5	**		Material crumbles under firm blows of geological pick, can be scraped with knife	highly weathered or altered rock
Extremely Weak	0.25 - 1	**		Indented by thumbnail	clay gouge

*Well interlocked crystal fabric with few voids

**Rocks with a uniaxial compressive strength below 25 MPa are likely to yield highly ambiguous results under point load testing

1.3. Characterisation of Intermediate and Semi-finished Products

Natural Stones Sampling

The aim of sampling is to obtain representative natural stone specimens from quarries, plants or buildings. A sampling plane should be prepared taking into account the following:

- Stone type (according to EN 12440 and 12670);
- Sampling aim;
- List of the properties to be tested;
- Sampling points;
- Size and number of samples;
- Sampling apparatus to be used (cutting or drilling equipment);
- Sampling methods to be used;
- Marking, packages and dispatch of the samples.

The sampling methods are obviously different if applied in a quarry, a plant or a building.

Sampling from quarries establishes the structural properties of the stone deposit and the variations in structure, fabric and physical - mechanical characteristics of the stone. If there are present geological structures in the deposit, not necessarily visible at the sample scale (stratification, massive bedding, lamination, cleavage etc.), this shall be marked on the sample. Petrographic analysis can be made on hand specimens taken from all distinct varieties characterising the stone deposit from the point of view of mineral composition, fabric and structure.

Sample blocks of 400 mm x 250 mm x 250 mm or more can be extracted for physical mechanical tests. Their number and location depends on the results of the petrographic analysis and on the required test methods (at least one sample for each variation of esthetical or mineralogical variation of the stone in the stone deposit). Care has to be taken during sampling so as not to obtain samples affected by blasting or the extraction process. The samples may also be cut from rough blocks or slabs.

Sampling from plants depends in terms of number, shape and dimensions on the properties of the natural stone to be tested.

Sampling from buildings should be made taking into account any differences in the esthetical or mechanical properties of the slabs for cladding. If there is a visible homogeneity in the characteristics of the slabs a single slab will be sufficient.

Characterisation of rough blocks

Definition

Rough blocks are erratic rocks just extracted from quarries and/or shaped only by cutting or splitting. They can be characterised as shapeless rough blocks if they are without a regular shape and size, squared rough blocks when corresponding approximately to a regular parallelepiped.

Shape and dimensions

The dimensions of a squared rough block are: length (*l*) that is the greater side, width (b) that is the smaller size, height (h) that is the side at right angle to the plane containing *l* and b. The gross size of a block may be defined by the length of the edges of the smallest parallelepiped circumscribed to this block, while the net size may be defined by the greatest parallelepiped inscribed. The latter parallelepiped shall contain only sides with right angles and flat surface without drill holes etc. Each dimension should be reduced by 50 mm considered as waste fraction (Figure 42).

The commercial size of a block is defined by the length of the edges, considering any reduction of dimensions as consequence of irregularities of block faces, or some characteristics of the block which affect its conformity relatively to the quality requirements. The block's shape measurements should be carried out following pr EN 13373 "*Natural Stone test methods - Determination of geometric characteristics on units*" and all measured values should be indicated in millimetres. In general, for commercial purposes the measures of a rough block are done by mass in tones or by volume in cubic metres.

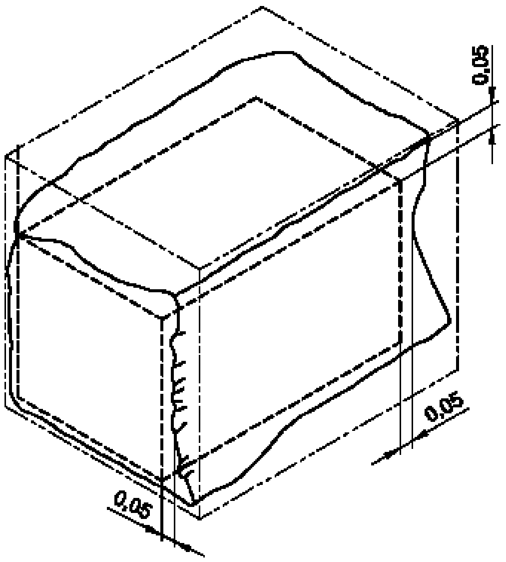


Figure 42. Gross and net size of a rough block.

Characterisation

The characterisation of a rough block consists of:

- *Denomination of the Natural Stone* in accordance with EN 12440: traditional name, petrologic family, typical colour and place of origin or better name and address of the quarry;
- *Visual appearance* identified by one or more samples representing the variability range of the esthetical quality of the stone. All these variations are consequences of the variability of the stone mineralogical composition, fabric, texture, presence of any kind of anisotropies, geologic structure of the stone deposit, etc.
- *Apparent density* and *open porosity,* determined according to EN 1936;
- *Flexural strength* determined according to EN 12372 or to EN 13161;
- *Compression strength* determined according to EN 1926.
- Additional tests may be performed if the stone is to be used for specific purposes.

Moreover, the main problem in the choice of a block is to locate defects like cracks and fractures, not apparent externally and colour variations. The choice of a block by the purchaser is based mainly on the competence of a qualified specialist able to determine the quality of the block both from the esthetical and the mechanical properties point of view.

Characterisation of rough slabs

Definition

Rough slabs are obtained from a rough block by sawing or splitting. They are semi-finished products with flat surface and unfinished edges.

Shape and dimensions

The dimensions of a rough slab are: length *l*, width b, thickness h all given in millimetres. The gross size of a rough slab is the smallest circumscribed rectangle, while the net size of a rough slab is the greatest inscribed rectangle not containing irregularities and fractures. The commercial size of a rough slab is defined by the dimensions of the useful rectangle according to the relevant requirements, and normally it is not less than the 50 % of its gross size. The measurement of the slab shape should be carried out following pr EN 13373 “Natural Stone test methods - Determination of geometric characteristics on units” and all measured values should be indicated in millimetres.

The thickness of a rough slab should be given with tolerances depending on the nominal thickness: for example, with a nominal thickness up to 15 mm the tolerance could not be over 1.5 mm, while for a slab more than 80 mm thick the tolerance could be of 5 mm. However this should be agreed between the supplier and the purchaser who may choose stricter tolerances. The deviation from flatness, with the exception of split rough slabs, should be regulated in the same way by an agreement between the supplier and the purchaser or by an appropriate standard. However, it normally should not exceed 0.2 % of the slab length and 3 mm. The surface finish should have regular appearance and may be obtained by sawing or by finishing processing. The different surface finishes obtained by grinding may be:

- rough ground surfaces obtained, e. g. by means of a grinding disk of grain size F 60;
- medium ground surfaces obtained, e. g. by means of a grinding disk of grain size F 120;
- fine ground surfaces obtained, e. g. by means of a grinding disk of grain size F 220;
- matt finished surfaces obtained, e. g. by means of a polishing disk with grain size F 400;
- highly polished surfaces obtained e. g. by means of a polishing disk or felt.

The surface finishes obtained by means of hammer type tools may be, for example:

- bush hammered surfaces;
- trimmed surfaces: finish obtained by using pointed chisel and mallet or a grooving machine;
- striated surfaces: finish obtained by using a claw chisel (percussion tool for surface roughening, with the cutting end covered by several teeth of various sizes) or a ruling machine.

The surface finishing obtained by other finishing operations may be, for example:

- flamed finishing;
- sand blasted finishing;
- water jet streamed finishing: a matt textured surface finish, accomplished by exposing the surface to a steady jet of water under pressure;
- machine tooled finishing;

- rive cut finishing: rugged surface produced by splitting stone with a guillotine.

Many stones demand the use of patching, fillers or other similar products to fill or cover natural holes, faults or cracks. If the finishing processes may alter the stone properties, the characterisation should be performed on samples obtained from the final finishing processes as the results of these tests will probably differ from those obtained from the rough slabs.

Characterisation

The characterisation of a rough slab includes:

- *Denomination of Natural Stones* in accordance with EN 12440: traditional name, petrologic family, typical colour and place of origin or better name and address of the quarry;
- *Visual appearance* identified by samples representing the variability range of the esthetical quality of the slab. All these variations are results of the variability of the stone mineralogical composition, fabric, texture, presence of any kind of anisotropies, geologic structure of the stone deposit, etc. There should be an agreement between the supplier and the purchaser for the selection of the samples, which should have the required surface finish.
- *Apparent density* and *open porosity,* determined according to EN 1936;
- *Flexural strength,* determined according to EN 12372 or to EN 13161;
- Additional tests may be performed if the stone is to be used for specific purposes.

1.4. Finished products characterisation

The finished product market is the reason of the Ornamental and Dimensional Stones industry existence. Therefore, the characterisation of a finished product, whatever the product or the market segment is, is of major importance. National and International standards focus on such characterisation. The present paragraph refers only to the “pure” stone finished product and does not consider other similar but not only made by stone finished products, such as the so called “agglomerated”.

A coherent presentation of the finished product characterisation must take into account that each characterisation difference follows a different perspective. The characterisation “object” can be the same, for example a tile, but it can be seen as a product to be characterised according to the dimension; or depending on the rock type; or again according to the surface finishing; or according the final use and so on. Two main perspectives can be considered: a product classification based on actual marketing and another based on product qualification. The first one is linked to the pricing or other economic parameters; the second one is related to the standards.

In each of the two approaches, the properties that characterise the finished products normally are different or have a different impact. For instance, the economic classification is based on what can be generically defined as the product “type”; whilst in the case of product certification or marking, the characterisation depends on the product “final use”.

1.4.1. The economic classification of finished product and the related characteristics

There are many criteria for classifying finished product types, the most interesting ones being those linked to their economic parameterisation. Such is the market value or the class used by industry statistics. One can peer through the advertising and price lists; he will realise that there are many inhomogeneous ways to offer a finished product and present its characteristics. Sometimes the product final use is also stressed, but it is less relevant to its economic classification than to its product quality characterisation, presented in paragraph 1.4.2. The criterion of presenting the finished products in statistical reports is much more "stable", but the related macro coding for describing the finished product type in that case has to be rather summarising. Consequently the characterisation seems to be quite generic. Nevertheless, it could be useful starting by this standard classification.

Finished product characterisation according to statistical reports

The macro coding used to describe the finished product statistics considers mainly the categories of the so-called "rock type" (Figure 43). It is not a matter of petrographic definition, but the reason of this classification relies on some historical perception by a non-scientific market. We can try to link this subdivision to the broad criterion of the presence/absence of silicates (granites/marble), but the items "slate" and "other stone" frustrate this attempt.

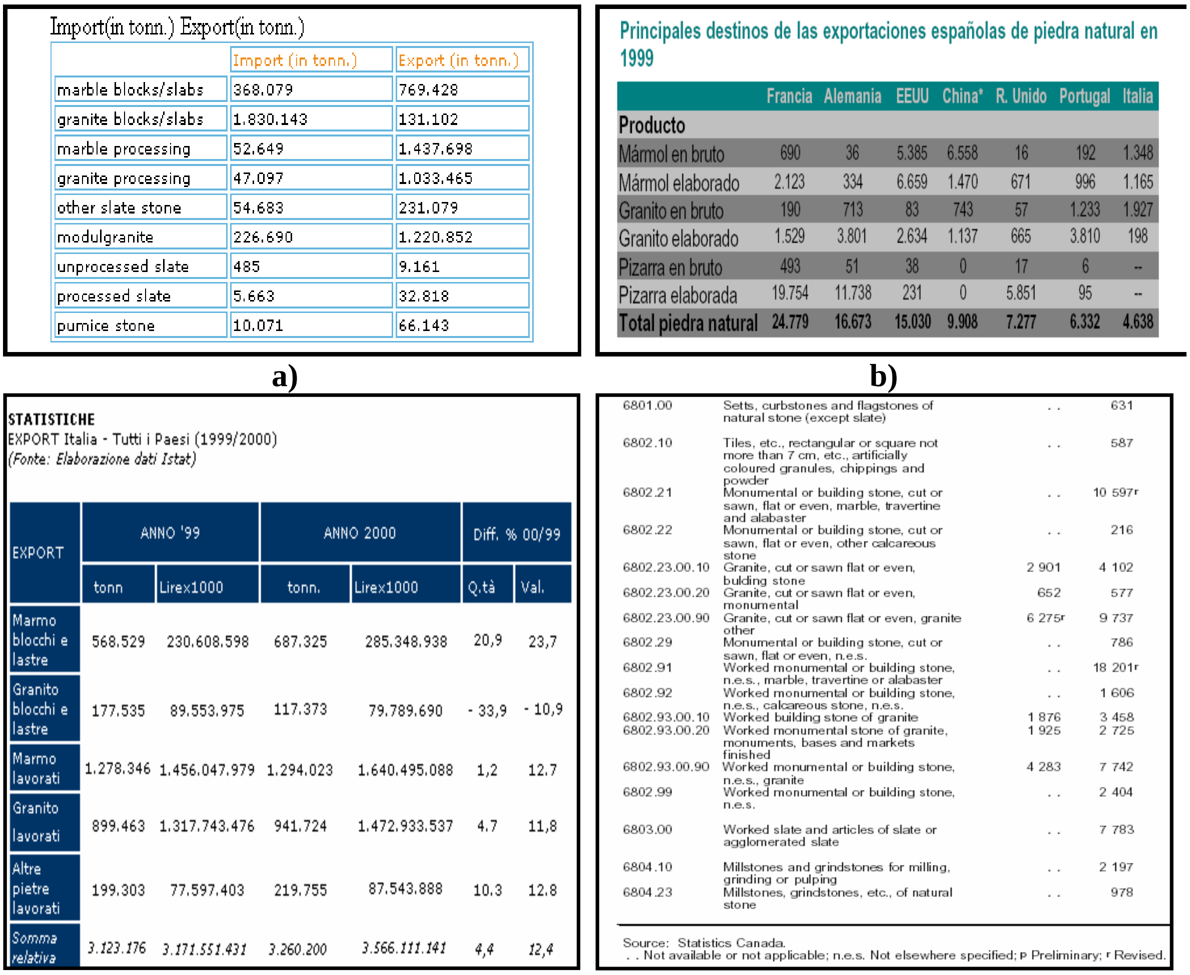
In some cases, statistics deepen the economic classification by considering some simple subdivisions, as Simple or Special finished products, Modular tiles, Slates. Again a heterogeneous criterion is assumed, making reference to a very broad class of products in one case (Simple or Special) or to a specific class type in others (tiles, slates). Characterisation is still difficult; it can make reference to the product dimensions but be absolutely imprecise. In conclusion, the characterisation of finished products according to statistical reports is mainly linked to a generic definition of the rock-type (granite/marble/other) and to a generic or broad definition of the class type (tiles/slates). Do not confuse the finished products classification per "type" with those per end-use that are much more standardised (Figure 44).

Finished products characterisation according to the market

By viewing at any commercial site, in the newspapers or in the web, it is clear that the price of the offered finished products needs a more detailed definition. For some finished products of wide consumption, many characteristics are considered as standards and/or understood; only the most "usual" properties are given. For example, in the case of tiles, typical offer/request is as follows: *Arabescato Tiles: colour: white; dimension: 60x60x3; quantity: 5000* m^2 or *Bianco Carrara Tiles: 20 USD/sq.m, C/D.*

The information given by such classification is the following:

- Product type: tile
- Material denomination: arabescato, bianco carrara
- Colour: white
- Commercial quality class: C/D
- Specific dimensions (in cm): 60x60x3
- Surface finishing: polished
- Total quantity: 5000 sq.m.
- Price: 20 USD/sq.m.



Import(in tonn.) Export(in tonn.)

	Import (in tonn.)	Export (in tonn.)
marble blocks/slabs	368.079	769.428
granite blocks/slabs	1.830.143	131.102
marble processing	52.649	1.437.698
granite processing	47.097	1.033.465
other slate stone	54.683	231.079
modulgranite	226.690	1.220.852
unprocessed slate	485	9.161
processed slate	5.663	32.818
pumice stone	10.071	66.143

a)

Principales destinos de las exportaciones españolas de piedra natural en 1999

	Francia	Alemania	EEUU	China*	R. Unido	Portugal	Italia
Producto							
Mármol en bruto	690	36	5.385	6.558	16	192	1.348
Mármol elaborado	2.123	334	6.659	1.470	671	996	1.165
Granito en bruto	190	713	83	743	57	1.233	1.927
Granito elaborado	1.529	3.801	2.634	1.137	665	3.810	198
Pizarra en bruto	493	51	38	0	17	6	--
Pizarra elaborada	19.754	11.738	231	0	5.851	95	--
Total piedra natural	**24.779**	**16.673**	**15.030**	**9.908**	**7.277**	**6.332**	**4.638**

b)

STATISTICHE
EXPORT Italia - Tutti i Paesi (1999/2000)
(Fonte: Elaborazione dati Istat)

EXPORT	ANNO '99		ANNO 2000		Diff. % 00/99	
	tonn	Lirex1000	tonn.	Lirex1000	Q.tà	Val.
Marmo blocchi e lastre	568.529	230.608.598	687.325	285.348.938	20,9	23,7
Granito blocchi e lastre	177.535	89.553.975	117.373	79.789.690	- 33,9	- 10,9
Marmo lavorati	1.278.346	1.456.047.979	1.294.023	1.640.495.088	1,2	12.7
Granito lavorati	899.463	1.317.743.476	941.724	1.472.933.537	4.7	11,8
Altre pietre lavorati	199.303	77.597.403	219.755	87.543.888	10.3	12.8
Somma relativa	*3.123.176*	*3.171.551.431*	*3.260.200*	*3.566.111.141*	*4,4*	*12,4*

c)

6801.00	Setts, curbstones and flagstones of natural stone (except slate)	. .	631
6802.10	Tiles, etc., rectangular or square not more than 7 cm, etc., artificially coloured granules, chippings and powder	. .	587
6802.21	Monumental or building stone, cut or sawn, flat or even, marble, travertine and alabaster	. .	10 597r
6802.22	Monumental or building stone, cut or sawn, flat or even, other calcareous stone	. .	216
6802.23.00.10	Granite, cut or sawn flat or even, bulding stone	2 901	4 102
6802.23.00.20	Granite, cut or sawn flat or even, monumental	652	577
6802.23.00.90	Granite, cut or sawn flat or even, granite other	6 275r	9 737
6802.29	Monumental or building stone, cut or sawn, flat or even, n.e.s.	. .	786
6802.91	Worked monumental or building stone, n.e.s., marble, travertine or alabaster	. .	18 201r
6802.92	Worked monumental or building stone, n.e.s., calcareous stone, n.e.s.	. .	1 606
6802.93.00.10	Worked building stone of granite	1 876	3 458
6802.93.00.20	Worked monumental stone of granite, monuments, bases and markets finished	1 925	2 725
6802.93.00.90	Worked monumental or building stone, n.e.s., granite	4 283	7 742
6802.99	Worked monumental or building stone, n.e.s.	. .	2 404
6803.00	Worked slate and articles of slate or agglomerated slate	. .	7 783
6804.10	Millstones and grindstones for milling, grinding or pulping	. .	2 197
6804.23	Millstones, grindstones, etc., of natural stone	. .	978

Source: Statistics Canada.
. . Not available or not applicable; n.e.s. Not elsewhere specified; p Preliminary; r Revised.

d)

Figure 43. a, b, c, d. Examples of statistical reports (sources IMM-Carrara, ICEX-FDP, ACIMM-ANAMP, Statistics Canada).

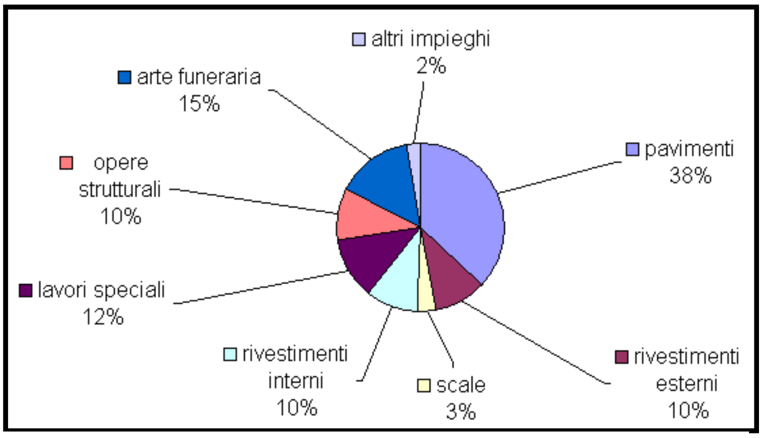
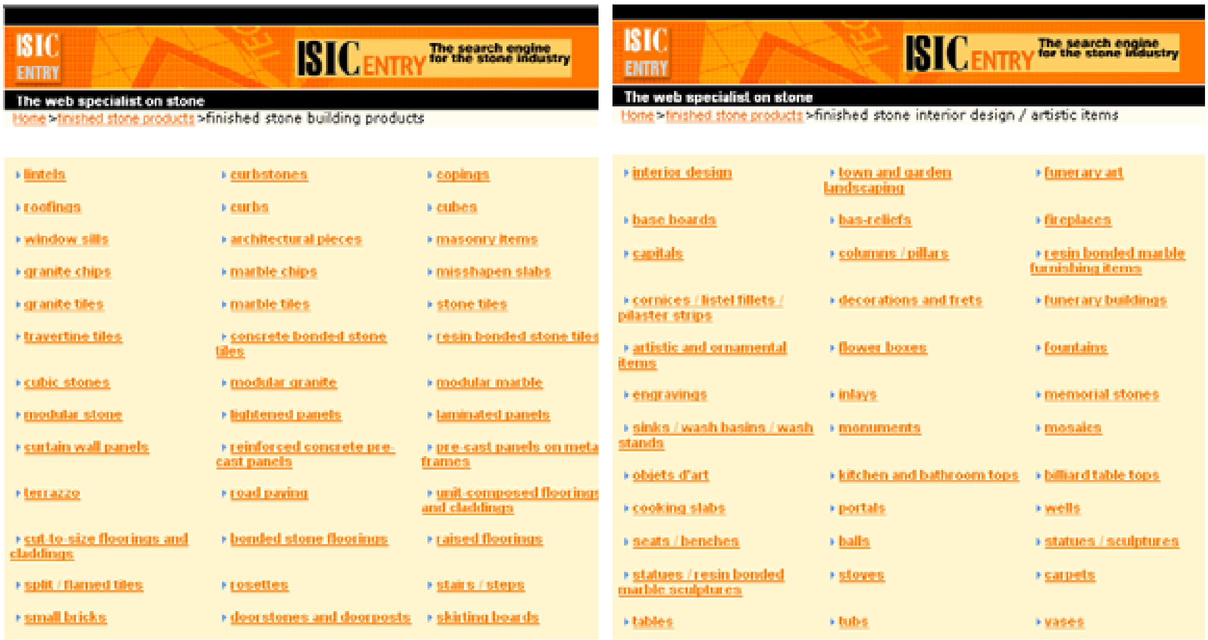


Figure 44. Uses of finished products (source “Stone 2000”).

Take note that no information is given about physical-mechanical-durability properties. Concerning the product type, classification is not as simple as it looks at first glance. The broad categories of the statistical reports do apply: slabs, tiles, slates, etc. This is because these product categories represent the more consistent part of the stone market; but there are a lot of stone finished product types, so that the statistical reports have to consider just a couple of summarising categories as are the “Simple” and “Special” finished products.

A few web sites attempt a more complete organisation of finished products. For example this is the case of ISIC where the finished products are presented in two different tables, according to two macro-sectors destination, the building sector and the interior design/artistic items (Figure 45).



Home >finished stone products >finished stone building products

lintels	curbstones	copings
roofings	curbs	cubes
window sills	architectural pieces	masonry items
granite chips	marble chips	misshapen slabs
granite tiles	marble tiles	stone tiles
travertine tiles	concrete bonded stone tiles	resin bonded stone tiles
cubic stones	modular granite	modular marble
modular stone	lightened panels	laminated panels
curtain wall panels	reinforced concrete pre-cast panels	pre-cast panels on meta frames
terrazzo	road paving	unit-composed floorings and claddings
cut-to-size floorings and claddings	bonded stone floorings	raised floorings
split / flamed tiles	rosettes	stairs / steps
small bricks	doorstones and doorposts	skirting boards

Home >finished stone products >finished stone interior design / artistic items

interior design	town and garden landscaping	funerary art
base boards	bas-reliefs	fireplaces
capitals	columns / pillars	resin bonded marble furnishing items
cornices / listel fillets / pilaster strips	decorations and frets	funerary buildings
artistic and ornamental items	flower boxes	fountains
engravings	inlays	memorial stones
sinks / wash basins / wash stands	monuments	mosaics
objets d'art	kitchen and bathroom tops	billiard table tops
cooking slabs	portals	wells
seats / benches	balls	statues / sculptures
statues / resin bonded marble sculptures	stoves	carpets
tables	tubs	vases

Figure 45. Stone finished products classification by ISIC Entry, with reference to the building sector and interior design/artistic items.

In the case of finished products for the building sector, the driving distinguishing element in general is the shape (tile, cubic stone, panels, bricks) but most of the times it coincides with the use (roofing’s slate, stairs/steps, curbs). For the characterisation of these finished products, and namely for finished products in great use, it is useful to resort to the material type (travertine/ marble /granite tiles) and the dimensions.

In the case of interior design / artistic items it is the final use which makes the difference among finished products (wells, mosaics, flower boxes, etc.). The variety of uses makes impossible to define any specific characterisation modality.

Concerning the denomination, the problem of an objective identification is going to be solved, thanks to standardisation bodies and technology. In fact commercial material denominations are well known and fixed. Nevertheless, in recent years at least two situations affecting the uniqueness of denomination have emerged, namely the possibility of using an existing name from a classical product by a new one, even though it is produced in a different area or country; and the possibility of using the name of the stone original material by a ceramic imitation. The TC246 intervention, with the EN 12440 standard contributed to the solution of the first problem; a future product quality classification, able to certify the finished product nature and origin, coupled with some advertising and marketing new rules will solve the second one.

Concerning the colour, the characterisation of this property seems again very simple and intuitive at first glance. The colour is a preliminary choice parameter, depending essentially on the project and on taste. But finally it is an element, even if not always present, for finished product valorisation, which defines, directly or indirectly, the commercial quality class of finished products. Some finished products are not linked mainly to colour, but to texture characteristics, defect existence (spots, etc.) or other aesthetical properties. The weak point of this "visual" characterisation was that, until now, it was a subjective evaluation, therefore causing many marketing conflicts, solved only by the intervention of an expert. Today, image analysis allows an objective definition not only of the colour property, but also in general of the commercial quality class.

Concerning the specific dimensions, this is an intuitive characteristic of finished products. For products of an equal thickness, it is just a project specification, which generally does not affect the price, given as €/sq.m. There is, anyway, a quality control linked to the dimensions, or, better to geometric characteristics (squaring, thickness, length and width, tolerances, etc.).

Regarding surface finishing, market accepts many finishing types namely polishing, hammering and flaming, rough-medium-fine grounding, and finishing, sandblasting and water-jet streaming. Just sawn and semi-polished surfaces can be referred to both, finished and semi-finished products. The characterisation of surface finishing is well stated and can be measured and controlled objectively, even if it happens quite rarely. Again this point will be discussed in the next paragraph, with surface finishing being an element of product quality characterisation.

In short, it can be concluded that the market makes reference to intuitive properties that, in case of large-use finished products, seems to be almost reasonable. Given the culture level behind the stone industry and market, the system was until now justifiable and operational. Nevertheless, times are changing and such practice has to be seriously criticised for many reasons, mainly linked to the fact that stone is a natural product, with many varying properties: no two finished product elements can be considered exactly the same. The culture of product qualification was missing until now. It is well accepted that visual properties, aesthetical and geometrical, were and still are forming the prices. Aesthetical properties naturally vary, depending also on processing of finished products. Therefore, no objective evaluation could be considered until now, when the image analysis made objective evaluation fully available. The point that just a few laboratories can correctly characterise physical-mechanical properties can be accepted. The fact that characterisation of a selling lot is not immediately linked to a standard sample, which has different properties of shape and size from those on sale and that will be often destroyed, can also be understood. In fact, a comparative evaluation of finished product quality, based on already standardised physical-mechanical properties, was subjected to a narrow circle of experts. Even in the case of perfectly measurable and standardised properties, as for example finished product geometry or surface finishing, the knowledge of property control was rarely able to spread. It is time that the valorisation of the finished product would be based on product qualification, both because of market competition and because of new EN standards ruling the EC marking.

1.4.2. Stone product characterisation depending on product use

The characterisation of a stone finished product may concern: geometric characteristics, visual appearance, and technical properties.

The geometric characteristics normally determined are:

- Dimensions, that is the length *l*, the width *b* and the thickness *d* (or height *h* for cubic work), given in the stated sequence, preferably in millimetres
- Flatness
- Squareness.

The tolerances for dimensions, flatness and squareness are a function of the type of processing and are normally stated by the manufacturer. Other things being equal, a finished product with stricter tolerances is more expensive than another with larger tolerances. For instance modular tiles are normally divided into two classes (Table 20): not calibrated tiles and calibrated tiles, the latter having been submitted to specific mechanical finishes for obtaining more precise dimensions (and being therefore more expensive).

Table 20. Tolerances for dimensions and shape of modular tiles.

PROPERTY	**TOLERANCES**	
	Not calibrated tiles	Calibrated tiles
Dimensions (mm): *l*, b	± 1	± 0,5
d	±1,5	± 0,5
Flatness (%)	0,15	0,10
Squareness (%)	0,15	0,10

As the required tolerances may vary according to the type of application, it is considered good practice that the client specifies tolerances. The surface finish of all exposed faces is another important characteristic of stone finished products. Surface finishes are classified according to the finishing processes into:

- finish obtained by grinding (e.g. rough ground, fine ground, honed, matt finished, polished surfaces);
- finish obtained by means of hammer type tools (e.g. bush hammered, trimmed, striated surfaces);
- rive cut finish, obtained by splitting the stone along anisotropy planes;
- flamed finish, obtained by thermal treatment of the surface ,using a high temperature flame;
- sand blasted finish, resulting from the impact of sand expelled by a sand jet;
- water-jet streamed finish, obtained by exposing the surface to a steady jet of water under pressure.

Examples of the different surface finishes are given in Figure 46. The surface finish is usually specified by means of the same reference sample used to identify the visual appearance. Taking into account the fact that ornamental stones are used because of their aesthetical qualities, it is clear that the visual appearance of a stone product must be characterised for every end-use. It is, therefore, customary to identify visually the colouring, the vein pattern, the texture, the specific characteristics of the stone and the surface finish of all exposed faces by means of a reference sample.

Figure 46. Examples of surface finishes.

The sample shall be an adequate number of pieces of sufficient size (as a rule between 0.01 and 0.25 square metres in face area) to indicate the range of appearance of the finished work. Particularly the reference sample shall show the specific characteristic of the stone such as holes for travertine, wormholes for marble, crystalline veins.

As far as the petrographic, physical and mechanical characterisation is concerned, the different properties usually determined on ornamental stones can be classified into two main categories:

- identification data
- properties qualifying the stone as suitable for the different end uses.

The identification data (petrographic name, apparent density and open porosity) are generally determined whatever the end-use is. In the following paragraphs are examined the main end-uses of Natural Stones and the related qualifying characteristics.

External paving

The Natural Stone finished products for external paving can be classified into:

- slabs (flat units having a minimum thickness of 30 mm and a width exceeding 150 mm)
- sets (small paving blocks with minimum thickness of 50 mm and no plan dimension exceeding twice the thickness)
- kerbs (units greater than 300 mm in length, used as edging to a road or a footpath).

The characterisation of these products requires the determination of the following properties:

- water absorption at atmospheric pressure
- water absorption by capillarity
- flexural strength (for slabs and kerbs) or compression strength (for sets)
- slip/skid resistance in wet conditions (excepting kerbs)
- abrasion resistance (excepting kerbs)
- durability against freeze-thaw cycles, thermal cycles, aggressive atmospheric pollution, and salt sprayed marine atmosphere, as relevant.

An external paving made of sets of white granite is shown in Figure 47.

Floors and stairs

The finished products for floors and stairs can be either slabs (with thickness exceeding 12 mm) or modular tiles (with thickness not exceeding 12 mm). They are laid onto a structure by means of mortar or adhesives. A slab for stairs can form either the horizontal part of a stair step (tread) or the vertical part (riser). These products are normally intended for internal use and are characterised by determination of the following properties:

- water absorption at atmospheric pressure
- water absorption by capillarity (only when the pieces will be in contact during use with a horizontal surface where water may be present)
- flexural strength
- slip resistance in dry condition (excepting risers)
- abrasion resistance (excepting risers).

An example of the use of sandstone slabs (Pietra Serena) for internal paving is given in Figure 48.

Figure 47. Example of granite sets use for external paving.

Figure 48. Internal paving of a show room made of slabs of Pietra Serena sandstone.

Wall coverings and ceiling finishes (external and internal)

These products can be either slabs (with a thickness exceeding 12 mm) or modular tiles (with a thickness not exceeding 12 mm).They are intended for both external and internal use and are placed onto a structure either mechanically or by means of mortar or adhesives. Their characterisation requires the determination of the following properties:

- water absorption at atmospheric pressure (only for external use);

- water absorption by capillarity (only when the pieces will be in contact during use with a horizontal surface where water may be present);
- thermal linear expansion coefficient (only for external cladding installed in zones with high temperature ranges);
- flexural strength (for external use and for internal ceiling finishes);
- resistance to fixing (only for slabs to be mechanically fixed);
- durability against freeze-thaw cycles, thermal cycles, aggressive atmospheric pollution and salt sprayed marine atmosphere (for external use only).

An example of external cladding is shown in Figure 49.

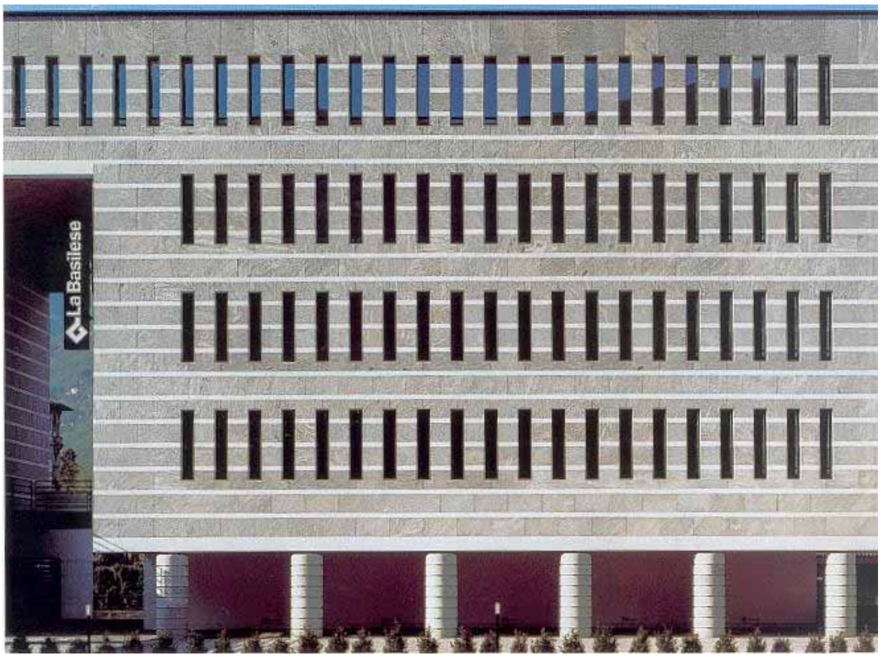


Figure 49. External cladding made of rows of slabs of Indian granite divided by strips of white Carrara marble.

Roofing

Natural Stones that are easily split into thin sheets along a plane of cleavage can be used for roofing. The most important category of stone products for roofing is represented by the slates (low grade metamorphic rocks in which the cleavage planes result from a schistosity flux), but also other metamorphic rocks like the gneisses and some types of sedimentary rocks are used. The characterisation of these products is based on the determination of the following properties:

- water absorption at atmospheric pressure
- flexural strength
- carbonate content (only for slates)
- durability against freeze-thaw cycles, thermal cycles, aggressive atmospheric pollution and salt sprayed marine atmosphere.

Masonry

Masonry units manufactured by natural stones are classified into the following categories:

- rubble stones (units of any shape with variable dimensions)
- regular shaped masonry units (units having an overall rectangular parallelepiped shape)
- dimensional stones (unit worked on all faces to declared dimensions).

The following characteristics must be determined for stone masonry units:

- total porosity
- water absorption by capillarity
- compression strength
- flexural strength (only for units that could be subjected to flexural stress during use)
- durability against freeze-thaw cycles, thermal cycles, aggressive atmospheric pollution and salt sprayed marine atmosphere.

Dimensional Stone work

Dimensional stone works are stone elements worked to any specific dimension for external and internal use. They include:

- flat elements having ≥80 mm thickness;
- curved stones or three-dimensional shaped elements.

Figures 50 and 51 show some examples.

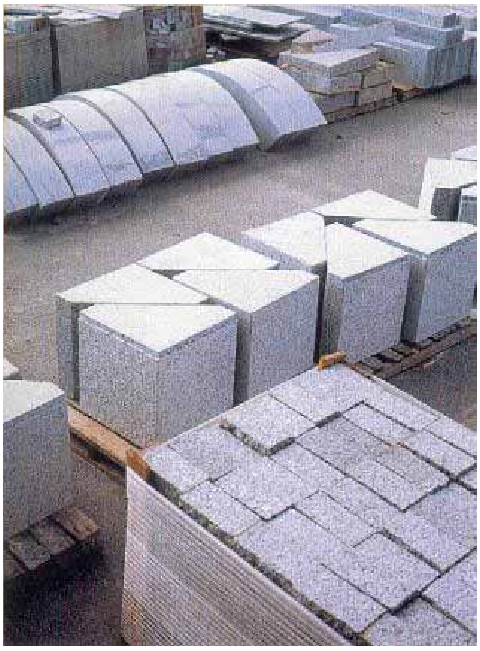


Figure 50. Transport-ready pieces of dimensional stones.

Figure 51. Pillar in Bianco Montorfano granite

The characterisation of these products is based on the determination of the following properties:

- total porosity (only for load-bearing elements)
- water absorption at atmospheric pressure (only for external uses and fountains)
- water absorption by capillarity (only when the elements will be in contact during use with a horizontal surface where water may be present)

- thermal linear expansion coefficient (only for fireplace elements)
- flexural strength (only for elements that will be subjected to flexural stress during use, e.g. lintels, block stairs, balustrades)
- compression strength (only for load-bearing elements)
- durability against freeze-thaw cycles, thermal cycles, aggressive atmospheric pollution, and salt sprayed marine atmosphere, as relevant (only for external uses).

Funerary art

It comprises a great variety of elements, all of them being generally subjected to severe exposure conditions: both external use and contact with the ground. These products are characterised by determining the following data:

- water absorption at atmospheric pressure
- water absorption by capillarity
- flexural strength
- compression strength (only for load-bearing elements)
- durability against freeze-thaw cycles, thermal cycles, aggressive atmospheric pollution and salt sprayed marine atmosphere.

2

Stone characterisation and methodologies

ANTONIO CASAL MOURA, MODESTO MONTOTO AND ANGELICA FRISA MORANDINI

2.1. Technical characterisation

The technical characterisation of ornamental stones can be performed either in laboratory or *in situ*. Laboratory characterisation is based on tests (both destructive and non destructive) performed on samples taken for this purpose either in the quarry or from semi-finished or finished products. The i*n situ* characterisation (in the quarry, processing plant or building) is based on non destructive tests that are performed directly on stone elements. The latter can be semi-finished products (e.g. blocks, raw slabs), finished products (e.g. slabs, tiles, sets) or even finished products after they are installed in structures. The advantage of the *in situ* testing is that no specimen preparation is needed and the element after testing is still apt for the intended use.

On the other hand the results of non destructive testing are indirect measurements (e.g. fundamental resonance frequency, sound speed propagation, rebound hardness) whose relationship with the actual mechanical behavior of the stone is in some extent uncertain.

2.1.1. Laboratory characterisation

The laboratory characterisation of ornamental stones is based on the use of a wide range of tests. These tests are divided into four categories namely petrographic, chemical, physical and mechanical characterisation. As a general rule, petrographic characterisation is needed to assign a correct petrographic name to the stone, while chemical characterisation is needed in some cases (e.g. when it is not possible to assign a petrographic name on the basis of petrographic analysis as in the case of studying the decay and conservation of stone elements in monuments). Physical and mechanical characterisation focuses on the proper evaluation of a stone for the various end-uses.

Petrographic characterisation

Petrographic characterisation means assigning a petrographic definition to a rock. But in the case of stone this is not enough: the main target of petrographic characterisation is to highlight all the features which influence the durability and the mechanical behavior of a stone. According to EN 12407, the petrographic description is based on both macroscopic and microscopic examination. Figures 52-56 compare the macroscopic and microscopic images of different stones.

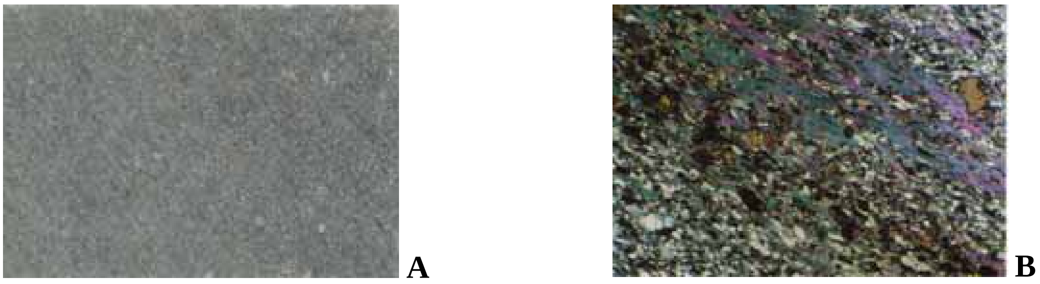


Figure 52. Quartzite (Portugal). A: macroscopic image of the hand specimen, B: microscopic image of a thin section in crossed polarised light

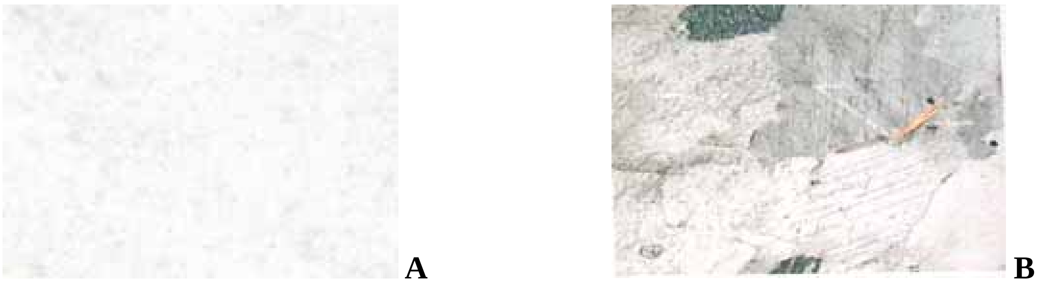


Figure 53. Calcite marble (Greek). A: macroscopic image of the hand specimen, B: microscopic image of a thin section in crossed polarised light

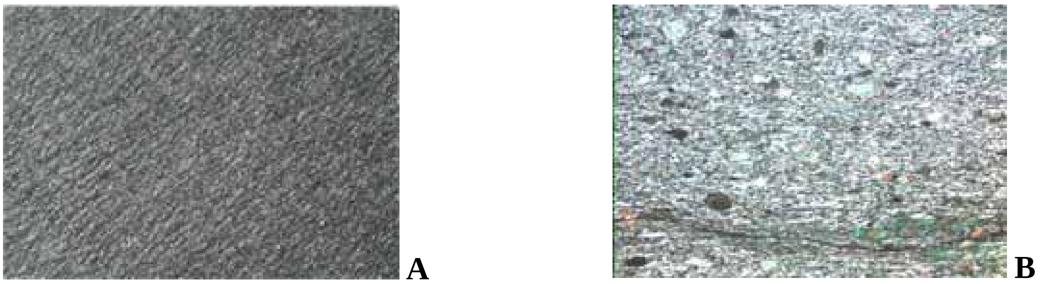


Figure 54. Schist (Sweden). A: macroscopic image of the hand specimen, B: microscopic image of a thin section in crossed polarised light

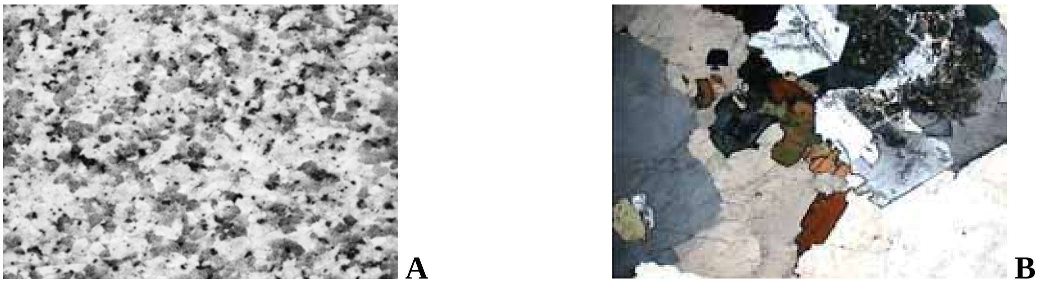


Figure 55. Granite (Italy). A. macroscopic image of the hand specimen, B: microscopic image of a thin section in crossed polarised light.

Figure 56. Sandstone (Italy). A. macroscopic image of sandstone affected by decay phenomena, B: microscopic image of a thin section in crossed polarised light.

The macroscopic examination is carried out by visual inspection of a stone specimen giving a description of the following characteristics: general colour or range of colours, fabric, grain size, presence of discontinuities (open and filled cracks, pores and cavities), presence of macrofossils, evidence of weathering and alteration (e.g. staining by sulphide alteration, diffusion of iron hydroxides, alteration of feldspars). If necessary the visual inspection may be aided by a hand lens.

The microscopic examination requires the preparation of one or more thin sections. A thin section is a portion of material mechanically reduced to a thin sheet measuring about 30 μm in thickness, mounted on a slide (normally protected by a slide cover).

The section normally measures about 33 mm x 20 mm, but in the case of larger grain size stone, larger dimensions may be used (e.g. 75 mm x 50 mm) or several sections of normal dimensions can be prepared. If the rock is anisotropic it is necessary to prepare at least two sections with different orientation with respect to the anisotropy (e.g. parallel and perpendicular to bedding planes, cleavage planes). The thin sections are examined under the petrographic microscope in order to obtain a microscopic description. After the identification of the mineral components, the following data are specified for each mineral (if relevant): percentage by volume; range of dimensions, habit, shape, type of boundaries (e.g. straight, lobate); distribution (e.g. homogeneous, in layers, in patches); orientation.

If there is any evidence of weathering and alteration (e.g. staining by sulphide alteration, chloritisation of biotite, sericitisation of feldspars, radioactive decay of zircon, diffusion of iron hydroxides) it has to be mentioned. If other components are present (e.g. groundmass, organogenic remains) they are as well described. Particular attention has to be given to the description for all kinds of discontinuities:

- pores (size and shape),
- cracks and open fractures (the range of widths and lengths, the orientation and the distribution),
- filled fractures and veins (the same data given as in the open fractures and also the nature and structure of the filling).

On the basis of the data generated from the macroscopic and microscopic examination relating to grain size, fabric and mineralogical composition, a petrographic definition shall be assigned to the stone. If the petrographic description provides insufficient data to assign a petrographic definition, further testing may be necessary. That investigation may include chemical or X-ray diffraction determinations.

Chemical characterisation

Geologists, and in particular petrologists, study rocks in order to discover their origin, find relationships between them, date their geological formations, etc. In the field application usually, specific analysis is performed in order to quantify a particular element and decide the best stone application or the best treatment suitable for stone protection. Analyses are also performed aiming to characterise of a particular product, or to distinguish very similar rocks. The different methods used for chemical characterisation are briefly described.

Extensive chemical analysis of rocks has been carried out since 1850. R.W.E von Bunsen was one of the pioneers who applied chemical techniques to analyse rocks. The analytical procedure used by him became popular among scientists under the name “wet chemical analysis” and it has been used for more than one century. The method consists of a classic gravimetric and volumetric analysis and the results are given as weight percent (%) of oxides because oxides of single elements are obtained from these procedures.

After the improvement of technologies, since mid 1900s several electronic devices have been created to perform chemical analysis after examining the behavior of chemical elements either to different kinds of stimulation or from emission or absorption of electromagnetic energies. The energy intensity is directly proportional to the quantity of element present in the rock and the results are expressed as p.p.m. (parts per million) of elements.

In the latter years, rock chemical analysis is usually performed by automated instruments, but for historical reasons reports from the chemical analysis of a rock are expressed as oxides for major (> 1%) and minor (0.1 ÷ 1 %) elements and as single element (< 0.1 % or < 1000 p.p.m.) for those called “trace elements”. In addition, the list of oxides is traditionally sequenced as follows: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, H_2O^+, H_2O^- and CO_2. H_2O^+ and H_2O^- refer to “structural water” and “adsorbed water or natural humidity”, respectively. The term “structural water” means water or hydroxyl ions bonded to a framework of hydrous minerals. This kind of water can be removed in a furnace at a temperature range between 110 – 1000°C. H_2O^- is water weakly bonded on the surface of minerals or inside the channels in some of them and can be easily driven off after heating up to 110°C. Table 21 presents the chemical composition of some ornamental stones. Some elements are present with different isotopes and their ratio or a ratio towards others isotope is reported in the analytical list (i.e. $^{87}Sr/^{86}Sr$; $^{232}Th/^{204}Pb$; etc.).

Table 21. Chemical composition of some Ornamental Stones.

Petrological family	Chemical analysis (% mass)						
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O
Marble	0,1	0,2	0,1	20,0	34,0	<0,1	<0,1
Marble	<0,1	<0,1	0,1	0,4	55,0	-	-
Limestone	0,1	0,7	0,1	0,5	54,8	0,1	<0,1
Ophicalcite	24,0	0,6	5,6	22,6	23,5	<0,1	<0,1
Granite	70,3	14,5	1,9	0,5	0,8	3,9	5,9
Granite	71,4	13,8	3,4	1,5	0,4	3,7	4,7

Main chemical analysis

The methods to determine the chemical composition of rocks are many and they vary from traditional to more modern and sophisticated techniques. The analytical range of each element is related to the technique type and a total rock analysis may need the application of two or more techniques.

Wet Chemical Analysis (WCA)

The sample is completely decomposed in acid ambient and the obtained solution is examined with gravimetric, volumetric, colorimetric and titration methods in order to quantitatively determine its composition. This was the only technique applied before the second part of 20th century and the procedure was very slow and tedious and in order to perform a good analysis it was as much of an art as of a technology.

Atomic Absorption Spectrophotometry (AAS)

The sample must be completely decomposed and the solution passes through a flame, which is perpendicularly crossed by a beam of monochromatic light. The monochromatic light with a particular wavelength (each for every single element analysed) is absorbed if the element is present in the solution. The absorbance is directly proportional to the element quantity. Atomic absorption spectrophotometry is particularly useful for low concentration elements.

X-ray fluorescence spectroscopy (XRF)

There are many methods to prepare the sample but they generally fall into two main types: powdering or fusing. Initially, X-rays emitted from a tube hit the sample and produce secondary X-rays from every element present in the rock. These secondary X-rays are diffracted according to Bragg's law. They are isolated by analyzing crystals and counted by different kinds of detectors.

Inductively Coupled Plasma – Atomic emission spectrometry (ICP)

The sample needs to be completely dissolved and the solution is mixed with argon gas and inserted into a radio frequency generator where inductively coupled plasma at very high temperature is produced. Inside this plasma, atoms are in a stimulated state and their emissions are detected by a photomultiplier tube. This has recently evolved into the most popular analytical technique because simultaneous determinations of many elements with good accuracy and precision are achieved.

Instrumental Neutron Activation Analysis (INAA)

This technique has not been widely used because the sample needs to be activated by a nuclear reactor or by a synchrotron. Rock powders are bombarded with neutrons and short-life radioisotopes are artificially generated. Their number is measured by a proper detector and the intensities to be reported for each element are recorded. The results are proportional to the different elements concentrations in the rock. The method is particularly suitable for trace elements and more specifically for rare earth elements (REE).

Mass spectroscopy (MS)

The method analyses stable isotopes, as long as the sample is reduced in liquid or gas form. The procedure requires that the heavier isotopes (larger mass number) are isolated from the others by a large magnet and are detected and counted by a sort of “Faraday cup”. This is a very expensive technique but it is the unique way to analyse stable isotopes. ICP-MS analysis means that the sample has been prepared as for “inductively coupled plasma” analysis and has been measured by a mass spectroscopy system. Table 22 summarises the fields of application for the different chemical analysis methods.

All the analytical procedures mentioned are “destructive methods” because the sample must be destroyed. This aspect may not be very important for geological samples but it can be a limit in performing chemical analyses in cultural heritages. Recently a portable XRF has been created and by this device it is possible to analyse alloys, paints and some stone elements *in situ* without any damages on the monument.

Table 22. Fields of application of the different analytical methods.

Analytical Method	Major elements	Minor elements	Trace elements	Isotopes
WCA	X	X		
AAS	X	X	X	
XRF	X	X	X	
ICP	X	X	X	
INAA			X	
MS				X

Physical characterisation

The physical characteristics usually determined for ornamental stones are the following:

- apparent density and open porosity (identification data);
- real density and total porosity (only for porous stones);
- behavior in the presence of water, i.e. water absorption at atmospheric pressure and water absorption by capillarity (the latter only for stones having an open porosity exceeding 1-2%);
- thermal linear expansion coefficient (needed to determine the width of the expansion joints for end uses in which wide temperature ranges are expected, e.g. slabs for external paving and cladding, elements for fireplaces).

The test procedures for the determination of these characteristics are briefly described in the following paragraphs.

Apparent density and open porosity

Apparent density is defined as the ratio between the mass of a dry specimen and its apparent volume (i.e. the volume limited by the external surface of the specimen including any voids). It is, therefore, measured in kilograms per cubic metre. The open porosity is the ratio (expressed as a percentage) of the open pores volume to the apparent volume of the specimen.

Both data are obtained from the same test (described in EN 1936). Six cubic or cylindrical specimens are dried, then weighed (m_d), put into an evacuation vessel and exposed to a vacuum of about 2 kPa. After 24 hours water is poured into the vessel until the specimens are completely immersed. The vacuum is maintained for another 24 hours. After this time has elapsed the vessel is returned to atmospheric pressure and the specimens are left under water for another 24 hours in atmospheric pressure. Then each specimen is weighed under water (m_h), then quickly wiped and weighed in air (m_s, mass of the saturated specimen). The apparent density (ρ_b) and the open porosity (p_0) are expressed by the following equations 12, 13:

$$\rho_b = \frac{m_d}{m_s - m_h} \cdot \rho_w \ \ (kg/m^3) \qquad \text{(eq.12)}$$

$$\rho_0 = \frac{m_s - m_d}{m_s - m_h} \cdot 100 \ \ (\%) \qquad \text{(eq.13)}$$

where: m_d is the mass of the dry specimen (g);
m_s is the mass of the saturated specimen in air (g);
m_h is the mass of the saturated specimen in water (g);
ρ_w is the density of water (kg/m^3).

Table 23 presents the range for apparent density and open porosity for some common stones.

Table 23. Apparent density and open porosity for some common stones. (Winkler 1994)

Rock	Apparent Density (kg/m^3)	Open Porosity (%)
Granite	2600 – 2700	0,5 – 1,5
Gabbro	3000 – 3100	0,1 – 0,2
Rhyolite (felsite)	2400 – 2600	4.0 – 6.0
Andesite (felsite)	2200 – 2300	10.0 – 15.0
Basalt	2800 – 2900	0.1 – 1.0
Sandstone	2000 – 2600	5.0 – 25.0
Shale	2000 – 2400	10.0 – 30.0
Limestone	2200 – 2600	5.0 – 20.0
Dolomite	2500 – 2600	1.0 – 5.0
Gneiss	2900 – 3000	0.5 – 1.5
Marble	2600 – 2700	0.5 – 2.0
Quartzite	2650	0.1 – 0.5
Slate	2600 – 2700	0.1 – 0.5

Real density and total porosity

The real density is defined as the ratio of the dry specimen mass to the volume of its solid part. It is therefore measured in kilograms per cubic metre. The total porosity is the ratio (expressed as a percentage) of the open pores volume to the apparent volume of the specimen. For dense, low porosity stones the differences between real and apparent density, as well as between open and total porosity are very small. For these stones it is sufficient to determine the apparent density and open porosity. In other cases also the real density and the total porosity should be determined. Both data are obtained by the same test (described in EN 1936).

For this test, after the determination of apparent density and open porosity, each specimen is separately ground to powder size and dried. About 20 g of the powder are weighed (m_e) and introduced into a picnometer half full of water. Then the picnometer is filled with deionised water and weighed (m_1). Finally the picnometer is emptied and washed, filled with deionised water only and weighed (m_2). The real density (ρ_r) is expressed as the ratio of the mass of the ground dry specimen m_e to the volume of liquid displaced by this mass, by the following equation (eq.14):

$$\rho_r = \frac{m_e}{m_2 + m_e - m_1} \cdot \rho_w \quad (kg/m^3) \qquad \text{(eq.14)}$$

where: m_e is the mass of the ground dry specimen (g);

m_1 is the mass of the picnometer containing the ground dry specimen and water (g);

m_2 is the mass of the picnometer full of water (g);

ρ_r is the density of water (kg/m^3)

The total porosity p is expressed as the ratio (as a percentage) of the volume of pores (open and closed) and the apparent volume of the specimen by the following equation (eq.15):

$$p = \frac{\frac{1}{\rho_b} - \frac{1}{\rho_r}}{\frac{1}{\rho_b}} = (1 - \frac{\rho_b}{\rho_r}) \cdot 100 \quad (\%) \qquad \text{(eq.15)}$$

where: ρ_b is the apparent density (kg/m^3) and ρ_r is the real density (kg/m^3).

Behavior in the presence of water

The behavior of a stone in the presence of water can be determined by two different test procedures: water absorption under atmospheric pressure and water absorption by capillarity. The test procedure for determining water absorption under atmospheric pressure is described in EN 13755. The specimens (having the form of a cylinder, cube or prism) are dried and weighed (m_d) and then gradually immersed in water under atmospheric pressure and left totally immersed for 48 hours. Then the specimens are taken out of the water, quickly wiped with a damp cloth and weighed. The test will continue by immersing the specimens again in water and taking them out and weighing every 24 hours up to constant mass. The result of the last weighing is the mass of the saturated specimen (m_s). The water absorption at atmospheric pressure A_b of each specimen is calculated by the following formula (eq.16):

$$A_b = \frac{m_s - m_d}{m_d} \cdot 100 \quad (\%) \qquad \text{(eq.16)}$$

The procedure for determining the water absorption coefficient by capillarity is given in EN 1925. Six specimens (having the form of a cube or a cylinder) are dried, weighed (m_d) and measured to calculate the area of their base (A). The base is then immersed in water to a depth of 3mm. At time intervals, initially very short then longer, each specimen is removed from the bath, weighed (m_i), after having wiped its immersed base with a damp cloth, and finally replaced in the container. A minimum of 7 measurements is necessary. For each weighing the following data should be recorded:

- Elapsed time since the start of the test;
- Mass of the absorbed water ($m_i - m_d$) divided by the area A of the immersed base.

The mass of water absorbed in grams divided by the area of the immersed base in square metres is shown in a graph as a function of the square root of time expressed in seconds (Figure 57). In general the obtained graphs can be approximated by two straight lines.

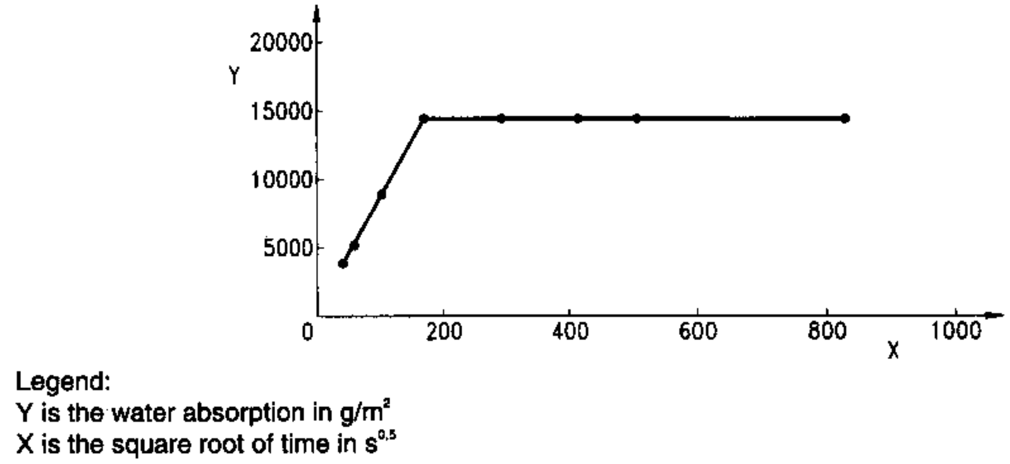


Figure 57. Water absorption by capillarity perpendicular to the planes of anisotropy as a function of the square root of time for a specimen with a low water absorption coefficient ($C1 = 86\ g/m^2\ s^{0,5}$).

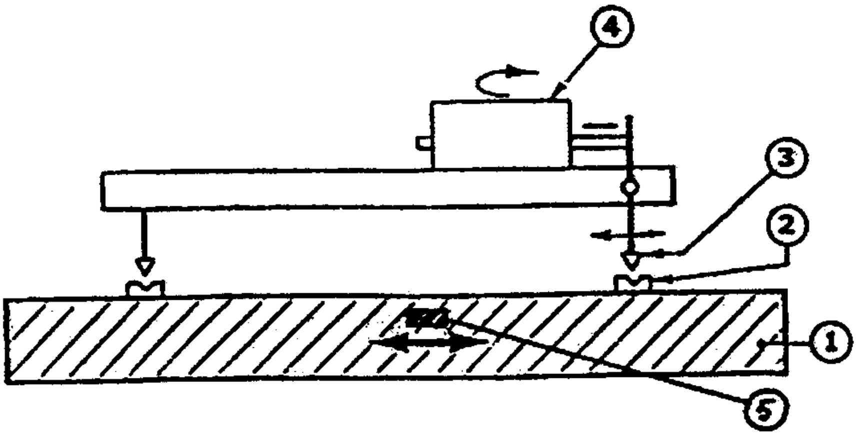
The coefficient of water absorption by capillarity C (in grams per square metre per square root of time in seconds) is represented by the slope of the regression line of the first part of the graph. It can be calculated as the ratio of the ordinate to the abscissa of any point of this line using the following formula (eq.17):

$$C = \frac{m_i - m_d}{A \cdot \sqrt{t_i}} \qquad \text{(eq.17)}$$

Thermal expansion coefficient

The principle of this test is to measure a prismatic small stone section, at least 250 mm long, at two different temperatures at least. If the stone is to be used in building, the appropriate temperatures to conduct the measurements are: room temperature and 80°C. Even if generally the relationship between thermal expansion coefficient and temperature is not linear, it can be supposed that it is linear in the 20 – 80 °C range. Intermediate measurements can be taken in order to verify this assumption. The thermal expansion coefficient of many stones is dependent on direction. Therefore, it should be measured in several directions preparing specimens with their long axis differently oriented with respect to the anisotropy planes.

A calibrated reference sample with a known thermal expansion coefficient in the test temperature range is also needed. Length measurements can be performed by means of a mechanical measuring device as shown in Figure 58 with an accuracy of at least 1/100000 of the measuring length. Each specimen and the reference sample should be equipped with a thermocouple and two bonded rivets at a minimum distance of 200 mm along the longitudinal axis. The samples are placed in a ventilated oven at the temperature of 20°C until their temperature is stabilised. Then they are extracted from the oven and their length is measured as quickly as possible (L_{20}).



Legend:

1. test specimen
2. rivets bonded on the specimen
3. measuring tips of the device, one is mobile
4. mechanical measuring device
5. temperature measuring device

Figure 58. Example of a mechanical measuring device for the determination of thermal expansion coefficient.

This procedure is repeated for the temperature of 80°C (L_{80}) and also for intermediate values of temperature if needed. The coefficient of thermal expansion α is calculated by the equation (eq.18). Table 24 presents data on thermal expansion coefficients for different rocks.

$$a = \frac{\varepsilon_s - \varepsilon_r}{\Delta t} + \alpha_r \qquad \text{(eq.18)}$$

where: $\varepsilon_s = \frac{L_{80} - L_{20}}{L_{20}}$ is the unitary expansion of the test specimen;

ε_r is the unitary expansion of the reference sample;

Δt is the change in temperature;

α_r is the coefficient of thermal expansion of the reference sample.

Table 24. Thermal expansion coefficients (α) (Winkler, 1994).

Rock	**α (10^{-6} °C^{-1})**
Granites	8
Basalts	5,4
Limestones	8
Sandstones	10
Quartzites	11
Marbles	7
Slates	9

Mechanical characterisation

The mechanical characterisation of ornamental stones is generally based on destructive testing. In some cases, however, non destructive tests are used: e.g. for monitoring the changes in mechanical properties during successive steps of accelerated ageing tests. (For non destructive testing see paragraph 2.1.2). The mechanical parameters most frequently determined are:

- compression strength (on masonry, sets and load-bearing elements)
- flexural strength (on modular tiles, slabs for paving, flooring and cladding, lintels, block stairs, balustrades). The test can be performed under either under concentrated load or constant moment.
- abrasion resistance (on elements for paving, flooring and stairs)
- impact resistance (on elements for paving, flooring and stairs)
- slip/skid resistance (on elements for paving, flooring and stairs)
- resistance to fixing (on slabs for cladding to be mechanically fixed).

In special cases other mechanical properties are determined (e.g. elastic modulus, microhardness distribution). The test procedures for the determination of these characteristics are described in the following paragraphs.

Uniaxial compressive strength

The uniaxial compressive strength is the load per unit area under which a block fails by shear strain. According to the test procedure described in EN 1926 six test specimens having the shape of a cube or a cylinder are prepared. The axis of each specimen shall be normal to the planes of anisotropy (e.g. bedding, foliation). If a test with the orientation of loading parallel to the planes of anisotropy is required, another set of specimens with different orientation of the axis shall be prepared (Figure 59).

The faces which the load is applied on must be flat. This can be obtained by processing the specimens with a surface grinder. After drying the specimens their cross sectional area (lateral dimension for cubes, diameter for cylinders) is measured by averaging two measures taken at right angles to each other at about the upper height and two at about the lower height of the specimen. From this data the cross sectional area of the specimen can be calculated.

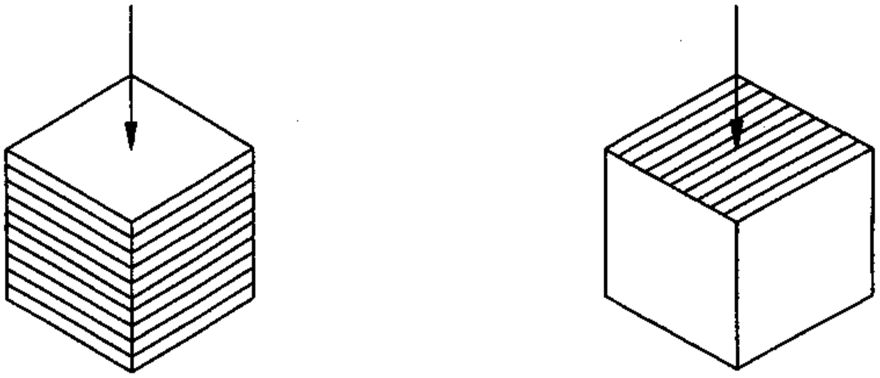
Each specimen is placed between the bearing surfaces of the testing machine and aligned carefully, using the centre of the ball-seated plate, to obtain a uniform seating. The specimen is then loaded continuously at a constant stress rate until failure. The failure load is recorded. The uniaxial compressive strength R of each specimen is expressed by the ratio of the failure load of the specimen to its cross sectional area before testing. The following equation is used (eq.19):

$$R = \frac{F}{A} \ (MPa) \qquad \text{(eq.19)}$$

where: F is the failure load expressed in Newton and A the cross sectional area in square millimetres.

The result of the test is given as the mean value of the individual uniaxial compression strength values. Values of compression strength for different types of stones are given in Table 25.

load normal to the planes of anisotropy load parallel to the planes of anisotropy



load normal to the planes of anisotropy load parallel to the planes of anisotropy

Figure 59. Orientation of loading with respect to the planes of anisotropy for the compression test.

Table 25. Values of uniaxial compression strength for different stones (direction of loading normal to the anisotropy planes).

Stone type	Compression strength (MPa)
soft limestones	20-30
conglomerates and breccias	20-40
travertines	50-70
polishable limestones	100-140
marbles	100-140
granites	140-160
gneisses	140-160

Flexural strength

The flexural strength is the resistance of a rock slab to bending. The test can be performed according to two different test procedures, namely, either under concentrated load (EN 12372) or under constant moment (EN 13161). For the flexural test under concentrated load (according to EN 12372) the test specimen is a prism with thickness h between 25 and 100 mm, width b=2h, length L=6h.

If the stone shows planes of anisotropy the test specimens should be prepared accordingly to at least one of the following arrangements: planes of anisotropy parallel to the major faces of the specimen, planes of anisotropy parallel to the minor faces of the specimen; planes of anisotropy parallel to the intermediate faces of the specimen. For each test arrangement 10 specimens are needed. The dried specimen is placed centrally on two supporting rollers set at a distance l equal to five times the thickness h of the specimen. A loading roller is then placed in the middle of the specimen (Figure 60).

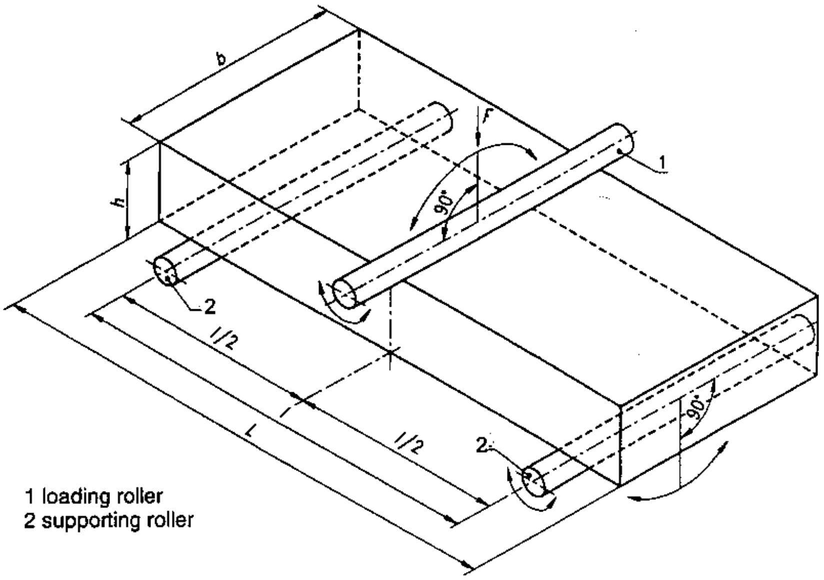


Figure 60. Loading arrangement for flexure strength test under concentrated load (centre – point loading).

The load is increased uniformly until the specimen breaks. The breaking load is recorded. The width and the thickness of the specimen are measured adjacent to the fracture plane. The flexural strength R_f under concentrated load of each specimen is calculated using the formula (eq.20):

$$R_f = \frac{3Fl}{2bh^2}\ (MPa) \qquad \text{(eq.20)}$$

where: F is the breaking load in Newton;
l is the distance between supporting rollers in millimetres;
b is the width of the specimen adjacent to the plane of fracture in millimetres;
h is the thickness of the specimen adjacent to the plane of fracture in millimetres.

The result of the test is given as the mean value of the individual values of flexural strength. Values of flexural strength under concentrated load for different types of stones are given in Table 26. For the flexural test under constant moment (according to EN 13161) the number and dimensions of test specimens and the arrangements of the specimens with respect to the anisotropy planes are the same as for the test under concentrated load. The only difference is in the arrangement of loading (two point load, Figure 61). The dried specimen is placed on two supporting rollers set at a distance of l = 5h. Two loading rollers are then placed at a distance of $l/3$ from each other and from the adjacent supporting roller.

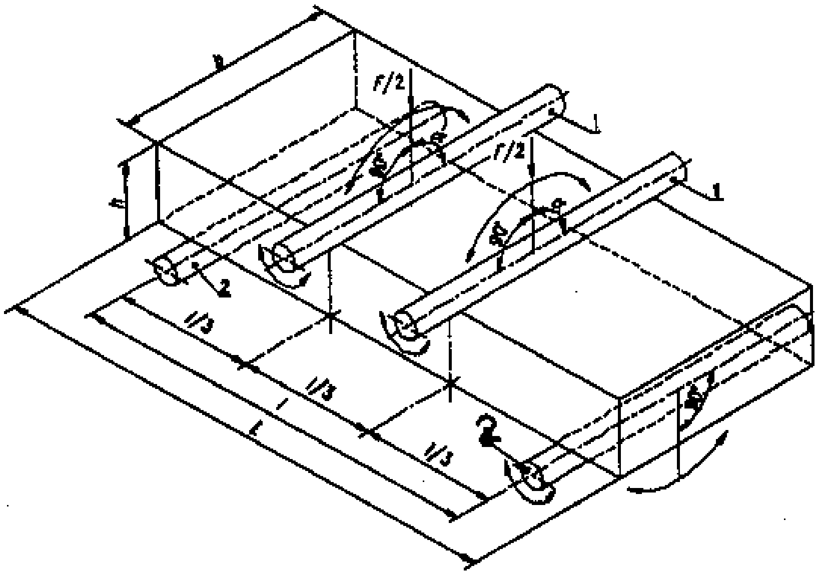
Table 26. Values of flexural strength under concentrated load for different stones (direction of loading normal to anisotropy planes).

Stone type	Flexural strength (MPa)
soft limestones	3-4
conglomerates and breccias	4-5
travertines	6-10
polishable limestones	10-14
marbles	12-20
granites	10-15
gneisses	15-25
slates	50-60

The load is uniformly increased until failure. The failure load is recorded and the width and thickness of the specimen are measured adjacent to the fracture plane. The flexural strength R_c at constant moment of each specimen is calculated using the formula (eq.21):

$$R_c = \frac{F \cdot l}{b \cdot h^2} \ (MPa) \qquad \text{(eq.21)}$$

where: F is the failure load in Newton;
l the distance between supporting rollers in millimetres;
b the width of the specimen adjacent to the plane of fracture in millimetres;
h the thickness of the specimen adjacent to the plane of fracture in millimetres.



Legend:
1. loading roller
2. supporting roller

Figure 61. Loading arrangement in flexure test under constant moment (two point load)

Abrasion resistance

This test aim is to evaluate the resistance of a stone surface to the wear caused by vehicular and pedestrian traffic. Many methods based on the use of different devices have been developed to determine this property. In the European Standardisation (EN 1341) the wide wheel abrasion test has been adopted.

According to this method, one of the major faces of a prismatic specimen is brought into contact with a wide rotating steel wheel, while a steady flow of abrasive (carborundum) is fed from a slot of a guidance hopper on the leading edge of the wheel. Contact between the specimen and the wheel is obtained with a mobile clamping trolley which is forced forward by a counterweight. The scheme of the wearing machine is given in Figure 62.

The test stops after 75 revolutions of the wheel. The specimen is then examined under a big magnifying glass and the width of the groove cut by the abrasion wheel is measured. This procedure is repeated on six specimens and the results of the test are given as the mean value of the groove width, in millimetres.

At specific intervals (after grinding 400 grooves or every two months) the device is calibrated against a reference sample of Boulonnaise Marble and the counterweight is adjusted so that after 75 revolutions of the wheel the length of groove produced is 20 mm.

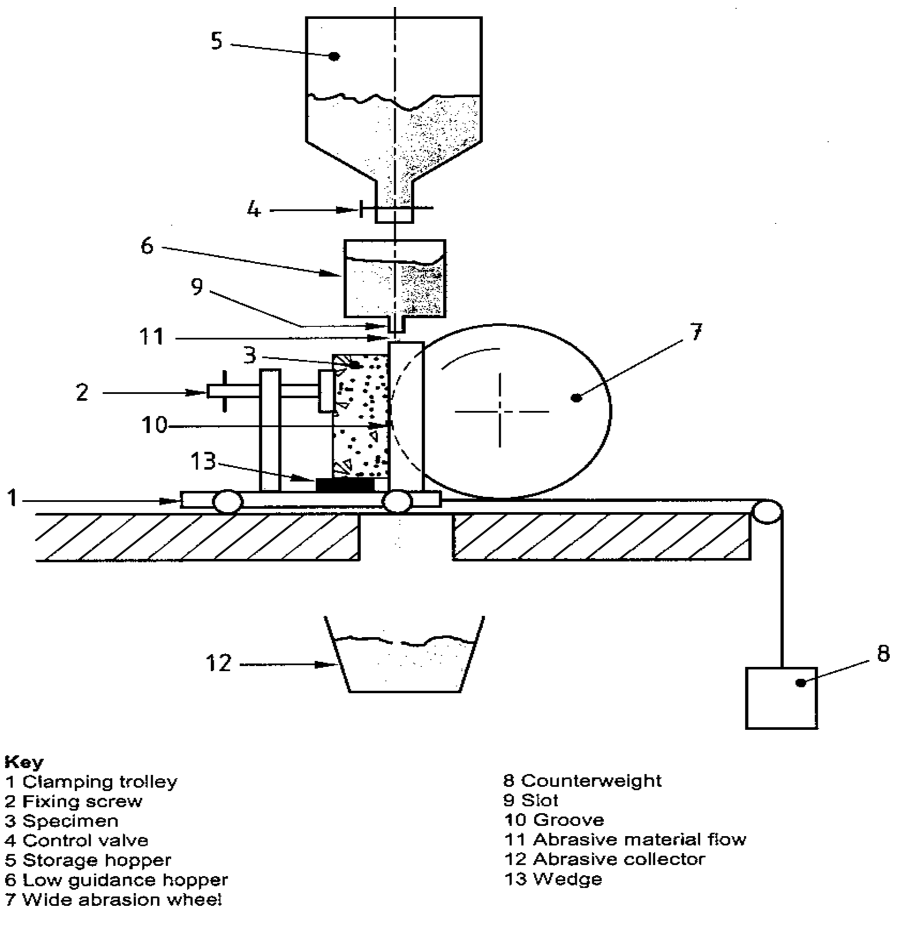
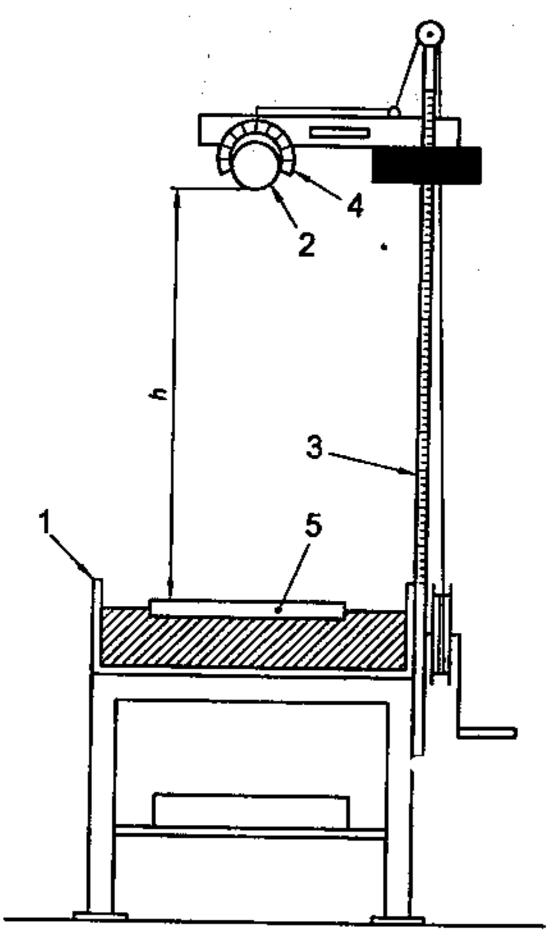


Figure 62. Scheme of the wide wheel abrasion machine.

Impact resistance

Various tests have been proposed and used for the evaluation of impact resistance, and all of them are based on the impact of a standard hard body on the specimen. According to the European standardization, the test which has been adopted is the method of the determination of rupture energy by impact, according to EN 14158. It is a fast, inexpensive test, which can be used also for factory production control.

A device like the one showed in Figure 63 is used: a steel ball having a mass of about one kilogram is dropped from increasing height on a test specimen put on a sand bed until the specimen breaks. The specimens are either 200 x 200 x 30 mm slabs or finished products (for factory production control). From the six specimens to be tested, one is selected as a control specimen and it is tested before the others. It is placed on the sand bed in such way that the centre of its major face is on the vertical line through the centre on the ball. The steel ball is dropped from an initial height of 100 mm. If the specimen does not break the height of fall is increased gradually with a 50 mm stepping until the specimen breaks.



Legend:
1. container with a bed of sand
2. steel ball
3. graduated metal column
4. electromagnet
5. test specimen
6. height of fall

Figure 63. Device for determining the energy of rupture by impact.

The height at which the control specimen breaks (h_t) is recorded. The test is repeated on the other five specimens beginning from an initial height of $h_i = (h_t - 150)$ mm and a minimum of 100 mm. The height of rupture for each specimen, h, is recorded. For each of the five specimens the energy of rupture by impact (W in Joules) is calculated by using the following equation (eq.22):

$$W= m \cdot g \cdot h \qquad \text{(eq.22)}$$

where: W is the energy of rupture, in Joules
m is the mass of the steel ball, in kilograms

g is the acceleration of gravity (9,806 m/s^2)
h is the height of rupture in metres.

The result of the test is given as the mean value of the individual values of energy of rupture. Values of energy of rupture for different types of stones are given in Table 27.

Table 27. Values of energy of rupture by impact for different stones.

Stone type	**Rupture energy (J)**
limestone and travertines	2 - 4
marbles (including green marbles)	4 - 5
granites, syenites, diorites	5 - 6
gneisses	8- 9
slates	9 - 10

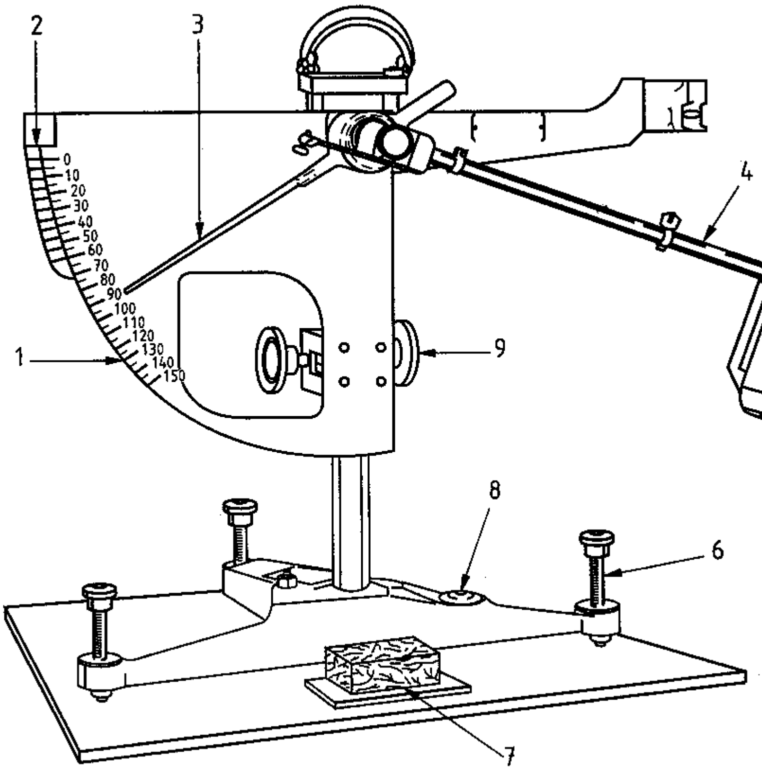
Slip resistance

The slip resistance is an important property of stone slabs aimed to be used to floors and stairs in order to guarantee the safety of people walking on them. It depends mainly on the surface finish of the stone elements, so it must be determined only on finished products or on parts of them and on the face that will be exposed during use. Many methods based on the use of different devices have been developed and used to determine this property. In European standardisation (EN 1341) the adopted test method is based on the use of the pendulum friction tester (Figure 64). In this device, a spring loaded slider made of rubber is attached to the end of a pendulum. The pendulum on its swing traverses the surface of the test specimen over a fixed length. The frictional force between slider and test surface is measured by the reduction in length of the swing. Five specimens are needed for the test.

In order to perform the measurements, the friction tester is placed on a flat surface and the leveling screws are adjusted, so that the pendulum support column is vertical. Then the suspension axis of the pendulum is raised so that the arm can swing freely and the friction in the pointer mechanism is adjusted so that when the pendulum arm and pointer are released from the right-hand horizontal position the pointer comes to rest at zero position on the test scale. The test specimen is steadily placed along its longer dimension and across the track of the pendulum. The height of the pendulum arm is adjusted so that when traversing the specimen, the rubber slider will be in contact with it over a specified swept length. The swept length is normally 126 mm and in this case a wide slider is used. The readings are taken on the C scale. For smaller specimens a reduced swept length of 76 mm may be used and in this case a narrow slider is used, while the readings are taken on the F scale. When adjustments are over, the pendulum and pointer are released from the horizontal position, the pendulum arm is caught on its return swing and the position of the pointer on the scale is recorded. This operation is performed five times and the mean of the last three readings is recorded. The whole procedure is repeated after rotating the specimen by 180°.

The test is performed both in dry and wet conditions and the two results are given separately. For testing in wet conditions the surfaces of the specimen and of the rubber slider are wetted immediately before the test with a copious supply of water.

The calculating procedure for the slip resistance (pendulum value) differs for measurements made with the wide or the narrow slider. If a wide slider was used over a swept length of 126 mm the pendulum value of each specimen is the mean of the two recorded mean values measured in opposite directions on the C scale. The result is given as the pendulum mean value obtained from testing all five specimens, both in dry and wet conditions. When the narrow slider is used, the pendulum value of each specimen is calculated as the mean of the two recorded mean values measured in opposite directions on the F scale multiplied by 100. The result is given as the pendulum mean value obtained from all five specimens multiplied by 1,2 (correction factor for the effect of the different swept length), both in dry and wet conditions. If a stone slab is to be used for exterior floorings the results obtained in wet conditions are considered, while for interior floorings the results obtained in dry conditions are considered.



Key
1 C scale (126 mm sliding length)
2 F scale (76 mm sliding scale)
3 Pointer
4 Pendulum
5 Rubber slider
6 Levelling screw
7 Test specimen holder
8 Spirit level
9 Vertical adjustment screw

Figure 64. Pendulum friction test equipment.

Breaking load at a dowel hole

This test has the purpose of evaluating the resistance of slabs which are going to be mechanically fixed on their edges.

It consists of a force application in a direction perpendicular to the face of the specimen through a dowel, previously placed in a hole drilled in one of its sides and the measurement of the breaking load of the specimen. The specimens are square slabs of 200 x 200 mm faces and with a thickness of 30 mm. Before the test, a hole is drilled in the middle of each side of the specimen and a dowel is placed in each hole and fixed with mortar. The number of specimens depends on the presence of planes of anisotropy. If the stone does not show any planes of anisotropy three specimens are prepared for performing 10 tests (Figure 65). If the stone shows planes of anisotropy:

- three specimens with the major faces parallel to the planes of anisotropy are prepared for performing ten tests with the load perpendicular to these planes (Figure 66)
- five specimens with the major faces perpendicular to the planes of anisotropy are prepared. Ten tests are then performed with the load applied parallel to the planes of anisotropy and another ten tests are performed with the load applied parallel to the edges of the planes of anisotropy (Figure 67).

For each test the specimen is clamped in a clamping device consisting of two metal plates of not more than 60% of the specimen length. A uniformly increasing load is applied in a direction perpendicular to the axis of the dowel, at a maximum distance of 2 mm from the edge of the specimen, until the specimen breaks. The breaking load (F, in Newton) is recorded. After the specimen fails the following measurements are taken (Figure 68):

- the distance from the hole to the face in the direction of the force (d_l , in millimetres);
- the maximum distance from the centre of the hole to the fracture edge (b_a , in millimetres).

For each relevant direction of loading the following mean values are calculated from the individual results:

- the mean value of the distance from the hole to the face where fracture occurs ($\overline{d}_l$ in millimetres)
- the mean value of the maximum distance from the centre of the hole to the fracture edge ($\overline{b}_a$ in millimetres)
- the mean value of the breaking load ($\overline{F}$, in Newton).

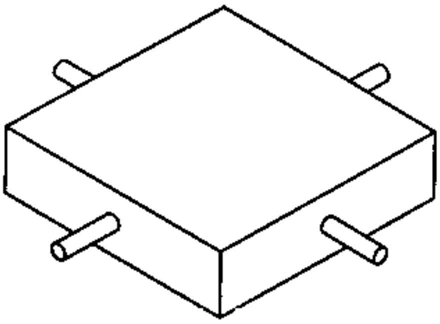


Figure 65. Test arrangement for determining breaking load at dowel hole in a specimen without planes of anisotropy.

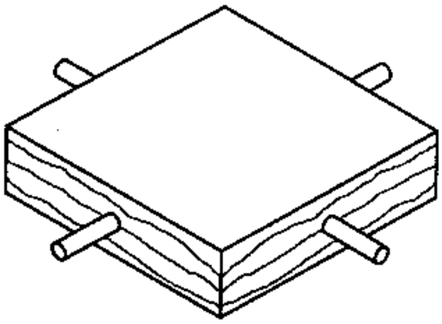


Figure 66. Test arrangement for determining breaking load at dowel hole with a load applied perpendicular to the planes of anisotropy.

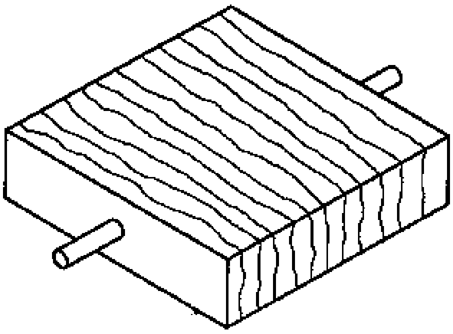


Figure 67. Test arrangement for determining breaking load at dowel hole with the load applied parallel to the planes of anisotropy.

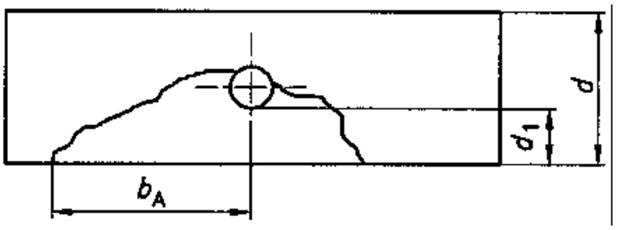


Figure 68. Measurements to be taken on a specimen after dowel hole failure.

Durability assessment

In exterior applications the durability of stone elements (that is the capability of maintaining their visual appearance and technical properties during the service life of the building in which they are installed) is a crucial parameter for their selection. In the past, when stones were used only locally, their durability could be learned by practice but nowadays, in global market conditions, we must resort to accelerated ageing tests. These tests aim in verifying the behavior of a stone in different environmental conditions: e.g. when exposed to freeze-thaw cycles, thermal cycles, aggressive atmospheric pollution, salt water, salt sprayed marine atmosphere.

The parameter chosen for measuring the changes in mechanical properties caused by durability tests may be the result of either a destructive or a non destructive test. If a destructive test is used (e.g. flexure test) it is necessary to determine the flexural strength on two kinds of specimen, one in natural conditions and another subjected to the accelerated ageing test, respectively. Therefore small decreases in mean flexural strength (up to 15%) should not be considered as significant because of the variability of the natural stone.

On the other hand, if a non destructive test is used (e.g. the determination of dynamic elastic modulus by means of fundamental resonance frequency) the measurements are performed on the same specimens before and after the durability test. Therefore, a small decrease in fundamental resonance frequency is also insignificant, but unfortunately the relationship between this indirect measurement and the changes in mechanical properties are uncertain. Other parameters that can be used for durability assessment are:

- changes at visual appearance (colour changes, splitting, swelling, cracking, erosion) determined by comparison with a reference specimen;
- change at each specimen mass percentage (although only stones with very low durability will have a significant mass change after the test).

The subject of durability is analysed in detail in Chapter 5.

Frost resistance

The durability test most frequently performed is the frost test. Many tests have been proposed and used for many years for this purpose. Here is described the procedure given in EN 12371. This standard foresees two types of tests: identification test and technological test. In both cases the specimens are subjected to freeze – thaw cycles and their resistance to these cycles is measured by means of non destructive methods for the identification test and by means of destructive methods for the technological test. Each cycle consists of an exposure to freezing air over a six hour period, followed by a six hour thawing period during which the specimens are immersed in water. During a cycle the temperature changes and the centre of the specimen should remain within the limit zone shown in Figure 69. To monitor the core temperature, an extra specimen is used with a thermocouple placed in a hole drilled to its centre.

During the identification test seven specimens (one of them for monitoring the core temperature) having the shape of a rectangular prism are used and the following non destructive test measurements of the damage caused by frost are performed: apparent volume and dynamic elastic modulus. These measurements are repeated before the cycling and every 14 cycles. A specimen is classified as failed when the decrease of apparent volume reaches 1% or the decrease of dynamic elastic modulus reaches 30%. The test continues until two or more specimens are classified as failed up to a maximum of 240 cycles. The test result is expressed by the number of cycles performed before failure.

During the technological test, the parameter used to evaluate the frost damage is the result of a destructive test (in general a flexural test, but also compression test may be used in some cases). The number and size of specimens are those required by the chosen destructive test. Another set of specimens is needed to determine the flexural (compression) strength in natural conditions. The number of cycles to be performed is fixed taking into account the end use (e.g. 100 cycles for roofing, 50 cycles for paving). At the end of the test, the mean values of flexural (compression) strength obtained for the specimens in natural conditions and on the specimens after the freeze-thaw cycles, respectively, are compared and the test result is given as the change in flexural (compression) strength after the prescribed number of cycles. Due to the natural variation of stones, decreases in flexural strength up to 15% are considered not significant.

In recent years other accelerated ageing tests have been developed: e.g. thermal shock tests (simulating the effect on exterior cladding and roofing of day-night temperature changes), exposure to acid mist (simulating the action of aggressive atmospheric pollution) and exposure to salt mist (simulating the effect of salt sprayed marine atmosphere). The procedures for these durability tests are briefly described.

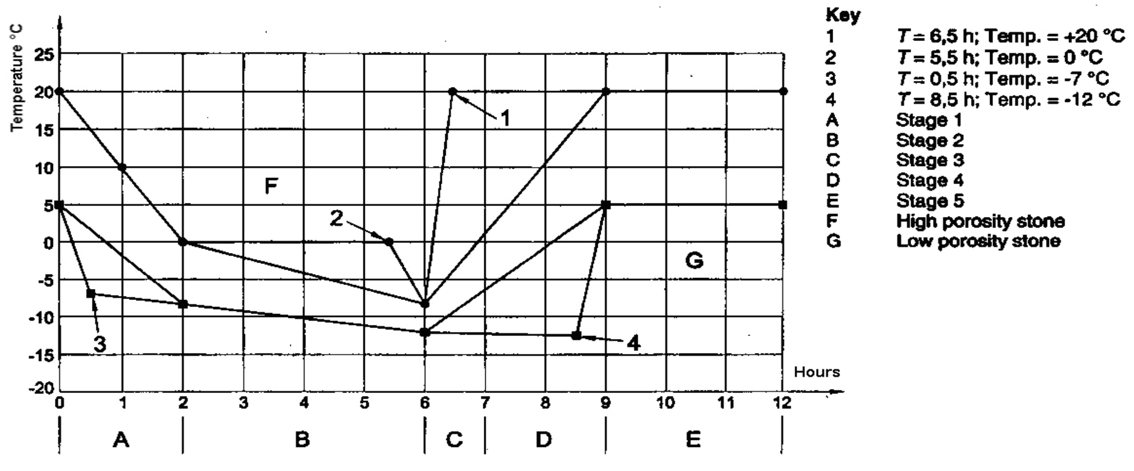


Figure 69. Zone of permitted temperatures at the centre of the monitored specimen during a freezing and thawing cycle.

Thermal shock resistance

This test aims to assess the durability of a stone when subjected to sudden changes in temperature. The test procedure described here is in accordance to EN 14066. Seven specimens having 200 x 200 x 20 mm sizes and one of the major faces polished are required. One of them is used as reference specimen and it is not subjected to any test. Before the test the dried specimens are visually inspected and compared with the reference specimen. Any differences such as cracks, holes, spots etc, are recorded. Then the mass and the dynamic elastic modulus of each specimen are measured.

The specimens are subjected to thermal cycling: each cycle consists of an 18 hours period in a ventilated oven at 105°C followed by a six hours period of complete immersion in water at 20 °C. This cycle is repeated 20 times. After the completion of the cycles the specimens are dried and weighed. They are visually inspected and compared with the reference specimen recording any alteration (e.g. oxidation, changes of colour, swelling, cracking) that occurred. Lastly, the dynamic elastic modulus is measured. The results of the test are expressed by means of the following data:

- description of the alterations visually observed (such as oxidation, changes of colour, swelling, cracking, exfoliation)
- change in mass
- change in dynamic elastic modulus.

Resistance to acid mist

The test assesses the resistance of natural stones to damages caused by exposure to wet polluted atmospheres (sulphur dioxide in the presence of humidity). The test method described here is in accordance to prEN 13919.

Two aqueous solutions of sulphurous acid with different concentrations are prepared and each of them is placed at the bottom of an air-tight acid resistant container, with an approximate volume of eighty times the volume of the solution. A frame capable of holding the test specimens vertically and at a distance of about 100 mm above the acid solution is introduced into each container.

Seven specimens having 120 x 100 x 10 mm sizes and one of the major faces polished are required. One of them is used as a reference specimen and is not subjected to any test.

The specimens are dried, weighed and visually inspected and compared with the reference specimen and any differences are recorded. Afterwards, the specimens are immersed in water for 24 hours. Three of the specimens are placed into the container with the lower concentration solution and the other three into the container with the higher concentration solution.

The specimens are held vertically on a frame approximately 100 mm above the acid solution and are maintained in this position at a temperature of about 20 °C for 21 days. After this period the specimens are removed from the containers, washed in demineralised water, dried and weighed. All test specimens are then compared with the reference specimen and any observed alteration is recorded. The results of the test are expressed by:

- change in mass for each specimen and each solution concentration, and the mean change in mass for the specimens in each solution;

- description of any observed change in appearance (e.g. colour changes, spot, rust, swelling, cracking, etc.) for each specimen.

Resistance to ageing by salt mist

This test evaluates the resistance of natural stones to damages caused by salt-sprayed marine atmospheres. The test method described here is according to the prEN 14147. Six cube specimens, with side of 50 mm, are dried, weighed and visually examined to detect the presence of cracks. Then they are placed into a chamber at a temperature of 40°C. A sodium chloride solution with 10% concentration by mass is sprayed into the chamber for a period of six hours. After this period the spraying is stopped and the specimens are kept in the chamber at 40°C temperature for another eight hours. This cycle is repeated 30 times.

At the end of the test the specimens are immersed in deionised water to remove the deposited salt. This process is very slow and requires a week of immersion and periodical changes of the water. Following that, the specimens are dried, weighed and visually inspected. The presence of any cracks is recorded. The results of the test are expressed as:

- change in mass for each specimen after the test and the mean value of the change in mass for all the specimens
- description of any cracks created by the test for each specimen.

2.1.2. In situ characterisation

In situ characterisation is based both on non destructive and microdestructive testing. Both types of tests provide indirect indications from which some properties of the stone (mainly mechanical properties such as dynamic elastic modulus and compression strength) can be inferred. Their advantage lies on the fact that they can be carried out on stone elements installed in buildings with no or minor damage. Hence, these methods can be very useful in cases where it would be impossible to take samples for performing mechanical destructive tests. They can also be used for quality control of finished products. On the other hand, however, it must be noted that the relationship between these indirect measurements and the mechanical properties is uncertain and may vary from one type of stone to another. Therefore, great care and experience is needed in the interpretation of the test results. In general it is safer to consider these results as relative measurements, in order to use them in comparing different elements of the same type (e.g. the slabs of a cladding or a supply of finished products).

Non destructive tests

The Non Destructive Testing (NDT) or Non Destructive Examination (NDE) is defined as the development and application of technical methods for the examination of materials or components in ways that do not impair future usefulness and serviceability (Figures 70-72). The objective of these methods is to detect, locate, measure, and evaluate flaws; assess integrity, properties, and composition; measure geometrical characteristics. Through NDT, the defects and/or flaws in a material can be determined as false, relevant, or non relevant indications. This defect information is then evaluated to determine if the component meets specified acceptance criteria.

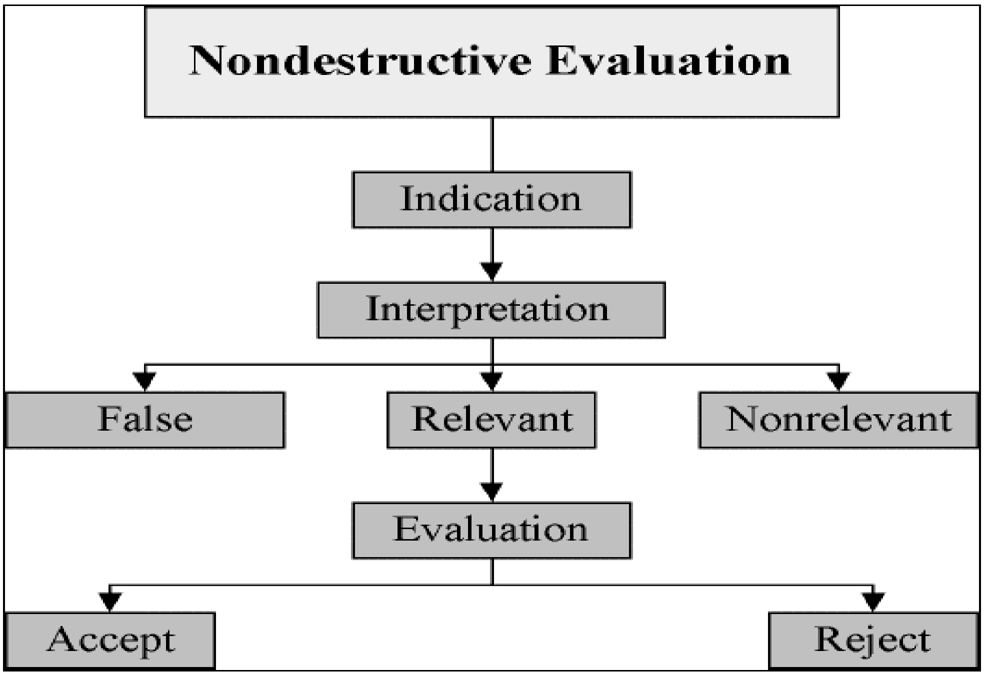


Figure 70. Schematic description of the procedure for NDE.

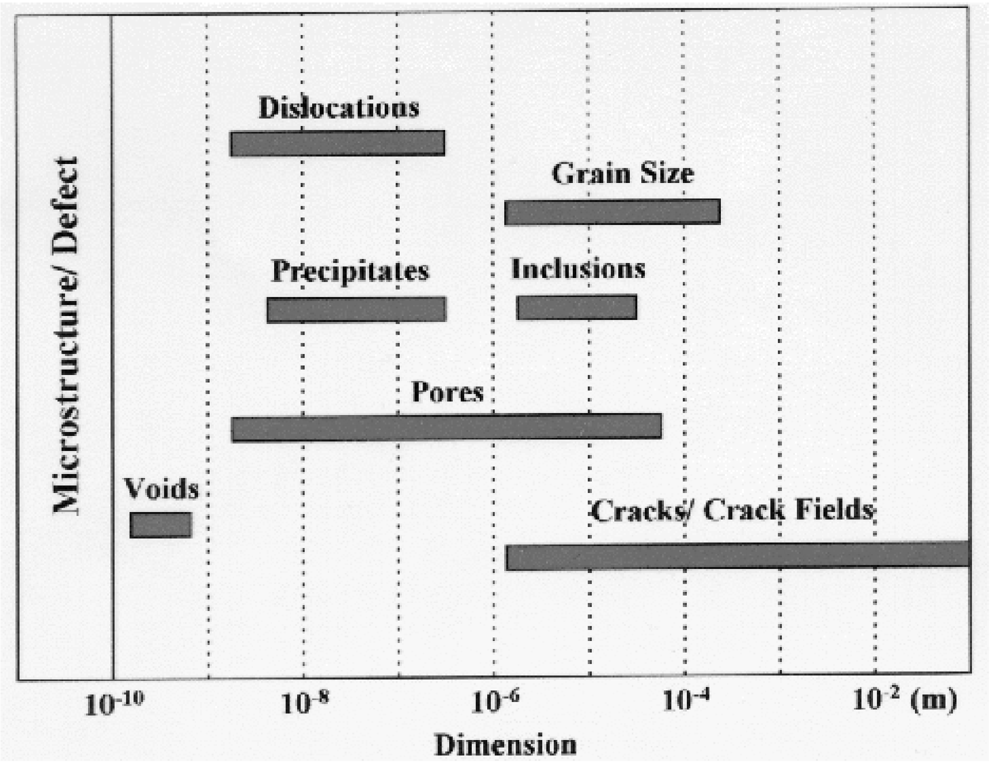


Figure 71. The linear dimensions of microstructures and defects.

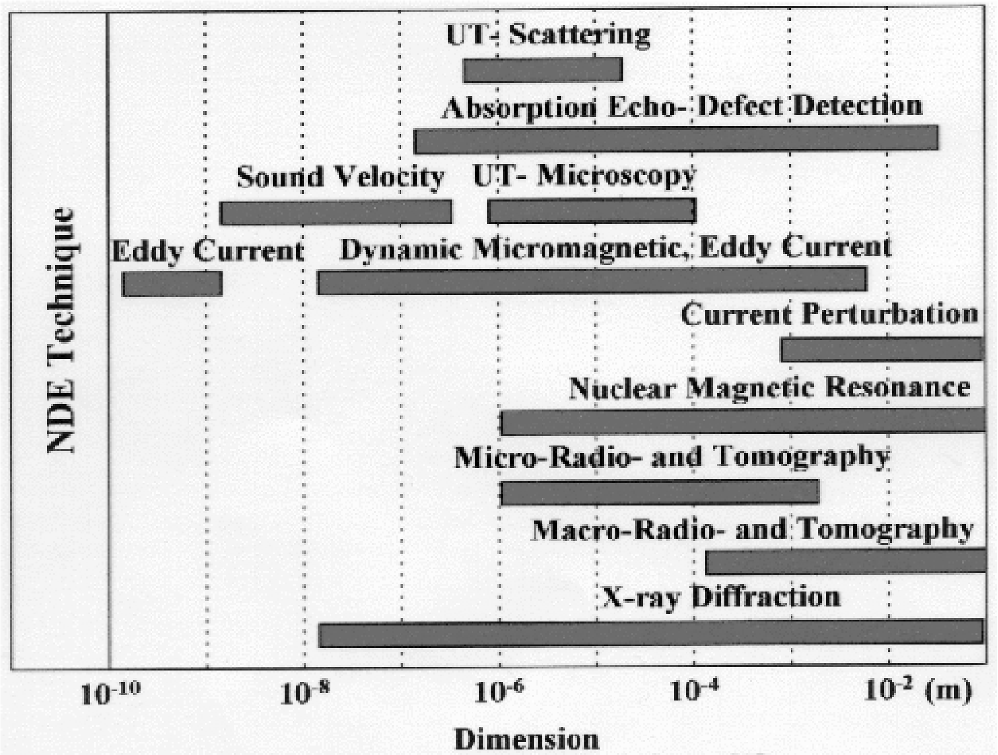


Figure 72. Resolution capabilities of NDE techniques.

Among the various NDT techniques which can be applied for the examination of stone materials, we report the following tests:

- Ultrasonic Testing (UT)
- X-ray Computed Tomography (CT)
- Acoustic emission (AE).

A comparison between the NDT techniques applied to stone materials is given in Table 28.

Table 28. Comparison of NDT techniques applied to stone materials.

Characteristics	Ultrasonic	X-ray Computed Tomography	Acoustic Emission
Principles	Sonic transmission	X-ray transmission	Stress wave emission
Variables	Scattering, attenuation, and velocity	Absorption and attenuation coefficients	Amplitude, counts, and number of events
Advantages	Suitable for thick materials relatively quick testing time	Creates cross-sectional view of the entire transmitted thickness	Real-time monitoring
Limitations	Requires acoustic coupling	Expensive; limited specimen size, radiation hazard	Requires a prehistory of stresses for flaw detection
Detectable Flaws	Voids, delaminating, porosity, and inclusions	Voids, delaminating, porosity and inclusions	Delaminating and inclusions

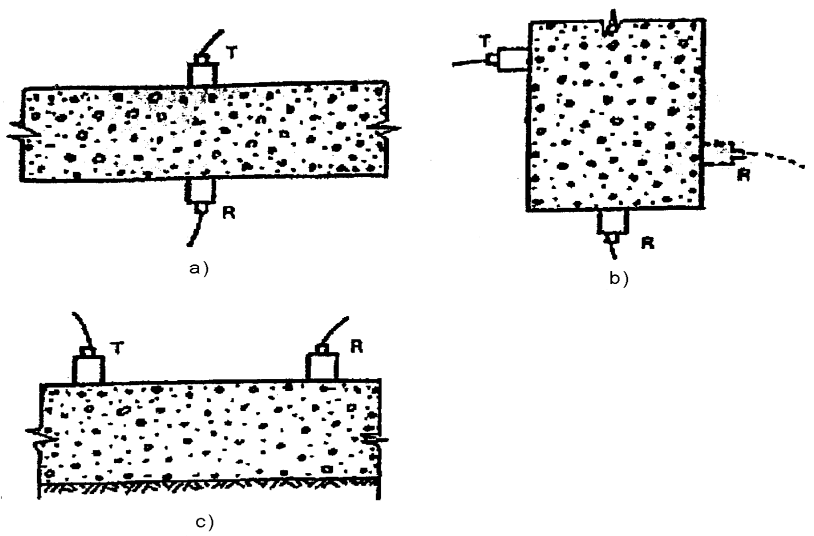
UT - Ultrasonic testing (Determination of the velocity of sound)

Ultrasonic testing is based on the following principle: a pulse of longitudinal vibration is produced by an electroacoustical transducer held in contact with one surface of the stone under test. After traversing a known path length in the stone, the pulse of vibration is converted into an electrical signal by a second transducer and an electronic timing device measures the transit time of the pulse. The procedure described here is according to prEN 14579.

The device basically consists of an electrical pulse generator, a pair of transducers, an amplifier and an electronic timing device for measuring the time interval elapsing between the onset of a pulse generated at the transmitting transducer and its arrival at the receiving transducer.

The natural frequency of the transducer is in general within the range 20÷150 kHz. High frequency transducers are preferable for short path length (i.e. for laboratory use), while low frequency transducers are preferable for long path length (i.e. for in situ measurements). Transducers with a frequency of 40 to 60 kHz are suitable for most applications.

The measurement of pulse velocity can be performed with different transducer arrangements, i.e. by placing the two transducers on opposite faces (direct transmission), or on adjacent faces (semi-direct transmission), or even on the same face (indirect or surface transmission) (Figure 73). An example of pulse velocity measurement by surface transmission is given in Figure 74.



Legend: T= Transmitting transducer, R= Receiving transducer

Figure 73. Different transducers arrangements for the determination of pulse velocity: a) direct transmission; b) semi-direct transmission; c) indirect or surface transmission.

In the case of direct transmission, the path length is the distance between the transducers, while for semi-direct transmission the distance measured from centre to centre of the transducers faces are taken as the path length. At indirect transmission the path length is not measured, but a series of measurements is made with the transducers at different distances apart.

Figure 74. Measurement of pulse velocity on a slab of a marble cladding by surface transmission.

To obtain an adequate acoustical coupling between the stones and the faces of each transducer, the use of a coupling medium (e. g. petroleum jelly, grease), is recommended. It is also recommended to press the transducers against the stone surface. For each measurement, the transit time is measured and recorded. For direct and semi-direct transmission the pulse velocity is calculated by the formula:

$$V = \frac{l}{t}$$

where: V is the pulse velocity in km/s;
l is the path length in mm;
t is the time needed by the pulse to transverse the length in µs.

With indirect transmission there is some uncertainty regarding the exact length of the transmission path due to significant size of the areas of contact between the transducers and the stone. It is therefore preferable to make a series of measurements with the transducers at different distances apart to eliminate this uncertainty. In order to do this, the transmitting transducer shall be placed in contact with the stone surface at a fixed point and the receiving transducer shall be placed at fixed increments x, along a chosen line on the surface. The transmission times recorded should be plotted as points on a graph showing their relation to the distance separating the transducers. An example of such a plot is shown in Figure 75. The slope of the best straight line drawn through the points is measured and recorded as the mean pulse velocity along the chosen line on the stone surface.

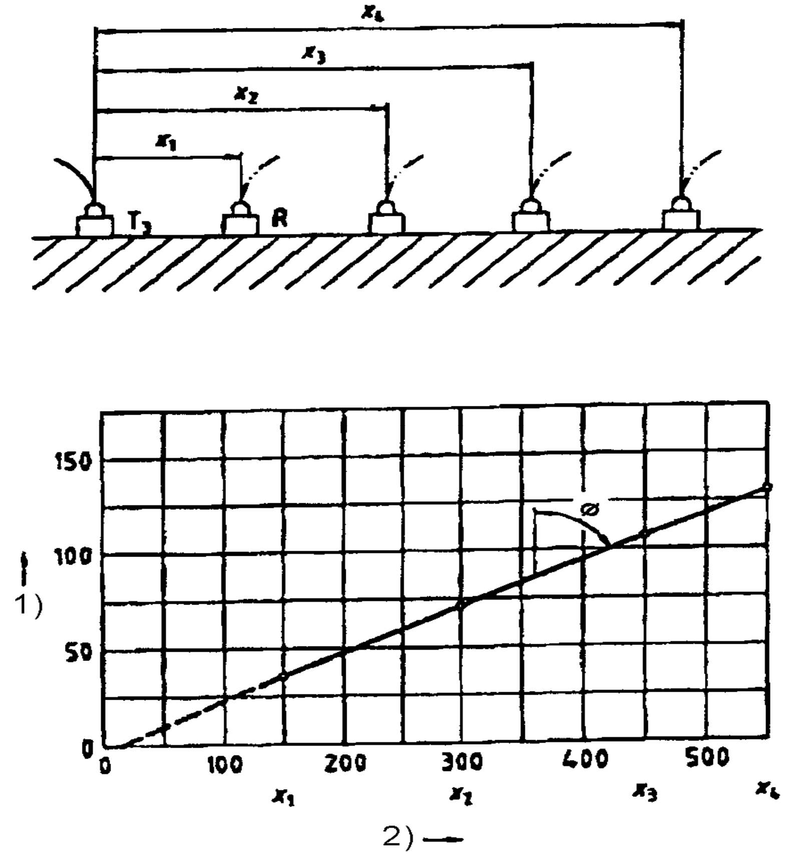


Figure 75. Pulse velocity determination by indirect (surface) transmission: 1) transmission tunes (in μs); 2) distances separating the receiving transducer from the transmitting transducer (in mm).

X-ray Computed Tomography (CT)

X-ray computed tomography provides a cross-sectional view of an object's interior and is well suited for characterizing a material's integrity. In essence, CT is an advanced form of x-ray radiography. Conventional radiography provides a two-dimensional presentation of a three-dimensional object as the image plane is approximately normal to the x-ray beam. CT creates a digital representation of a thin slice parallel to the x-ray beam. Typical slice thickness ranges from 0.025 mm to 3 mm, with pixel sizes (picture elements) ranging from 0.025 mm to 1 mm.

The CT system typically consists of a tungsten x-ray radiation source and a cadmium/tungstate radiation detector, as well as a precision manipulator to scan cross-sectional slices from different angles. The x-ray source, which can be operated at 420 kV and 3 mA, is collimated to form a thin fan beam. The fraction of attenuation of the x-ray beam is directly related to the density and thickness of the test object, the composition of the material, and the energy of the x-ray beam. To obtain a full set of imaging data, the test subject, x-ray source, or detector array moves and a sequence of measurements is made from multiple incremental angles. The data-acquisition system reads the signal from each detector in the array, converts the measurements into numeric values, and transfers the data to a computer for digital reconstruction. The reconstruction process uses an algorithm to identify the point-by-point distribution of the x-ray densities in the two-dimensional image of the cross-sectional slice. CT was used to demonstrate the correlation between the transmitted ultrasonic amplitude of a C-scan and the extent of porosity and/or internal flaws.

Acoustic Emissions (AE)

Acoustic emissions testing can be a very powerful NDT technique for in-situ monitoring of damage evolution during mechanical testing. When a material is subjected to stress, it experiences plastic deformation, formation of flaws, or fracture; these conditions produce small stresses or ultrasonic waves in the material and acoustic emissions are generated. For stone ceramic materials, an increase in acoustic emissions occurs before fracture, providing a potential means of either detecting crack initiation or predicting when failure is imminent. Acoustic emissions can be detected by AE piezoelectric sensors (transducers), which convert wave pulses into electrical impulses that can be amplified and displayed.

The process of wave generation and detection is shown in Figure 76. Generally, AE equipment includes piezoelectric transducers, amplifiers, single and multi-channel signal processing systems, acoustic-event counters, and coordinating plotters. A typical AE signal is shown in Figure 77 along with such AE parameters as amplitude (the highest peak voltage attained by an AE waveform), counts (the threshold-crossing pulses), energy counts (the measured area under the rectified signal envelope), duration (the elapsed time from the first threshold crossing to the last), and rise time (the elapsed time from the first threshold crossing to the signal peak).

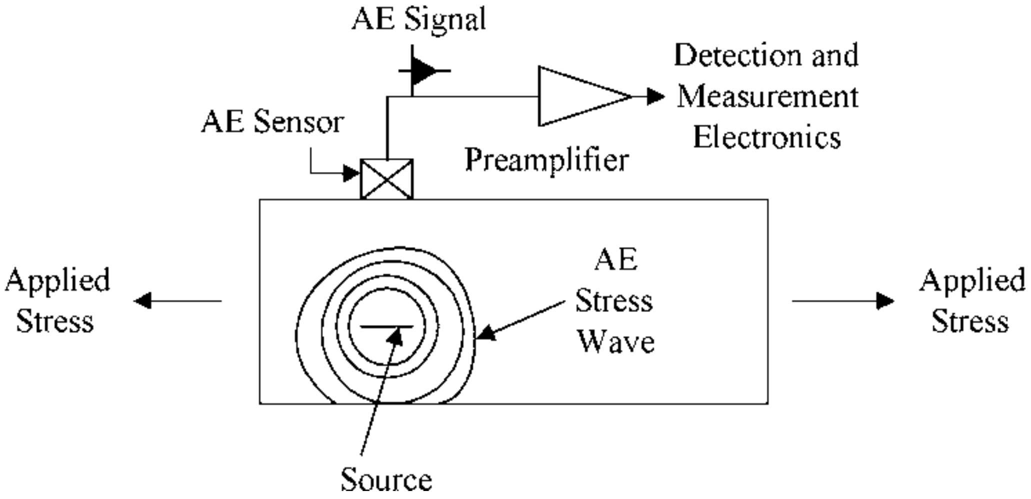


Figure 76. The basic principle of AE analysis.

Generally, the AE output can be in either continuous or burst forms. A continuous emission means the signal amplitudes are slightly higher than the background noise; the AE events are closely spaced in terms of time and form a single waveform. A burst emission occurs when the signal amplitudes are larger than the background noise; the AE events are of a short duration and are well separated in terms of time. Usually, a cracking event can be detected by a short rise time and exponential decay.

In terms of stone-based materials, the rate and intensity of acoustic emissions may be used to detect the initiation and propagation of cracks and delaminations, while acoustic emission NDT can be used to predict static and fatigue failure. Among the NDT techniques described the best approach is always the method that yields the most efficient results for a given application. When possible, a combination of techniques can be used to the greatest benefit.

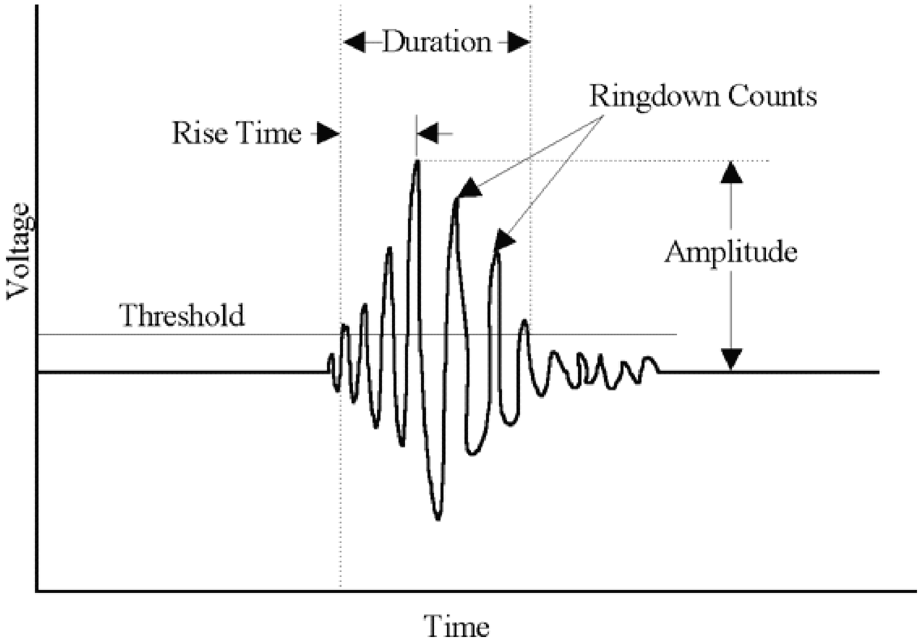


Figure 77. A typical AE signal.

The main advantages of UT are the ability to investigate relatively thick materials and obtain test results quickly. The approach does, however, require an acoustic coupling media. CT provides a cross-sectional view of the entire material, but the equipment cost is expensive. AE is a unique method in that it provides continuous surveillance during the testing, but it requires a prehistory of stresses for defect.

Microdestructive tests

Minor Damage Testing (MDT) is defined as: “Tests in which there is sufficient mechanical interaction between the test device and the building or building element and that causes change to both of them. This change is visible to the naked eye and produces useful structural data. However, they don not pose any threat to the structural stability of the building or element nor cause any irreparable aesthetic damage”.

Drilling energy - comparative (Dynamostratigraphie)

This is a device which monitors the force required to drill a small hole into a material or component. The force required varies with the strength or hardness of the materials. It is proposed for layered structures where the changes in force indicate the layer boundaries. The applications are self evident. The method is described by Chagneau and Levasseur and a commercial version is available in Germany.

Drilling energy (absolute)

This is a modification of the Dynamostratigraphie technique where the integrated energy consumed to drill a set depth into a material is measured and calibrated against known data for compressive strength. This method is suggested in (R2) and has been further developed in Italy to produce a commercially available instrument.

Drilling dust

By careful drilling it is possible to remove small samples from walling materials and to measure the moisture content (by weighing/drying/reweighing) and the salts content (by solvent extraction/drying and chemical analysis).

Drilling Resistance

A new portable device (Drilling resistance Measurement System) has been developed and validated for direct determination of stone mechanical features, such as "hardness", by measuring its drilling resistance. The test is essentially non-destructive, since stones can be tested with only minor patching of holes (Ø 5 mm) on exposed faces. With this system it was made possible to obtain affordable and sensible data on the mechanical and abrasive properties of stone specimens and monuments and to evaluate the consolidating performance of applied conservation treatments. The DRMS has no competitors for its application among "*in situ*" comparative tests and it has been suggested as standard method to UNI Normal (Italy), in order to assess the quality assurance of consolidating treatments. Furthermore, preliminary results obtained with standard operating conditions seem to indicate its possible application as portable diagnostic tool for determining the UCS directly in quarry. The method is described by Tiano et al. and a commercial version is available in Italy (Figure 78).

Flat jack

A flat jack is a thin diaphragm jack formed by two sheets of metal welded at their edges and pressurised with oil. Because of the restraint from the edges and the geometry, each jack has to be individually calibrated. A single jack can then be inserted in a strain-gauged slot cut in a structural element and the stress can be assessed when the strain state has been restored to the level before the slot was cut. Much of the development has been carried out in Italy for the assessment of the Roman masonry while an international standard is available in USA.

Flat jack (Dual)

Pairs of flat jacks have been used to assess the elastic modulus and occasionally the strength of the masonry between them or to apply a known stress field (e.g. in the shove test).

Helix pull-out technique

This is a simple test in which a shallow pitched helical ‘screw’ is self-tapped into the material then pulled out using a torque-compensated grip. A pilot hole is necessary in harder materials but not in some lightweight and aerated concretes. The cylinder of material engaged by the helix is sheared out and the force may be correlated by empirical calibration methods with other strength parameters. It is not suitable for strong materials because the steel yields. It can be applied to measure strength at varying depths by drilling a clearance hole to the depth required. The test has been described by de Vekey and Ferguson.

Figure 78. Measurement of the drilling resistance by means of the DRMS device on a marble block.

Internal fracture test

The principle of this test is that a re-entrant object is cast or fixed into the material and then pulled out using a standard diameter reaction ring and a force measuring device. The near-surface tensile strength is measured by the force required to cause a cone failure. This test was modified to use an expansion anchor in a cylindrical hole and can thus be used for *in-situ* tests on existing structures. The method has been reviewed by Bungey who proposed an alternative direct pull loading system. Arora has reported disappointing calibration data for blocks. A variant of the technique using undercut anchors on solid clay bricks, has been reported by Lui Hui and de Vekey

Penetration resistance

The original technique, available commercially as the Windsor probe, is an American development based on firing a pin into the surface of a porous material using a fixed explosive charge and relating the depth of embedment to strength, density or porosity of materials. A similar technique has been used as an absolute test for mortar but gave unreliable results with aerated mortars in BRE tests. Recently two more penetration techniques have been described by Felicetti and Gattesco and Schmiedmayer.

Schmidt rebound hardness

The Schmidt rebound hardness is an indirect measurement of the strength of a rock obtained using the Type L Schmidt hammer, having impact energy of 0.74 Joule (Figure 79). The basis for this test is the “Suggested method for determination of the Schmidt rebound hardness” published by the International Society for Rock Mechanics (ISRM). The plunger of the Schmidt hammer is placed against the test surface and depressed into the device by pushing the hammer against the test surface. Energy is stored in a spring which automatically releases at the energy level of 0.74 Joule and impacts a mass against the plunger. The height of rebound of the mass is measured on a scale and is taken as the measure of hardness.

Figure 79. Type L Schmidt hammer for in situ testing of a stone cladding.

The instrument is portable and may be used both in laboratory and *in situ* measurements. Prior to each testing sequence the hammer is calibrated using the calibration anvil provided by the manufacturer: for this purpose ten impacts are carried out, the average of the ten readings is determined and the correction factor is calculated as the ratio of the standard value of the anvil to the average of the ten readings. For laboratory use, test specimens having the form of rectangular prisms are prepared; the faces on which the test is performed must be smooth and flat (e. g. obtained by sawing). Each specimen is then placed into a specimen holder consisting of a steel cradle fixed on a steel base. For *in situ* testing the test surface must be smooth and flat across the area covered by the plunger. This area and the rock material beneath should be free from cracks or any localised discontinuity.

The hardness values are affected by the orientation of the hammer. The hammer should be used in one of the following three positions: vertically downwards, vertically upwards or horizontally. When this is not possible the test should be conducted at the necessary angle and the results should be corrected to a horizontal or vertical position using the correction curves supplied by the manufacturer. On each test area the test locations should be separated by at least the diameter of the plunger. On each test surface a minimum of 20 individual tests should be conducted. The measured values from individual tests are ordered in descending values. Then the lower 50 % of the values is discarded and the average is calculated from the upper 50 % values. This average is then multiplied by the correction factor to obtain the Schmidt rebound hardness.

Tensile pull-off test

During this test, a circular steel disc is glued to the material and pulled off together with a layer of the surface. The depth of the measurement may be increased by coring over the disc provided the surface layer is stronger than the interior. It is useful for checking layers of coatings, plasters and repair compounds. It is described by McMurray and Long.

2.1.3. Proposal of essential tests for stone and products

All the methods concerning technical characterisation either in laboratory or in situ were presented in the previous paragraph. It is hence essential to look for those tests which are most important, taking into account the fact that consumers nowadays, wish to be aware of the quality and ensured for the performance of the acquired goods. The most effective way for producers and processors in the ornamental stone industry to impose their products in a more and more competitive global market, implies a suitable knowledge of the massifs exploited, the raw materials and the products, through which they will be able to give justified arguments to the demanding customers, providing quality guarantees and transparency to their relation with them.

Natural stone products offered to the market vary from rough blocks, rough slabs, tile sets and other paving elements, kerbs, masonry elements and dimension stone in general, to slabs for lining and cladding, for flooring and stairs, for counter and kitchen tops, modular tiles, etc., each one of them containing a bigger or lesser degree of processing and surface finishing. In order for these products to be offered in a way to ensure quality, they have to comply with the standards prescribed in EN 12670, 1467, 1468, 1469, 12057, 12058, 12059, 1341, 1342, and 1343, concerning their initial characterisation and continuity control as well as factory control of the finished elements. Thus, a complete matrix of “Initial tests”, “Test to ensure consistency in quality” and “Factory production control” is established and presented in Table 29.

Table 29. Tests to be performed in stone products, according to EN standards.

Products: **Tests:**	**Rough blocks**	**Rough slabs**	**Slabs for cladding**	**Slabs for floors and stairs**	**Slabs for kitchens and vanity tops**	**Modular tiles**	**Dimension stone work**	**Slabs for external paving**	**Sets for external paving**	**Kerbs for external paving**
Geometric characteristics	FC	FC	FC	FC	FC	FC	FC	IT FC	IT FC	IT FC
Visual appearance			FC	FC	FC	FC	FC	FC	FC	FC
Surface finish		FC	FC	FC	FC	FC	FC	IT FC	IT FC	IT FC
Petrographic examination	IT	IT	IT	IT	IT	IT	IT	IT	IT	IT
Volumetric weight/ porosity	IT CQ (1)	IT CQ (1)	IT CQ (1)	IT	IT	IT	IT CQ (1)			
Water absorption at atmospheric pressure	IT CQ (1)	IT CQ (1)	IT CQ (1)	IT CQ	IT CQ	IT CQ	IT CQ (1)	IT CQ	IT CQ	IT CQ
Compressive strength	IT CQ (2)	IT CQ (2)					IT CQ (*)		IT CQ	
Flexural strength under concentrated load	IT CQ (2)	IT CQ (2)	IT CQ	IT CQ	IT CQ	IT CQ	IT CQ (*)	IT CQ		IT CQ

Breaking load at dowel hole			IT CQ						
Abrasion resistance	IT	IT		IT CQ		IT CQ	IT CQ	IT CQ	
Slip/skid resistance							IT CQ	IT CQ	
Impact resistance				IT	IT				
Frost resistance	IT	IT					IT	IT	IT
Thermal shock resistance	IT (*)	IT (*)							

Legend: IT – Initial tests
CQ – Tests to ensure consistency in quality
FC – Factory production control
(*) To be performed when relevant or upon request
Note: For tests upon request, the control frequency shall be at least 3 years
(1) - CQ tests to be performed alternatively for each product
(2) - CQ tests to be performed alternatively for each product

As stated in the relevant standards, “Initial tests” are to be repeated every 9 years on each type of stone produced, “Tests to ensure consistency in quality” each 3 years and “Factory production control” concern each lot. The fulfilment of all conditions in order to meet the total characterisation of the stone, control of quality and factory control requires the assistance of a specialized laboratory. Table 30 presents in relative importance the laboratory tests for physical-mechanical characterisation according to the end-use.

Table 30. Physical-mechanical tests for characterising ornamental stones

	External facings	**Internal facings**	**External paving**	**Internal paving and furniture tops**	**Load bearing slabs**	**Columns and pillars**
Petrography	B	B	B	B	B	B
Apparent volumetric weight	A	B	C	B	B	B
Water absorption/Open porosity	B	C	B	C	C	B*
Compression strength	B	C	B	C	B	A
Bending strength	B	C	B	B	A	
Elasticity modulus	A		B		A	B
Dowell-hole resistance	A	C				
Frost resistance	A		A		A*	A*
Linear dilation coefficient	A		B			A*/B
Abrasion test	C		A	B	B	
Impact test	C**	C**	A	B	A	

Legend:
In decreasing order of importance: A
B
C
*: Only if used in exteriors
**: Of importance A if slabs are to be used in zones vulnerable to hard body impacts (e.g., foot-panels)

“Factory control” concerns periodic quality control of raw materials and products control to ensure quality (Table 31). For factory testing, adequate sets of samples are selected and prepared. The quantity of the production lot shall be determined by the manufacturer according to the daily quantity of production, the quantity of delivery and the application of each natural stone product.

Table 31. Tests recommended for factory control

	Tests to ensure continuity in quality (to be performed each 3 years)	**Factory production control (to be performed each lot)**
Visual appearance		**x**
Surface finish		**x**
Geometric characteristics		**x**
Volumetric weight/ porosity	**x**	
Water absorption at atmospheric pressure	**x**	
Compressive strength	**x**	
Flexural strength under concentrated load	**x**	
Breaking load at dowel hole	**x**	
Abrasion resistance	**x**	
Slip/skid resistance	**x**	

2.2. Image analysis characterisation

In this paragraph, characterisation methodologies linked to new technologies are introduced. Image analysis nowadays is a common methodology, although its introduction in the stone world is recent. This is due to conservative attitude of the stone industry sector, as well as difficulties of managing the natural variability of stone visual properties.

Moreover the fact that an “image” is a bitmap representation of information collected by sensors has to be taken under consideration. The camera is the most used and immediate sensor, but many other sensors can be considered. In any case, their results are very interesting and promising, mainly because the information comes up by a classical Non-Destructive-Test. This means that the characterisation is fully repeatable and that it deals exactly with the selling product and not with a sample stored somewhere. In the following paragraphs two operational uses of the image analysis characterisation are introduced. They are quite different, concerning their techniques and application fields, but they both have the same basic approach: to exploit the information made available by artificial vision.

The first one uses the image analysis for detecting slate “defects”, under the frame of a production strategy, in order to optimise the choice of the stone to be cut. The image analysed is an artificial one, being the reflection of an array of light lines by the stone surface. Many properties can be checked, e.g. surface discontinuities or pyrite inclusions. The system, coupled with a vibratory checking unit, proved efficient during industrial production.

The second method deals with aesthetical properties of stone tiles; therefore the image is that corresponding to the human eye perception. The equipment does not define what is beautiful and what is not, but it measures the properties that control the aesthetical evaluation: colours, granulometry, vein forms and densities, etc. The starting point is the definition by the producer of what is 1st, 2nd, etc. quality parameter for any specific product. Then, the discriminating values of the meaningful properties are used by the system for the on-line product classification. If the fashion or the producer marketing strategy changes, it is sufficient to calibrate the discriminating values.

There is no particular reference to the theoretical or methodological aspects for neither of the methods, because what is considered important is the industrial usefulness of the technology. For this reason, the currently available industrial processing based on image analysis characterisation is emphasised the most.

2.2.1. Use of artificial vision and vibration analysis in a slate manufacturing process

Traditional slate manufacturing

Slates are manufactured all over the world: Spain (representing 90% of the marketed European production), France, Wales, Germany, United States (“Slate Valley” in Vermont - New England, “Slate Belt” of Pennsylvania, Virginia), Canada, Brazil (“Green Slate Mining”), Africa, China and India. In all of these countries, slate is hand-fashioned and eye-inspected. Only the large blocks that can be sawn into rectangular slabs before being split, are processed according to traditional methods. There are no countries where the slate production process is carried out by automatic non-destructive testing with optimisation of the raw material.

M. Stears, in the Slate Roof Quarterly (National Roofing Contractors Association’s 2000 Gold Circle Award in Atlanta, Georgia), wrote in the Fall 1999 issue: “The basic quarrying and production methods used at the turn of the century really haven’t changed much. Splitting, punching, and trimming of roofing slate are still done pretty much by hand. Fear not! Computer-assisted machinery has yet to infiltrate this industry.”

Nevertheless a first and significant step has been made towards the use of intelligent machines in this traditional industry: the replacement of human eye and ear by artificial vision and vibratory systems.

Recent research work

All began in a French slate quarry when it was discovered that, 40 out of 100 tons quarried from the deposit, consisting of small blocks each weighing about 400 kg, were not even hauled to the workshop because sawing them would not be profitable with the existing processes. It was estimated that these blocks contained about 4 tons of marketable roofing slates, which was as much as the current workshop output out of the originally quarried 100 tons. In order to stop wasting these natural resources and to improve profitability of the sector, a European funded research project was initiated in 1998 along with a French ministry of Industry funded project.

In order to process the smaller blocks in a profitable way, it was proven that sawing was no longer necessary and that raw blocks could be split along their fissility plane with a high pressure water jet. The second step was to find a method of automated inspection of the irregular non-rectangular slates to optimise the final dimensions of the slate. For this, two modern techniques were used: *artificial vision* with projection of a light grid on the surface of the slate and *vibratory analysis* using an accelerometer.

Features that can be automatically inspected

What is inspected concludes to:

- the limit of the slate surface,
- the surface flaws of the slate,
- the inclusions of pyrites,
- the direction of the length of the slate,
- internal fractures and cracks.

Building scale-one prototypes

Three inspection systems were designed for installation in an industrial production line and 3 scale-one prototypes were built and tested. An optical system examines the surface of a slate block, one side of which has been sawn, and determines which slate, rectangular or not, to cut according to 8 patterns sorted by order of priority (usually from the larger to the smaller). The slate to be examined is located on top of a pile; the results are not influenced by the slates underneath.

This system has been installed in a production line and it is connected in real time to a robot which cuts the best slate without any human intervention and it is particularly adapted to slates for the German market that are round-shaped and have one sawn edge. It is an optical system for inspecting the top plane of a raw slate block which allows to:

- Determine the shape of the slate that will be cut in the top part of the block without taking into account the part below.
- Locate the surface variations.
- Locate pyrites.
- Memorise the direction of the length of the slate indicated once by an operator with a chalk mark on top of the block.
- Insert on the surface a slate chosen out of 8 patterns sorted by order of priority, according to the length direction given and outside of the flaws zones detected.

This system was also tested in industrial conditions and connected to two robots, one splitting with a high pressure water jet, the other cutting the final slates. A system detecting internal fractures of irregular-shaped slates based on hitting them with a special hammer and analyzing the way the slate vibrates. This is an entirely automated system and allows detecting slates that are likely to break; fractures filled with quartz and slates that are unlikely to break are not detected. This system was tested in industrial conditions connected to a robot sorting the marketable slates.

Operating principles of artificial vision

Artificial vision is based on the use of special lighting systems. In order to detect the surface flaws on a pile of slates or on a block, a lighting system produces 2 successive perpendicular arrays of parallel and equidistant lines projected under an incidence angle of 60° onto the surface. A digital camera takes images of the arrays on normal incidence. Any deviation on the surface with respect to the reference plane distorts the image of the lines observed through the camera. The computer works out the outline of the slate or block by detecting the points where the lines are broken (Figure 80). The flatness defects are detected by measuring the distortion of the lines. The distortion amplitudes are proportional to the height of the defects so a pass criterion can be computed. The accuracy is about 1 mm. The computing duration depends on the nature of the block, and on the speed of the processor; with a standard 1998 computer (Pentium II) the average total duration to examine a surface (acquisition and computation) was measured to around 3 seconds in industrial conditions. The camera is in "E-Donpisha" mode with an exposure of 100 µs. The flash source produces a very short light pulse perfectly synchronised with the camera. This technique aims to eliminate any influence caused by surrounding light because its intensity is divided by 400. Therefore there is no need to work in reduced ambient light.

In some simple cases, only one array of parallel lines is sufficient and can be created by moving a laser plane (Figure 81). Then, a filter corresponding to the laser wave length is placed before the camera avoiding ambient light perturbations. The synchronization between the encoder and the camera is made by an electronic device. For each image, the following processing steps take place with using morphoanalysis techniques:

- Variable threshold because of the non-uniformity of the illumination,
- Examination of the lines and segmentation,
- Monitoring the segmented lines,
- Looking for the deviations from the straight line and breaking of the line.

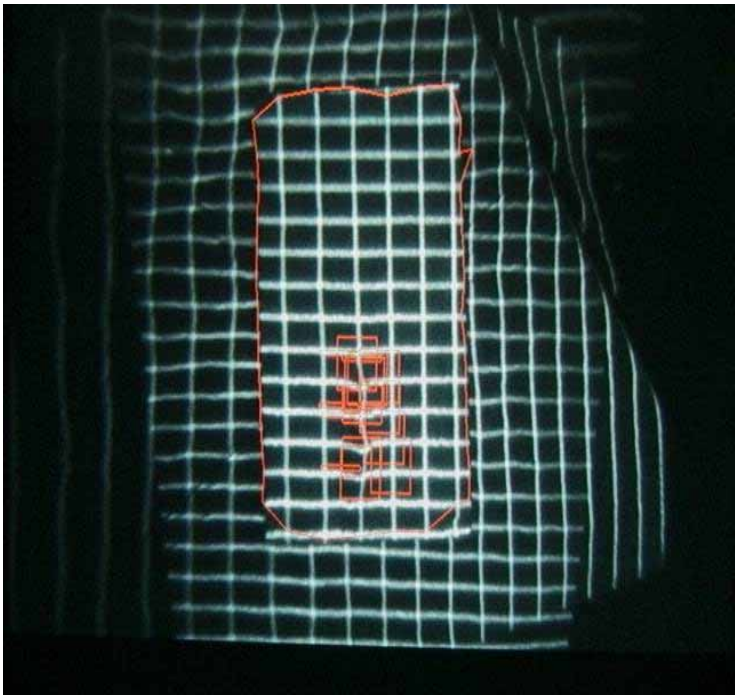


Figure 80. Results given by the computer.

Figure 81. Laser plane system during the scale-one prototyping phase.

In order to detect the pyrites inclusions, four simultaneous and equal flashes illuminate the block. As before, the camera is in “E-Donpisha” mode. This image allows the detection of included defects, again by morphoanalysis techniques.

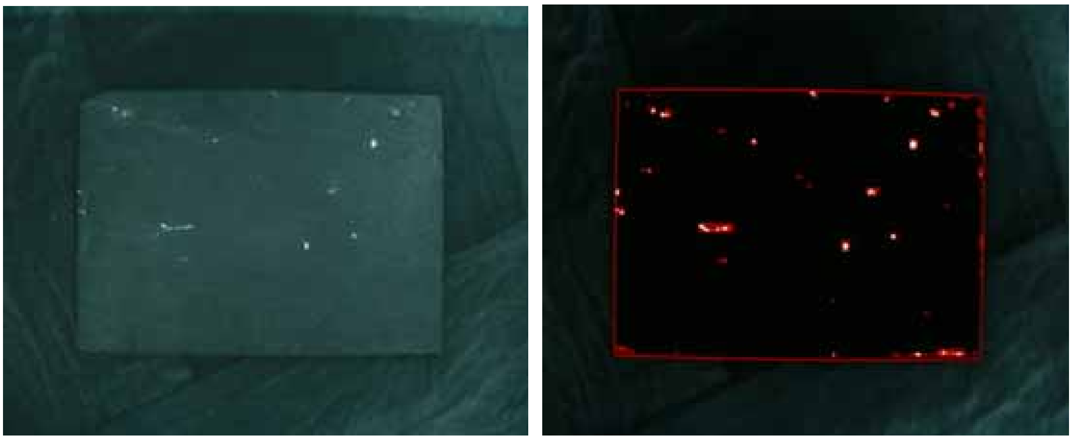
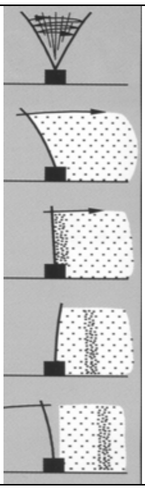


Figure 82. Images of inclusions after filtering and enhancement of contrast by computer analysis.

The smallest detected flaws are about 1 mm². They appear clear on the black schist background, while a large lighting incidence angle avoid reflections on the small defects of the block (Figure 82). Finally, the algorithm chooses the best possible slate to be cut taking into account the position of the defects, the outline of the schist and the priority of the patterns to be produced. This operation is relatively fast. The computer provides robots with information about the position of the gripping point and all the other parameters needed for the slate to be processed.

Operating principles of vibratory analysis

The basic principals used in vibratory analysis are depicted in Figure 83.



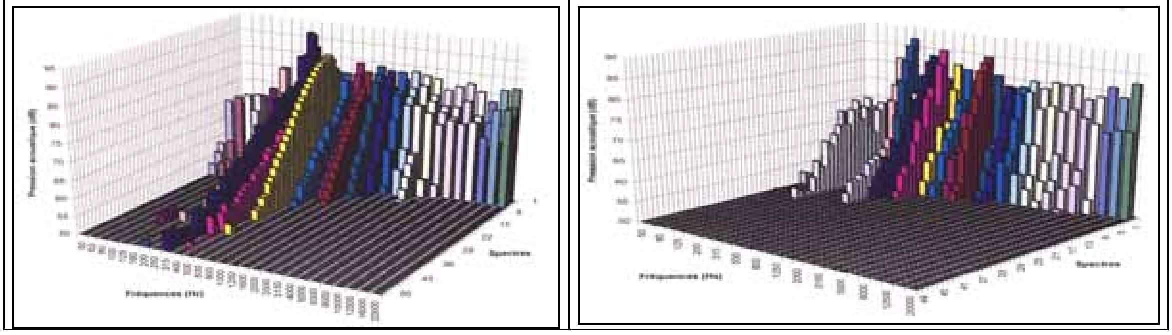
The vibrations of the thin plate generates air vibrations, therefore noise.
Two methods have been tested on slates with or without flaws :

- Acoustic method: after setting an acoustic analyzer and adjusting several parameters, the pressure of the air around the slate is recorded with a pre-polarized condenser

- Vibratory method : the vibrations are measured with an piezzo-accelerometer simply pasted on the slate.

Figure 83. Methods of vibratory analysis

The acoustic signal varies in the frequency bandwidth audible by human ear (20-20000 Hz). Both the sound and the natural vibrations emitted by slates after a shock are analysed. Different hammer-tip (plastic, steel, rubber) with different masses were tried, in order to diversify the hardness and the duration of the shock. Using a sample of 50 slates of different thicknesses (2.6 to 9.3 mm for rectangular ones and 4.7 to 7 mm for the Shuppen shaped ones), the procedure of the test was defined: the slate lies in the centre of 3 suction disks and a hammer strikes the slate.



Healthy slate

Cracked slate

Figure 84. Example of the results yielded by spectrum analysis.

Because of the variety of the slates, the criterion which gave the best results and allowed a clear detection of the flawed slate was the measure of the damping of the entire signal (sound or vibration). After studying the advantages and disadvantages of both acoustic and vibratory methods, the vibratory technique finally was selected for industrial use because the noise of surrounding machinery covers the sound of the slate after stimulation, thus proving the acoustic method inadequate.

Computer software allows quickly acquiring and automatically processing a wide range of slates. A simple user interface allows the specification of the required level of quality by using a single parameter and a single threshold that can be easily adjusted.

Figure 85. The checking system (foreground) in a real production line

The research was successful beyond expectation since the same adjustment of parameters allowed the system to be used for a wide variety of slates (rectangular or not, ranging from small to large patterns). The same cracks which can be detected by human ear only in a noiseless environment can be detected by the system while operating in a noisy environment (Figure 85). The detected cracks can be natural fractures in the original schist or cracks along the cleavage planes made by the cutting process of the slate. Even some cracks that cannot be spotted by eyes can be detected by the system. The criteria used by the system could be applied as a general norm, in order to define the quality of a slate regarding its risks to break because of an internal crack. No such norm exists at the moment.

Industrial usage of these techniques

An industrial use of these techniques was made by a small workshop in a former slate production area. The following machines have been used for about a year and a half and produced around 150 tons of marketable roofing slates:

- a saw to cut only one side of the blocks,
- an automated splitting machine capable of splitting blocks sawn on only one side,
- an optical system examining a slate located on top of a pile,
- a robot to cut a non-rectangular slate,
- a vibratory analysis system inspecting the possible internal cracks,
- a robot punching holes in the slate and sorting them according to their pattern.

Every block and slates pile is automatically conveyed horizontally from the beginning to the conditioning stage which is still done manually (Figure 86).

Figure 86. The only slate worker between the splitting machine and the production line incorporating the artificial vision and vibratory analysis methods.

Figure 87. Final production phase: sorting the slates and rejecting the defective ones (at the far right hand side).

Figure 88. Examples of slate types produced in the workshop.

In average, it has been measured that a slate can be produced every 14 seconds and that 4 seconds could be saved with a quicker communication network. The one used (Modbus) is now old-fashioned and new communication networks (such as DeviceNet) are far more efficient (Figure 89). The only perturbations observed during this industrial phase were that the vision system would not allow direct sun light through a roof window; apart from that, the machinery could be put in a normal artificial light environment. Even though humidity on slates was not a problem, although an irregular water cap on top of the slate can in some particular cases create light reflection that can be interpreted as a defect. This phenomenon happened only when the vision system operated right after the high pressure water jet splitting machinery. With a normal dust removal system onto the cutting machine, the camera could be left with no special protection against dust. Cleaning the optic lenses once a month was enough. This has proven that delicate optical systems, standard robots, computers and high technology sensors can be used even in the dusty and humid environment of a slate workshop. Computer assisted technologies are now very reliable and can be used instead of traditional methods. Every worker of the workshop was a former traditional slate worker.

Figure 89. Example of devices that are inter-connected (PLC, artificial vision box, robots).

Very promising techniques

Artificial vision and vibratory analysis systems are now available to be used in the slate industry. They opened the path to a new way of producing slates with intelligent machinery. They offer an alternative choice to man working in harsh and dangerous conditions. They allow a better preservation of our natural resources. Thanks to these techniques, it is now possible to imagine a design of an industrial workshop based on robots and machinery adapting to the natural defaults of the raw material without wasting it.

2.2.2. *Image analysis for stone deposit characterisation and evaluation*

For the mineral mining industry, every property of a mineral deposit is a natural variable and cannot be known at every point of space. For this reason every deposit is accurately sampled before becoming an ore body and the object of an exploitation project. In fact, sampling allows the identification, by an adequate estimation, of the spatial distribution of different useful variables, which are the basic information for the selection of the technically and economically interesting areas of the deposit. Of course both, mineral prices and mining costs are taken into account.

Until now, ornamental and dimensional stone deposits diverged from this logic. Many properties economically important are linked mainly to fractures distribution, which controls the block recovery, and to aesthetical quality, which determines the product value. Physical-mechanical properties finally play a secondary role in deciding if the deposit should be exploited.

The classical survey by coring, which is able to give certain information for both, fractures and aesthetical properties, in the past has been ignored or considered too expensive compared to the product value. It has been also considered useless for product characterisation and unreliable compared to the human evaluation. All these created a specific attitude in the stone sector that, until now, boreholes are rarely seen in quarries, with just a few of them being made merely for geological reasons, as is the case of studying stratigraphic contacts. Although today, the value of stone material continually rises with respect to sampling costs and data processing, still the same attitude towards surveys continues. However, fractures and aesthetical properties are considered, as soon as the geological survey is completed, but their examination is limited only to visible surfaces. The subjective evaluation of what lies behind visible surfaces, is however one of the main decision factors concerning the exploitability of a deposit. In most of the cases, the possibility that stone properties will vary in an uncontrolled way, is accepted as fatal.

In effect, today's instruments and methodologies do exist for improving the knowledge of useful properties of a stone deposit at a low cost. Even without coring, geophysics can provide information effective and economically to evaluate fracture distribution in the rock mass. Moreover, methodologies as Geostatistics allow modelling of the natural variable properties, which influence the deposit value. Of course, such properties have to be based on sample data.

Visible characteristics, which determine the aesthetical properties, can be spatially modeled as well. It is however necessary to define them a priori and select suitable measurement instruments for image analysis. The value of a stone product depends on its aesthetical properties besides the market conditions. The aesthetical characteristics that cause the classification of a stone material as 1st or 2nd choice are well known and clear to dealers, even if their objective definition is a bit shifty. These properties though, can be objectively measured as it will be presented in the following paragraphs, not only for finished products, but also for samples. Indeed, specimens obtained from a drill core can be polished according to different surface orientations. Then the different properties (colour, granulometry, veins, etc.) can be analysed by image analysis and the reference parameters ca be measured. The meaningful aesthetical properties depend on the working scale, namely by the dimensions of the finished product: the properties of a 30x30 cm tile are different from those of a 0.8x2.0 m slab. For example, the occurrence or absence of a spot can define a tile quality, but not the quality of a slab because of the spot spatial density.

Further more, the processing of aesthetically meaningful optical data which are deduced by samples, allows obtaining of important results in respect to characterisation and evaluation of a deposit. This is possible even if the information is obtained by surfaces of different form and dimensions from those of the final marketing products. For example, from coring sections it is possible to get surfaces perpendicular to the direction of drilling (10-50 cm^2), as well as longitudinal (100-500 cm^2). Then it is possible to measure meaningful optical characteristics on each surface such as the average value of lightness or the average dimensions of specific colour areas, and to locate them exactly inside the deposit, with x, y, z coordinates.

Moreover it's possible to evaluate the relevance of the spatial variability and anisotropy of such properties, at the sample section scale as well as at larger scales, by comparing the results of two surfaces as a function of their distance. Also the comparison among characteristics of surfaces oriented in different directions gives decisive information about the anisotropy. For example, it is possible to compare the spatial variability of optical characteristics of transversal sections with the longitudinal ones; or between longitudinal sections with different orientation.

The visible properties measured on every section type allow the evaluation of spatial variability at different scales of interest. At sample scale (0.1-1 m), it provides for product characteristics; at borehole length scale (10-30 m), it provides for the characteristics variability along the deposit thickness; at the deposit scale (500-1000 m), by processing the information of different boreholes, it provides for the homogeneity of the whole deposit. By an adequate modelling, typically geostatistical estimation or simulation, this information provides the aesthetical properties for evaluating the deposit. In practice, the percentage of deposit volume with constant aesthetical properties can be calculated as well as its spatial distribution. This is the most important information concerning the exploitation design.

It is possible to take advantage of these models, mainly the "simulated" ones, for more advanced decision making, a practice well known in the mining world. Comparing amongst different products mix, it is possible to calculate the recovery obtainable and the specific revenues/costs by defining the aesthetical properties and the corresponding unitary value for each marketable product. On the other hand, by comparing two alternative exploitation or investment plans it is possible to evaluate the corresponding alternative cash flows. Of course, the effectiveness of these models and the reliability of the corresponding results will depend on quality and quantity of the information available (sampling) along with the methodologies available for data processing.

2.2.3. Image Analysis during quarrying and pre-processing

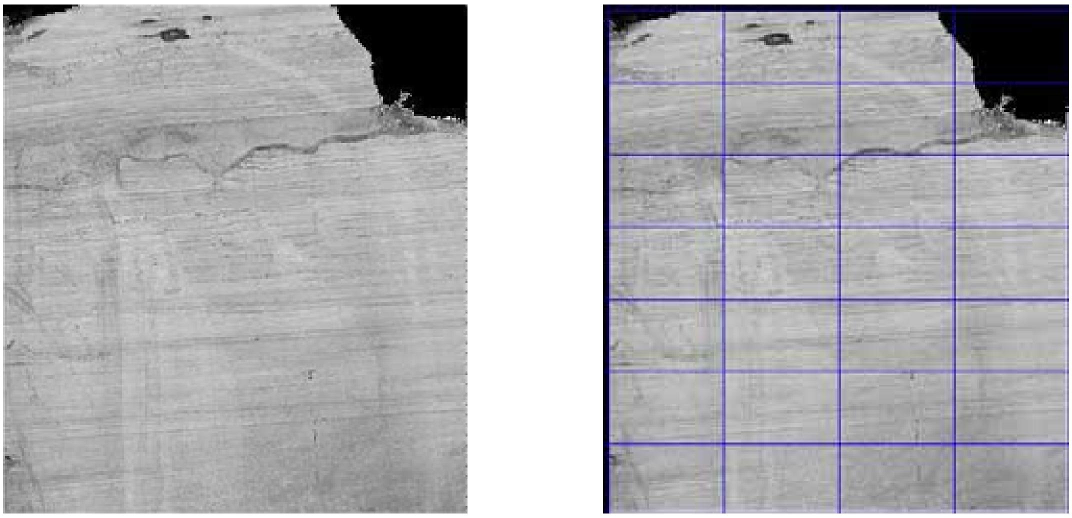
The choice of quarrying advancement direction or the bulk stone cutting orientation in order to obtain the blocks, are all relevant decisions because many of the properties which will affect the overall production recovery are anisotropic, that is they vary according to the particular direction considered. Stones derived from sedimentary formations or with oriented metamorphism or with whatever anisotropy, also have different aesthetical properties besides different physical-mechanical properties, according to the cutting-sawing plan orientation. This is the case of spot or veins or surface colours. These cutting choices, besides the existence of particular constraints, are always made today on the basis of subjective evaluations of the quarry operator (Figure 90).

This means that decisions are not based on analysis made by comparing alternative choices which derived from adequate processing of data. At this scale, from the point of view of properties being linked to image analysis, it is possible to model the volumes under the specific production phase (fronts, banks, and bulk stone). In fact it is not necessary to resort to particular sampling, because it is possible to take images of the visible surfaces. Naturally result quality will be affected because data will be processed using extrapolation methods.

Once the images of the external surfaces of interest with reference to the aesthetical evaluation are obtained, the set-up of the spatial model of useful properties allows an analysis of possible choices. The optimal choice of bench design or the bulk stone cutting orientation will depend on economic evaluations linked to the recovery and to the receipts maximisation.

On Figure 91 it is shown the case of bulk stone cut into a travertine bank and how this cut will affect the presence of dark veins into the block and accordingly the total obtainable value (Figure 91b). Alternative positioning of cuts will allow maximization of the economic recovery which can not coincide with the max volume recovery.

Figure 90. Irregular block cutting



a) b)

Figure 91. a) Travertine bank, b) Possible block-cutting solution

In the aspect of which bench to cut, the decision variables are constrained by the exploitation design. But if there is the possibility of choosing the thickness of the cut or its direction, image analysis can provide for precious evaluations in terms of block recovery or bulk stone value. In fact it can predict the fracture system behind the exposed surface and can estimate quantity and quality of the final product. In both cases the information available for data processing derives from the preceding exploited volumes and the (vertical) visible surfaces.

2.2.4. Image analysis during processing

Image analysis has several uses during stone processing in the plant and tends to substitute any decision and action connected to human intervention. At any stage of plant processing, from block sawing to tile/slab packaging, some decisions can be optimised or automated by the adequate image analysis. Image analysis can focus on different objectives, such as the form and geometry analysis for both margins and surfaces and as the aesthetical characteristics analysis.

Image analysis normally measures those object characteristics on which decision for the suitable processing is taken. Such decision can be based on current block characteristics or on a comparison between the current block characteristics and those of the previous one. Image analysis can also provide predictions for the expected characteristics of a processing stage. The optimisation function, on which the decision will be based on, is then applied to these expected characteristics obtained by the image taken before such stone processing stage.

The aim of image analysis in the plant is fundamentally the process control and the automation of production lines. The block orientation on the gang saw is, in many cases, constrained, on the grounds of specific resistance directions or structural anisotropies: sedimentation layering (primary, secondary), cleavage, etc. But in many other cases there are not preferential cutting orientations from the mechanical point of view, because isotropy exists for several rock properties. In this case the analysis of 5-6 visible surfaces can allow modelling of the aesthetical properties existing inside the block and, therefore, the visualization of the results from cutting in several orientations of the block on the gang saw, is possible. Moreover, the value for various products can be deduced by means of the simulation because the sensitivity of the economic result for a given sawing orientation can be tested, simply by sliding the saw forwards or backwards, by 0.5 - 1 cm.

Likewise, three-dimensional reconstruction of fractures by their surface traces is essential for slab recovery prediction, besides their value. Again, the final result varies depending on block orientation on gang saw and the image analysis can provide for the result evaluation. The block orientation on the gang saw, by-passing the human intervention, is an operation that can be semi-automated, as shown in paragraph 2.2.1. In fact part of that experimentation was focused on the cutting automation of blocks and slates by image analysis of geometries and unwanted inclusions in the intermediate product. The system decides if a raw slab is to be rejected or the best cutting geometry. From a general point of view, the geometric imperfections identification (cracks, etc.) is certainly one of most interesting fields for the application of visual systems: they are easy to implement and they are necessary for any automation in an industrial production process for finished products.

The selection problem for large final products, such as tiles, is however solvable in most of the cases though much more complex than the simple identification of geometrical imperfection. In effect, the intermediate or final choice of what is useful product derives from a subjective evaluation of aesthetical qualities, based on characteristics linked to colours, veins, granulometry, inclusions, etc. For each product these selection criteria vary, but can be made objective by a small in-advance study by means of the visual systems with respect to the parameter values which determine the aesthetical quality of the tile. The control of geometrical imperfections and aesthetical quality is fundamental for any process automation of tile production. A scale change, that is a variation in product geometrical dimensions, for instance from tile to slab, is not a problem for image analysis from the technological point of view. However the selection criteria change, so that useful parameters and values must be calibrated.

2.2.5. Introduction to product classification with respect to aesthetical properties

Price dependence on aesthetical properties

It is well known that in most cases the aesthetical properties determine the selling price of ornamental stones. Along with aesthetical properties other classic market factors, such as production costs, scarcity, local market conditions etc. Producing granites and silicate stones costs more than carbonate ones and this leads to higher prices. Sodalite is scarcer than “Azul Bahia”, and so its price is higher. Luanda-Angola civil-construction market pays for a “Black Africa” flooring more than Europe, even if it is closer to the production area. This is due to the need of transporting tiles to Angola from Europe, where they are produced from African blocks.

If a choice has to be made between stones with the same production and marketing costs, the same abundance and comparable physical-mechanical properties, then the choice is driven by taste. If there is a higher demand for one stone, then the market laws explain perfectly why selling prices are higher. Let us remark that taste is a completely subjective criterion. The exact same thing happens when choosing among different quality classes of the same material. Costs are higher for the first-choice class, i.e. one with “higher” aesthetical properties that has no defects as blots or darker background color. But, in fact, the aesthetical properties chosen for discriminating among quality classes are also subjective: I like / I don’t like blots, I like a darker /a lighter stone.

Finally, the discriminating aesthetical properties are those preferred by the majority of the market. Aesthetical discriminating properties for the same material vary, depending on a large number of factors. For instance, they change depending the market and time, as it happens with fashion. But they, also, change according to the surface finish or to the surface dimension. Nevertheless, it is important to focus on such aesthetical properties, at least for two reasons:

- they are perfectly measurable, because they rely on optical quantities: you can easily measure if there is or there is not a blot and how dark is a background;
- once decided on the final product, selecting between 1st or 2nd quality class material, which have different selling prices, depends only on the aesthetical properties.

Aesthetical evaluation and selection

The aesthetical evaluation is therefore a main decision factor on stone selection. The aesthetical selection criteria are subjective and they vary greatly. We can distinguish between selection criteria for choosing among different final products (material type, surface finish, dimensions, etc) and selection criteria for choosing among different types or among different quality classes (1st choice, 2nd choice, etc.) of the same final product. Industrially speaking, the selection is made among the produced types of the same final product. Normally, this selection is made “by hand”, that is a worker looks at the finished piece and decides if it should be discarded, or put on the 1st or 2nd quality choice stock (Figure 92). Recently, some automatic selection systems based on image analysis, have been introduced.

Figure 92. Handmade selection.

Aesthetical selection criteria among different final products

The factors that drive selection among different products are many, such as cost or adequacy of characteristics: for example a kitchen top of siliceous material is harder than a marble one. One of the selection criteria is also the aesthetics, but in this case, it is a matter of purely subjective criteria, whatever the comparison between two different finished products is.

We can consider what happens when just one property varies, while the rest remains constant. Let us consider two slabs of different material type, but of the same dimensions, with the same surface finish (polished, flamed etc.), with the same physical-mechanical properties (that is both adequate to the foreseen use), of the same price class and with the same commercial availability. Then, choice clearly depends just on the architect's personal taste. This is an oversimplified case, because it is rare that all the final product characteristics are constant except one. In fact, they generally come from different laboratories; moreover, two material types with the same properties do not exist.

Aesthetical selection criteria depend on a wide range of factors (project type, colour matching, personal taste, fashion, finish type, product dimension), all of them subjective and variable. Moreover, the variability is so high that it is quite impossible to define measurable selection properties. In order to make some points on the variability of aesthetical selection criteria, we have to acknowledge that they vary also with regard to market (country), time (century) and even ideology. For example, during the fascist period in Italy, the regime's ideology was referring to the Roman Empire and the architecture official stone was travertine. Every work of that period was made with travertine (Figure 93). The Southern Europe's baroque churches were made by polychrome marbles whilst the Northern Europe's churches were using more homogeneous materials (Figures 94, 95).

Figure 93. EUR quarter building

Figure 94. St. Maria Maggiore – Rome

Figure 95. Notre Dame – Paris

Aesthetical selection criteria on the same final products

Let us consider the case of a fixed-size final product, for instance the classical tile, of a given material, for example "botticino classico" polished, of given thickness and border finish. When it is being sold, a sample piece, which is either a sample image or a physical sample, is demonstrated to the customers. Therefore, it must be kept in mind that the final purchase will have tiles that may vary greatly with regard to the sample.

Current classification of Macael marble (Cosentino).

Any advertising leaflet or web site always reminds that the aesthetical properties are naturally variable. However, the expert buyer claims some specific aesthetical properties, those that define the so-called 1st class/quality/choice product. In most cases, the market (producer/buyer) is aware of such aesthetical important variations of the final products, so that it is natural to group together the similar elements.

For example, the "Macael" marble slabs are commercially classified into three main groups and, likewise, one group is subdivided into three subgroups, following classification criteria as uniformity of white colour, abundance of marks or stripes in other tones, presence of faults, etc. (Figure 96)

Typically, in the ceramic world, there is no preference if the selling lot is a bit dark or light, because it is sufficient for the lot to be homogeneous. On the contrary, in the stone world there is a clear preference for one class over the other that generates at least two selling prices, depending on what actually is the aesthetical quality. This is why we speak of 1st or 2nd choice material. As a matter of fact other properties besides the aesthetical ones concur to the definition of the material choice, but they rather discriminate what is waste from what is 1st / 2nd choice. Finally, the aesthetical quality is the more relevant property for defining the material choice.

Of course, no advertising refers to different prices for products of different aesthetical quality, but the market is strict and contestations, even trials, originate from discordant aesthetical evaluations of sold lots. The problem exists because of many reasons, among which is the lack of sound and objective definitions of aesthetical quality. That is the lack of objective and measurable aesthetical selection criteria.

In this case, technology offers some instruments based on image analysis, which allows the definition of objective criteria based on measurements. In fact, for each product type there are some discriminating properties, which are linked to human perception and evaluation. Many of them are simple to understand, as for instance the background colour, while others are less immediate, as the patterns.

Class A Class B –VN Class B - VV Class B – N Class C

Figure 96. Current classification of Macael marble (cosentino)

The choice is made by selecting a characteristic (colour) and by deciding the discriminating threshold (light beige). In practice, not just one, but a set of characteristics and thresholds is recommended. Some measurable parameters or, better, some functions of these parameters, represent more or less many of those characteristics. This is the case, for example, of the colour or of blot dimensions. Therefore, a cut-off value applied on the representative function of that measured parameter numerically identifies a threshold. Actually, things are more complicated, but the basic principle is the one described. We must highlight two important points regarding the aesthetical criteria for the objective selection:

- selection parameters and values change by changing the final product;
- selection parameters and values differ among markets and time periods

For example, veins are the marble characterizing properties, while granulometry characterizes granites. What is first choice in Italy is not in California. What is considered wonderful in the XX century it is not in the XXI century.

These facts allow the formation of a general conclusion: the image analysis technique does not define what is beautiful or ugly, but it can measure parameters linked to the beauty level**.** Consequently, it gives the tool for objectively discriminating what is considered 1st choice, for a specific material, a specific product, in that place, at that time.

Industrial selection processing in practice

In practice, human makes any aesthetical selection. In case of a stone industrial production, typically a tile production line, the need of selection is justified not only by the aesthetical quality, but also by other physical characteristics. In fact, many of these physical characteristics control if the tile should be rejected or not. This is the case where defects are present, such as scratches on the edges or cracks. In addition, geometrical features are relevant, as is the case of squaring or of flatness control. In both cases, some automatic detection systems exist, even if the problem of aesthetical selection still remains.

In reality, a worker at the end of the production line makes the aesthetical selection. He looks at the tile, which moves on a conveyor belt at a typical speed of 10 m/minute, and decides, on the base of the presence of aesthetical and other defects, if the tile has to be rejected or selected as 1st or 2nd choice product. Upon decision, he takes each tile and puts it on the "right" place, typically another belt. This operating solution has many drawbacks, among which:

- *Productivity reduction*. In fact, it becomes difficult to operate the plant on two or three shifts, mainly because of the need for keeping two workers per shift, just for the selection.
- *Costs*. Any shift needs two workers assigned to the selection, since it is not possible making this job for more than four hours. In fact, each tile weights at least 1-2 kg and in just one minute the worker should select 20 tiles. Such numbers mean that the worker has to lift 30 kg/minute that is 1.800 kg/h.
- *Tiredness lowers efficiency of choice*. This is quite evident, but let us just remark that at the end of the shift the rejected tiles rate is higher than at the beginning.
- The aesthetical selection criteria vary between different workers.

Today, image processing tools that detect tile defects on the conveyor belt and make some simple aesthetical analysis as the colour distribution control are available. However, the overwhelming majority of materials need a much more sophisticated selection procedure using criteria similar to the human ones.

Aesthetical properties measurement

Aesthetical properties refer to what the human eye is capable to see and perceive. Therefore, it is a matter of electro-magnetic radiation, whose frequency falls in the visible spectrum. From a digital image, it is possible to measure the properties of the visible radiation, obtaining an objective characterisation, as in the case of colour. In order to define the aesthetical properties in terms of the measured quantities, a processing phase of the numerical information acquired is needed. This phase is the so-called "image analysis". As a summary, a characterisation of the stone aesthetical properties requires two steps: a) acquiring the digital image; b) processing of the digital image.

Acquiring digital image

Taking a picture is a normal common experience, but it is understandable that the image we need for a targeted processing should be specific and taken by appropriate optical instruments. It is necessary to stress that images vary by altering any of the product or environment characteristics. For example, product dimensions (tile/slab), environment properties (lightness) or environment type (static/dynamic), etc. In fact, we need a digital colour image of sufficient quality/resolution; that is with a minimum pixel density. Moreover, we can exemplify the environment considerations by considering the best environmental conditions for taking the image, either in a laboratory or in an industrial production environment. The latter normally presents greater difficulty. There is also another important case of image taking, which refers to maintenance problems of stone elements of buildings and civil works.

Figure 97. Laboratory static photographing system

In such cases, we speak for "field" environment with conditions intermediate between laboratory and plant. This image analysis addresses mainly stone maintenance and aging control problems, rather than industrial and market stone selection. For these reasons, it will not be considered in detail in this text.

Laboratory systems

In a laboratory, it is possible to take care of the image quality as much as it is necessary. In fact, high technology optical equipment can be used and any image taking condition can be carefully controlled. Typically, the parameters adjusted for getting homogeneous quality images are: the resolution (for example 150 dpi), the number of bits per colour (for example 24bit colour), focus and lighting, lens type and illumination systems.

In practice, it is not necessary to get sophisticated and very expensive systems, since a good camera and a good illumination / focusing system are enough (Figure 97). Many times a good scanner for getting satisfactory images is sufficient. In fact, the aim of the laboratory analysis is the identification of the parameters that characterise the aesthetics of the product as well as the discriminating values in case of commercial classification. However, because of the fact that everything must work in industrial conditions, highly sophisticated equipment is unnecessary. In addition, the quantity of information should be controlled, since any subsequent processing has a time limit condition when applied in the industrial production. Finally, the image taking system can be tested in the laboratory. This needs the installation of a prototype of conveyor belt coupled with the image analysis equipment. Therefore, it is possible to simulate a dynamic environment and to test the system in controlled conditions (Figure 98). The final result is the set up of an image taking system.

Figure 98. Laboratory dynamic image recorder.

Figure 99. Industrial plant image selection system (Surface Inspection – Flow Master).

Industrial processing system

In an industrial plant, the image acquisition system must satisfy the environment constraint, in order to guarantee an efficient selection. The solution is based on robust equipment, self-regulating in terms of lighting and focus and with need for minimum maintenance. Typically, the aim of the industrial image analysis system is to automate classification and selection of produced tiles. The system-processing layout consists of different steps. The tile moving on the conveyor-belt is lightened and its image taken by a camera. A PC processes the digital image, in less than 3 seconds to allow the new processing of next image. The output is a classification code printed by an ink-jet printer marking the thickness, the tile number and class code. An optical system reads the class code and controls a mechanical selector that put the tile on the specific product line (Figure 99).

If an automatic packaging system is installed, a label reporting the tiles identification number and a CD containing tile images can be attached to every package. These systems, without image recording and tile identification numbering, are already operational in the ceramic industry. In this case, the variability check of homogeneous selected products, in contrast to the stone case, where no identical tiles exist, is not important. Nevertheless, the class number is larger than in the case of stones, where typically it is sufficient to consider three classes: waste, 1st and 2nd choice. The image analysis software is based on product-specific modeling, set up in the laboratory. However, the system must be self-regulating. Some properties, as the focus, are simple to make automatic, while others that control image quality variation depending on a variety of causes, need a periodic calibration phase. Moreover, industrial image selection systems should also consider other, non-aesthetical, information. It is imperative that the selection control must take into account the geometrical and physical defects as well as scratches on the edges or cracks. Again, an image analysis can easily solve the problem, but the specific processing needs a specific digital image, by a specific camera. For this reason, industrial selection systems are usually equipped with two consecutive though different image-recording cameras. In some cases, industrial image analysis systems do not target a complete selection control, but are limited just on a classification and recording of the tile images.

Digital image processing

The digital image acquired has to be appropriately processed depending on the product type and on the expected result. Specifically, the variable type to be studied is chosen first and then the type of processing. It is clear that both choices are strictly linked to the material type and to the aesthetical properties that bound the quality selection. When in laboratory, all these conditions are taken into account and there is a sequential, more complicated strategy. Therefore, the first processing generates new variables or parameters, which are again processed; then this new processing can generate again new variables or parameters, until obtaining a satisfactory and robust selection. In the following, a synthetic view of such processing will be done, after an introduction to the numerical representation of the digital image as a starting point.

Different coding

The standard colour digital image can be represented following several coding, as the RGB, LHS or CIELAB. Any of them includes the same information level, but makes easier specific calculations and characterisations. The basic logic is the same: the pixel information is given as a vector, defined in the chosen space by three independent components. Each component has, in practice, a physical meaning (Figure 100).

Typically, the RGB coding (red, green and blue) allows an easy detection of a predominant colour, while other calculations can be carried out using a grey-scale image. Often, just a single, particular RGB component can be useful. Nevertheless, the joint study of the three RGB components is essential for the classification of the marbles characterised by colored veins or by defects such as stains with specific tones. The selected area is a three-dimensional Cartesian space.

A more familiar coding is the LHS (lightness, hue, saturation) coding. Hue defines the colour type, saturation designates how vivid this colour is and lightness shows how bright the colour is. The three values are normally referred to as colour coordinates because in the specific space a point defines a colour. Lightness is treated as the vertical axis, saturation is the distance of the colour point from the lightness axis and hue is the angle between the saturation line in the horizontal plane (the colour plane) and a fixed reference axis. It is always possible and simple to pass from RGB coding space to LHS space.

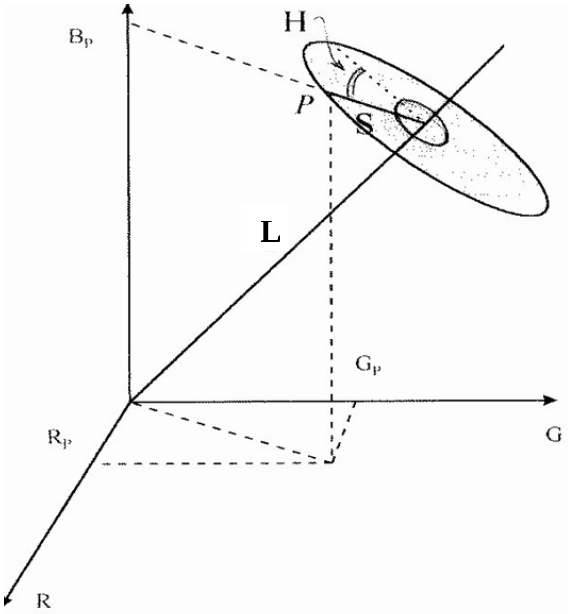


Figure 100. Colour point representation in RGB and LHS reference spaces.

Further developments in colour science overcome some difficulties posed by one or the other coding system. A mixed system, referred often as CIELAB colour space, is again a Cartesian space, with three orthogonal axes. The vertical one is the lightness; the two horizontal axes define the colour, the first one on a blue to red scale whiles the other one on a green to yellow scale.

The choice of the colour coding for each pixel is strictly linked to the specific image type and processing. The choice which simplifies results must be followed. For example, a “Serizzo” image produces a point cloud in the RGB space dispersed around the bisector line, so that the lightness explains by itself all the meaningful variability (Figure 101).

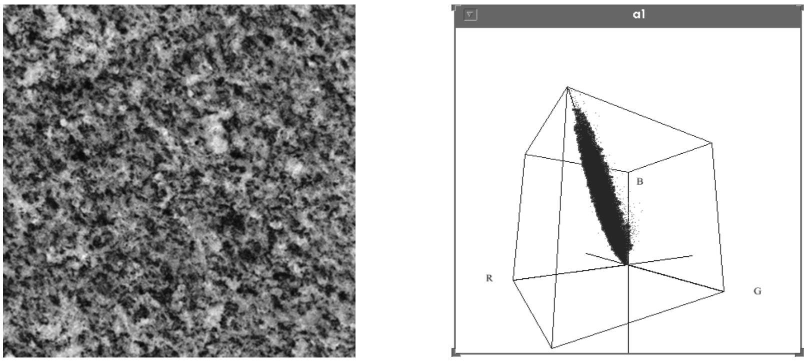
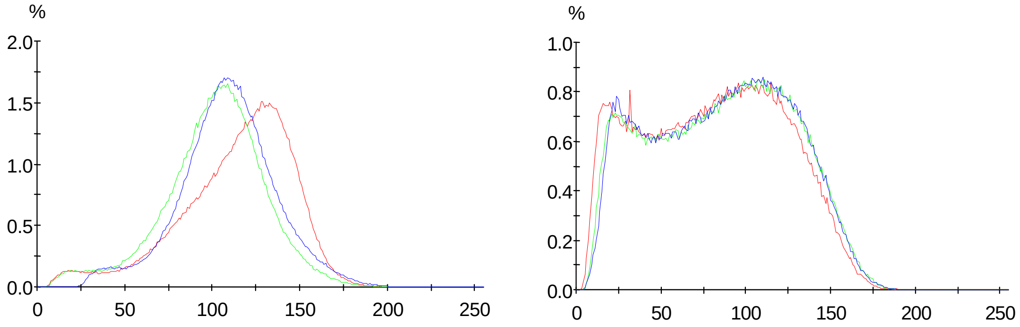


Figure 101. Image of a “Serizzo” sample and distribution of pixel intensities in RGB space.

Processing targets and methodologies

Attention must be paid to the objective of image information processing, which is to produce appropriate synthetic parameters that will allow an efficient selection. In practice this involves a two-step processing.



(a) (b)

Figure 102. RGB histograms of (a) Baveno and (b) Serizzo Antogorio images.

The image acquired has three kinds of information per pixel and a number of pixels depending on the resolution chosen. However, rarely the pixel number is less than hundred thousands. For the image characterisation appropriate tools are needed such as statistics (Figure 102). However, more sophisticated methodologies are necessary for getting particular results, as Geostatistics or Mathematical Morphology. The image analysis first-step results are parameter’s values and model functions.

A second step is the processing of each image synthetic parameters and model functions to obtain progressively fields of common variability. In order to achieve this, we can adopt very simple criteria, such as the intersection of variability fields of useful parameters, or more complicated ones such as factorial or discriminate analysis. In practice, most of the times, the simplest approach is sufficient for getting meaningful results. Typically, multivariate statistics applied to the variable chosen can be used to obtain:

- parameters as mean, variance, covariance, skewness, kurtosis, correlation coefficient;
- functions as histograms or correlation clouds.

Simple statistical parameters and functions are adequate in solving some problems as differentiation among product types and quality classes (Figure 103).

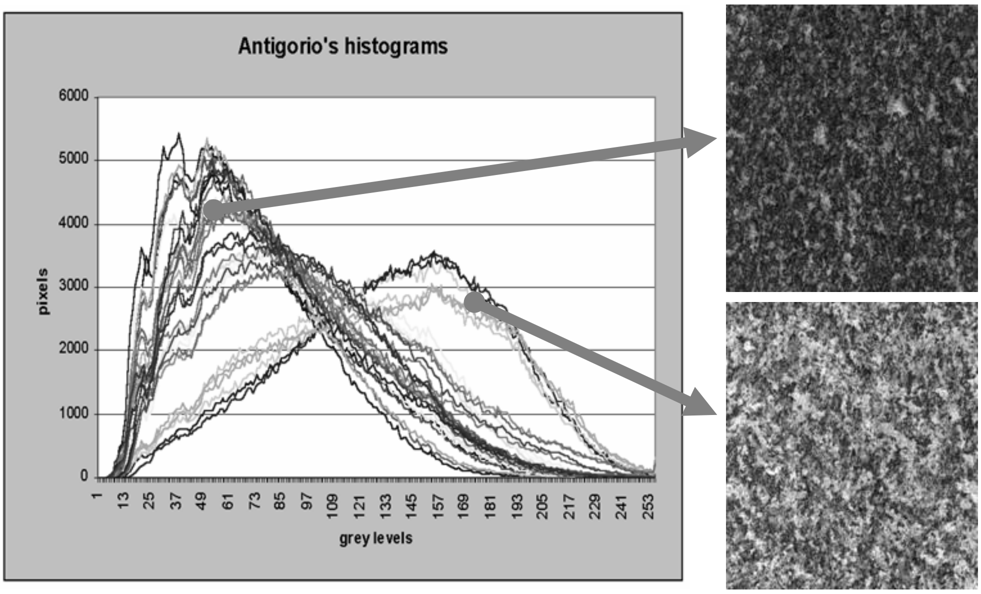


Figure 103. Grey-level histograms of two class of Antigorio.

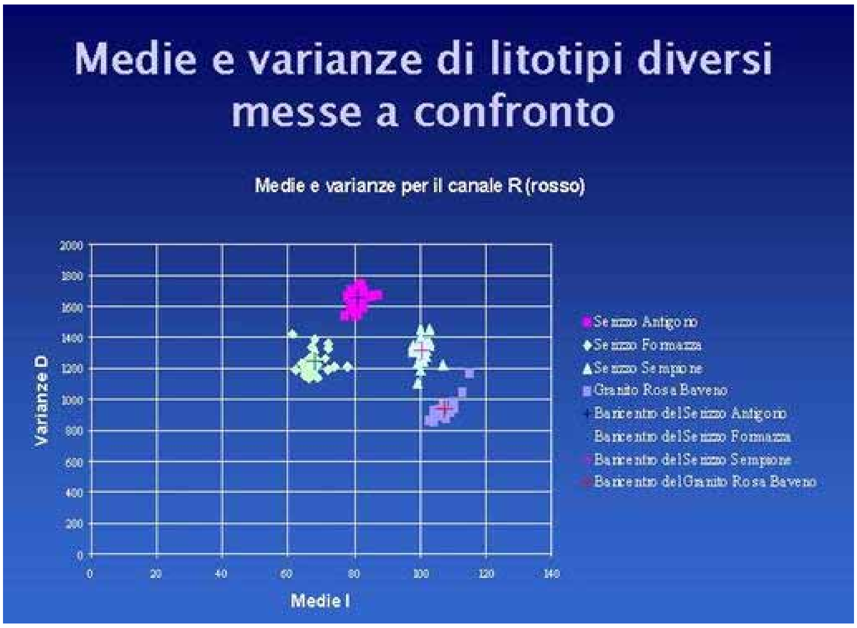


Figure 104. Mean-variance correlation cloud for Red channel and different stone types.

Simple processing, as the application of cut-off values to the data, can produce meaningful results for identifying pseudo-mineralogical phases or tile colour defects. This will generate new variables, for instance the indicator variable, which takes the value 0 or 1 (or 2), depending on the Lightness or the Red channel being below or above the cut-off value chosen (Figure 104).

When generated, new information is attributed to each pixel and using simple statistics meaningful results such as the image percentage of each indicator, can once again be produced. However, simple statistics cannot fully describe stone images and the variability of the information available in each pixel. There are at least two important aspects to be investigated, namely the object form and the image pattern. In fact, neither statistics nor percentages change by moving the base information from one pixel to another. This is the reason for resorting to geostatistical and morphological analysis.

Geostatistics considers the information of interest in combination with the spatial coordinates of the pixel associated to. The variogram function describes the correlation between two pixels by varying their distance. Moreover, it can detect if the spatial variability has different patterns depending on direction. For example, the texture characterisation of Figure 105, calls for the study of the spatial distribution of the pixel's different luminosities within the image. The luminous intensity variable coincides almost perfectly with an isotropic regionalised variable, which is "spatially stationary", that is without trends at the working scale whatever the direction. This is evident by the experimental and exponential model variogram, with distance range 19-20 times longer than the unitary distance of the pixels and sill equal to the dispersion of the values (Figure 106).

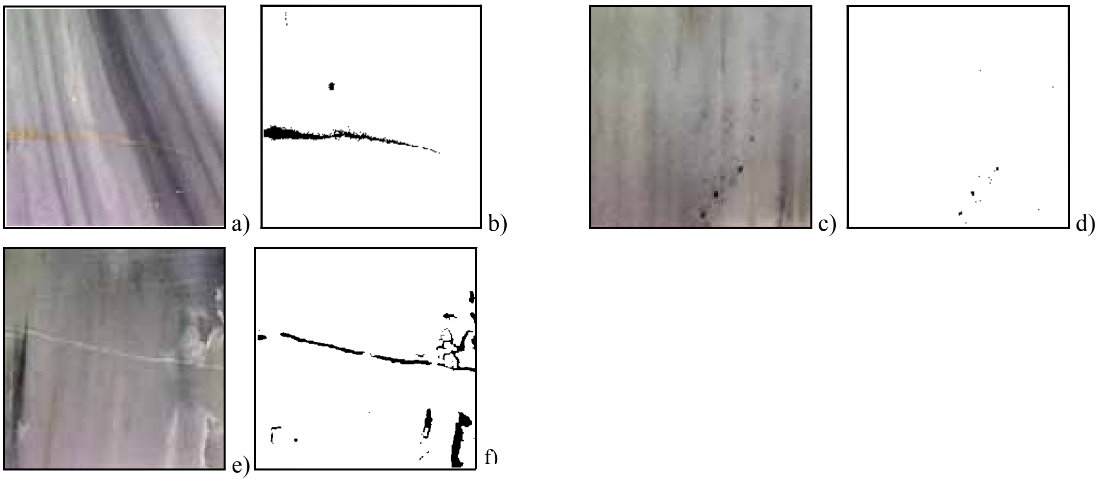


Figure 105. Segmentation of Spanish Macael marble by fixed thresholding. a, b) red stains; c, d) pyrite stains; e, f) white fractures.

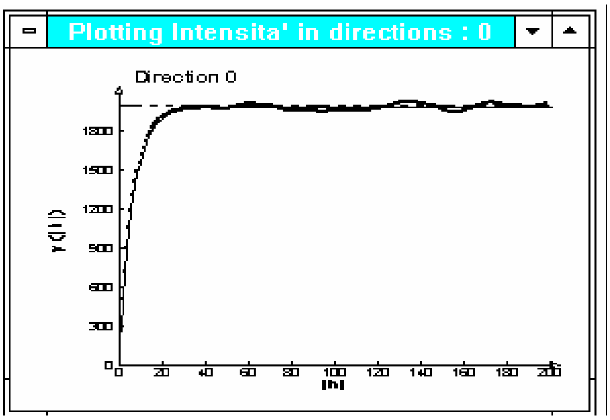


Figure 106. Experimental and model variogram of intensity.

In other cases, the behavior of the variogram varies across different directions. For example and with reference to the Spanish Macael marbles of different quality class seen on Figure 105, the experimental and model variograms, computed in four directions (0, 45°, 90° and 135°), "say" many things concerning the image pattern (Figure 107). In fact, variograms measure the anisotropic patterns of different images, regular and not much variable in one direction, more irregular in the orthogonal one, cyclical in presence of veins. But, most of all, what is very clear is the different variogram modeling for different quality classes (A, VN, VV, C).

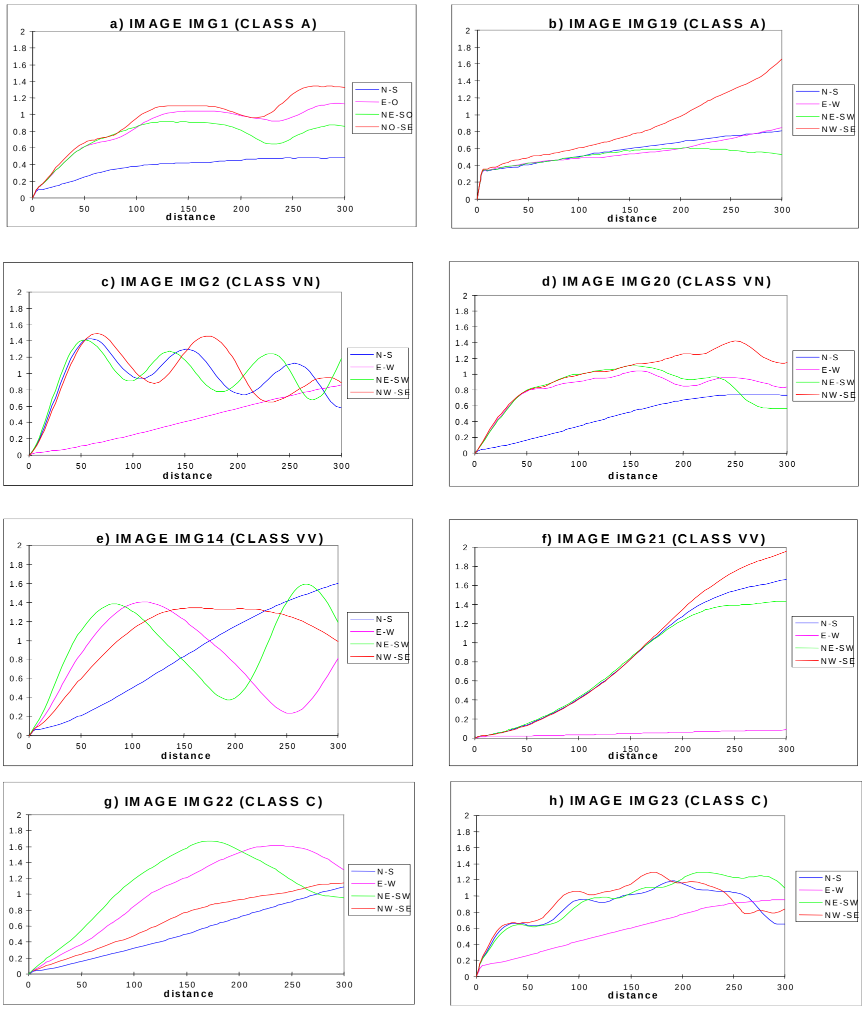


Figure 107. Model variograms of 4 directions, Macael marbles, quality classes A, VN, VV and C.

Spatial variability can be calculated from derived parameters, such as the indicators. Finally, variograms, which indeed describe the spatial variability, can be obtained not only for one variable (direct variograms), but for several variables simultaneously (cross-variograms). In this case the result is the measure of joint spatial variability, for instance of Red and Green channels together which is much more than the ordinary statistical correlation. Nevertheless, simple statistics and Geostatistics still do not measure some visual characteristics. A very appropriate methodology for image characterisation is the Mathematical Morphology.

The morphological approach requires, in the majority of its procedures, the binarization of the image. This means the transformation of the initial pixel information (for instance RGB), in an indicator variable. This is the operation known as segmentation. Various techniques of automatic segmentation allow one to identify zones with a relatively homogeneous luminous intensity. These techniques are based on the minimization of particular probability functions related to a pixel's luminosity.

One of most efficient is the "watershed" transformation technique. Considering a grey level image as a topographic surface, it relies on the identification of the "catchments basins" that are associated to each grey level minimum (Figure 108). One way of choosing the appropriate minima is through the establishment of a hierarchy by the so called "waterfall" approach.

A very interesting binarization can be found when a multi-mineralogical stone image, for example granite, is segmented in optical phases. These are not the mineralogical phases, but in practice they coincide given the homogeneity of visual characteristics of pixels that pertain to the same mineral.

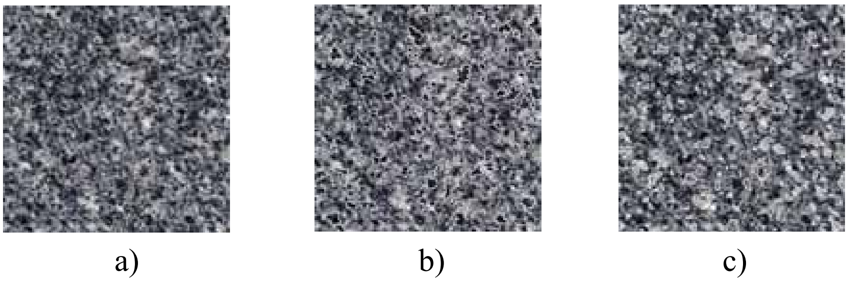


Figure 108. Segmentation of Serizzo Antigorio in three optical phases by watershed: a) original, b) dark phase, c) light phase.

Segmentation is also useful in a mono-mineral stone image, for identifying homogeneous colour area, as in the case of veins (Figure 109). One interesting result is the morphological granulometry, made up of successive elementary operations called "openings" and "closings" that are applied either to the grey-tone image or to the binary one.

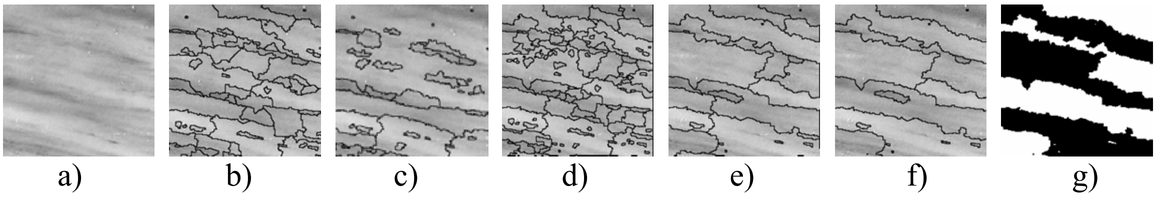


Figure 109. Results of a watershed segmentation on Spanish marble: a) original image, b) 5 iteration, c) 6 iteration, d) number of area<200, e) first phase of area unification, f) second phase and g) background.

Figure 110 shows the granulometry obtained on a grey-tone image. A Mathematical Morphology tool is the size-intensity diagram, which allows a deep characterisation of the image "granulometric" properties of a specific structural element. Figure 111 shows the morphological granulometry applied to the optical phases of some Portuguese granite. The difference of grain dimensions is clear for each pseudo-mineralogical phase. Finally, in order to deal with many variables, parameters and functions, a multivariable approach is applied for any subsequent processing.

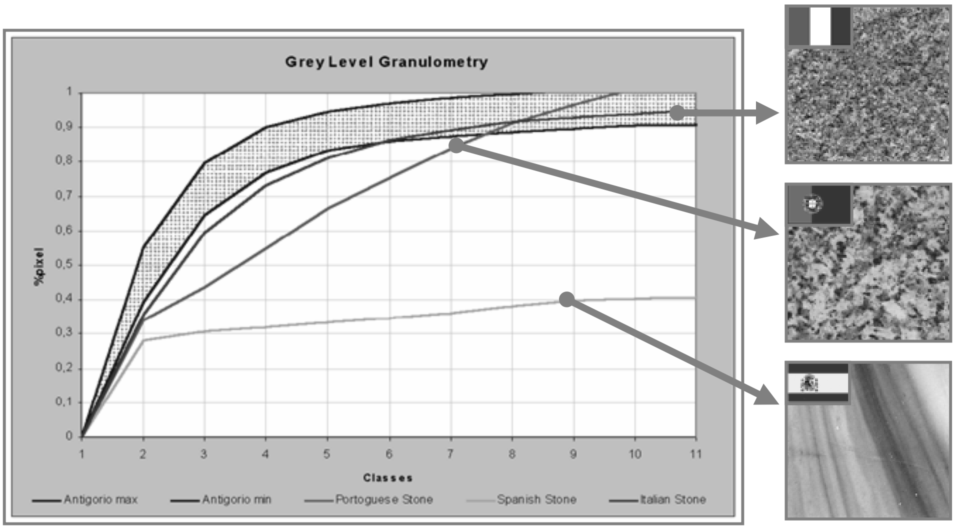


Figure 110. Grey levels granulometry computed on grey-tone image of Italian gneiss, grey Portuguese granite and a Spanish marble

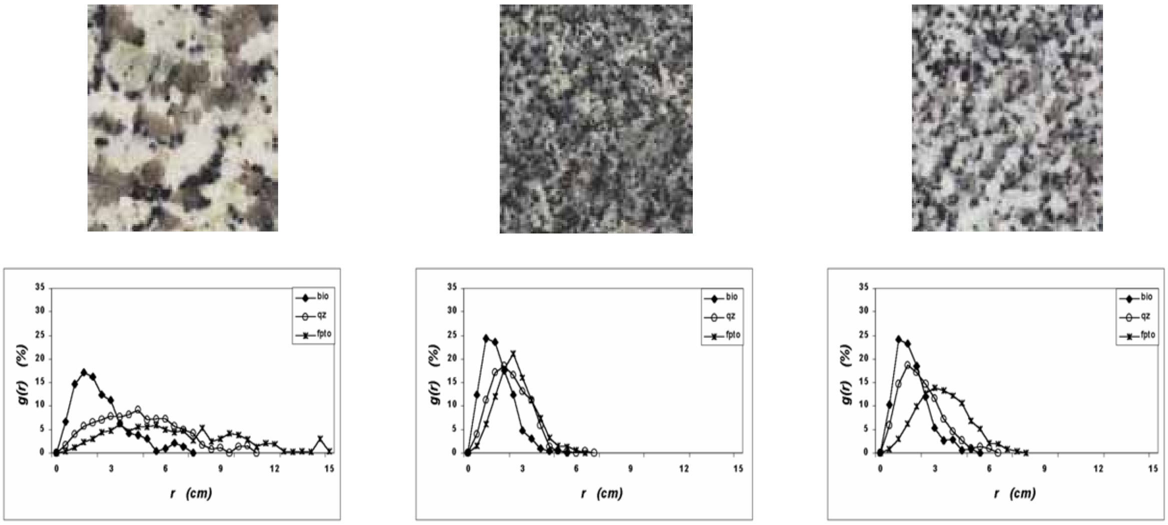


Figure 111. Morphological granulometry of each phase for three Portuguese granites (COL, EUL, EVO).

Other methodologies can be introduced when dealing with the problem of classification on the base of available parameters. Simple operations as the intersection of variability fields can solve the problem, but in many cases such approaches can be improved if applied to independent variables, which are the result of a factorial analysis. Moreover, it is possible to optimise the separation among classes by resorting to techniques, such as discriminant analysis.

Image properties

A digital image analysis can produce a great amount of numerical information, based on available methodologies. Nevertheless each stone type and each problem needs to identify the useful image properties. For example, a granulometric curve can be useful in the study of granites, but not in the study of marbles.

Specific Processing

There are quite a few types of image information processing tools so is a matter of selection to choose the right one for answering to a specific question. The simple initial statistics answer to most of the colour questions. In particular, RGB histograms clearly measure the visible colours and the importance of local colour "anomalies". It is also interesting to check if the image statistics are correlated to the whole sample available, that is if simple grouping criterions exist.

Again a simple mean-variance cloud can show any useful correlation of the statistical parameters used. But if it is necessary to measure the anisotropy of the image, the best thing to do is to resort to spatial variograms and check the variogram model parameters (range, sill etc.). In other words, it is important to identify the fluctuation range of those parameters.

Specifically for marble, it is always important not only in the case when histograms revealed great differences between the patterns of the three RGB components (Figures 112 and 113), to control colour homogeneity, veins and stains. In this case, the image segmentation is a base processing and watersheed techniques normally give the best results.

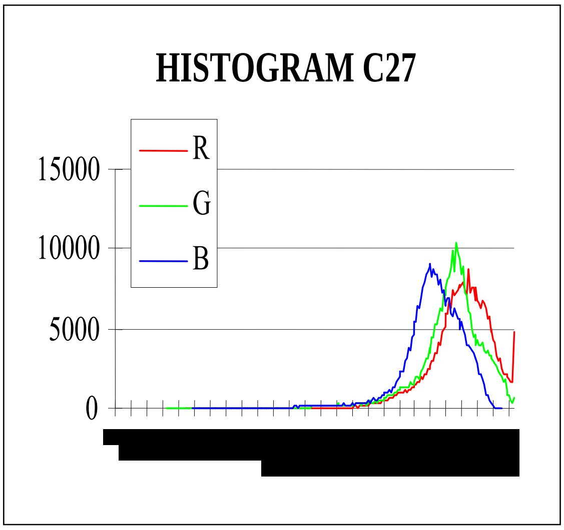


Figure 112. Histogram of RGB components of a class of marble with large red and yellow stains.

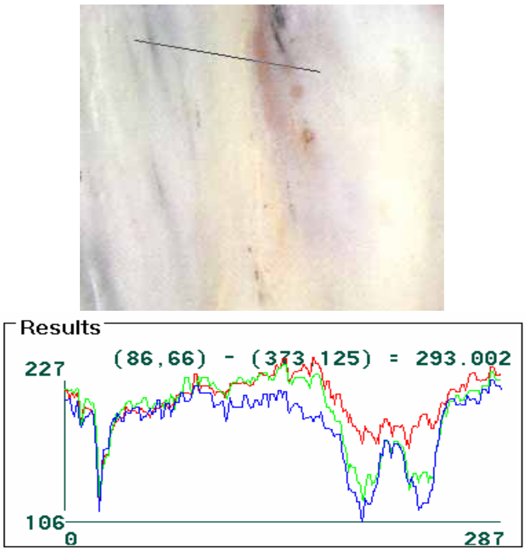


Figure 113. The corresponding image and RGB profiles for the line trace

Finally, morphology filters along with edge detection allow the identification of zones with veins or stains within the marble (Figure 114). Afterwards, a statistical study of these zones, together with an examination of their colour, will enable the discrimination of marble classes.

In case of multimineral stones, the best solution is to focus on optical-mineralogical phases, i.e. to make a specific image binarisation / segmentation. Again the morphological tools give optimal results. Indicator variogram coupled with phase granulometry characterise perfectly the image.

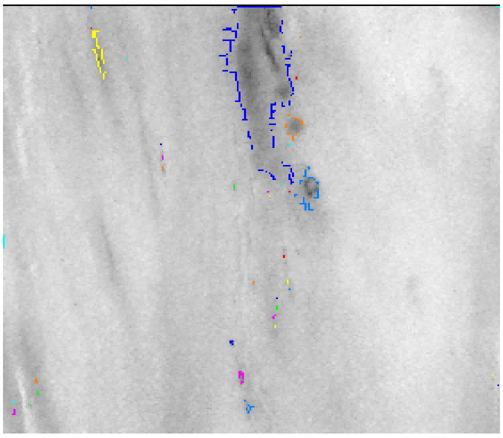


Figure 114. Automatic successful delimiting of the most obscure areas of an image.

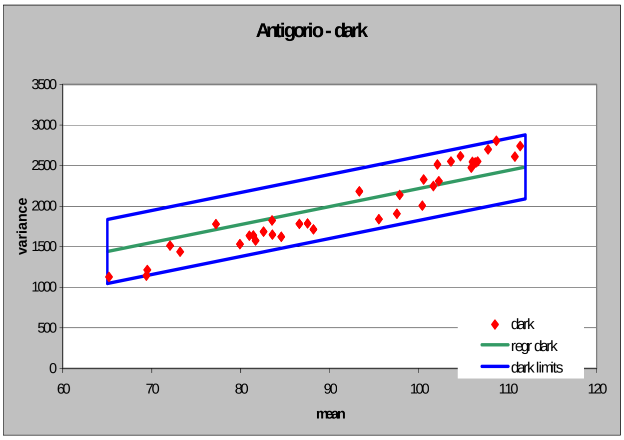


Figure 115. Admissible domain of grey level mean and variance of dark Antigorio with training set sample.

Specific quantitative results

The practical use of the aforementioned processing is linked to immediate, understandable and meaningful quantitative parameterisations. There is a huge range of parameters and functions, but it is impossible to say in advance which are the most important. In fact, again, it is a matter of stone type and product. Moreover, these are parameters and functions measured on each tile image and should be statistically post-processed in order to reach the final targets, as, for instance, the separation – classification. We can have an approximate idea of the image quantitative synthetic parameters by considering the following list:

For the original image:

- Mean, variance, skewness for each colour component, i.e. RGB or HLS.
- Covariance and cross correlations coefficient between each colour component couple.
- Variogram model parameters (range, sill, model type) for each colour component and for each couple of them.
- Grey granulometric functions.

Once the image segmented:

- Mean, variance, skewness for each colour component of each optical phase, i.e. veins or mineralogical phases.
- Percentage-surfaces of each optical phase.
- Variogram model parameters, in each optical phase, for each colour component and for each couple of them.
- Variogram model parameters for each phase indicator and for each couple of them.
- Phase’s granulometry function.

Aesthetical and image properties

Now it is possible to consider the quantitative measurements which are the chosen digital image properties and try answering the question of their meaning as aesthetical properties. It is very easy to find the congruence between a dark to light variation of a stone and its image properties. In fact, it can is only lightness that is needed to measure the visual "light" level. In some cases though, the grey level lightness cannot take into account the intensity of a specific meaningful colour. Hence, it is important to find the channel or channels mix in order to select the commercial qualities and this is easily done by simply applying a cut off value.

A defect is an aesthetical property, and generally it is quite easy to identify which process will reveal the presence of this defect. A stain is one of the simplest characteristics to identify. It only needs the right choice of efficient image segmentation, in terms of variable and technique. Typically a "watershed" segmentation applied to lightness is enough, but again it is possible to consider the RGB channels if the stain is coloured.

Other defects are less easy to measure, because they are mostly linked to patterns rather than colour/lightness variations. In this case, grey granulometry or size-intensity function or, even better, variograms, can reveal the "anomalous" tile. Defects linked to mineral granulometry are very simple to be identified by one of the specific morphological techniques. But, even if the meaning of a digital image property is easily understandable and can be linked to an aesthetical property, the fundamental dichotomy between human evaluation of the aesthetical property and the one resulting from the digital image property analysis, still exists.

This means that it is first necessary to decide what stone is beautiful and what is not. Only after that it is possible to identify the digital image properties that measure beautifulness levels; or, even better, the discrimination between beauty and not beauty. In practice, a preliminary study, based on representative samples of different quality classes, is sufficient to identify the controlling parameters and functions given by the digital image analysis. This study will provide a very important result, which gives not only the meaningful parameters, but above all the tolerance of the beautifulness exactly measured. The experience showed that it is absolutely possible and most of the times very easy to switch between aesthetical and digital image properties, so that from now on, we will not distinguish anymore the aesthetical and image properties.

Use of aesthetical characterisation

Aesthetical characterisation of stones has many uses and most of them are very important for the European stone industry, the stone production sector, as well as for the transformation sector. Some of these uses have a more immediate discernable value, while some other represent a strategy. A list of major aesthetical characterisation uses is presented in the following paragraphs.

Product classification

In the beginning of this chapter, the relevance of aesthetical perception to the ornamental and dimensional stone world was introduced. Moreover, it has been shown that product prices are very strictly linked to their aesthetical properties and that this fact affects the stone production and marketing. Therefore, at any point of the production and marketing process, an efficient discrimination among products with similar properties is fundamental. This, in most cases, means the existence of an aesthetical classification.

Industrial automation

During the production phase, the manual selection is the norm. An automation of the selection process though brings great benefits (Figure 116). In fact, substitution of the classical two-worker selection with the automatic selection system is possible to:

- Reduce the plant manpower, i.e. reduce costs.
- Increase the number of production shifts, and hence increase production rates and decrease production costs.
- Obtain a constant quality production, i.e. improve product value.
- Improve processing of the initial packaging and marketing phase, i.e. improve product value.

On the other hand, the industrial automatic selection in the stone sector, opposite to the ceramic sector, cannot be self-learning in the case of input product variations. In other words, changing stone type or product type, necessitates altering specific system algorithms. This reflects the need of a continuous maintenance in the case of continuous changes.

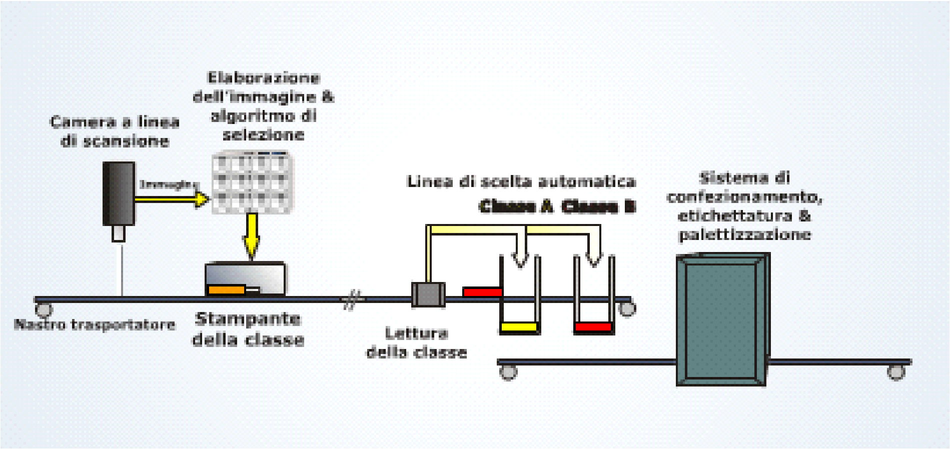


Figure 116. Automatic selection process.

Quality certification

One of the main marketing problems in the stone sector is the product quality disputes due to subjective evaluations. Nevertheless, using aesthetical characterisation, it is possible to objectively define the quality class, simply by defining numerical values for meaningful parameters (Figure 117). In practice, it is due to variation of those parameters that selection by image analysis is possible. Therefore, since these numerical values are perfectly known they can be also included in the selling contract.

On the other hand, it is necessary to have specific equipment for measuring the actual value of a tile parameter of doubtful quality. Nevertheless, if the software is hardware independent, whatever image taking equipment is sufficient to produce the image file input of processing software. This means that any customer can put the doubtful tile in his PC scanner and make his own measurements with the software for parameter measuring, which is included in just a CD and was provided to the customer along with the purchase.

This way, quality control is objective and undoubtedly results in cost reduction due to dispute reduction. But, it can provide even more benefits, because it allows the quality certification, which means a value improvement of the product. In fact, any certified product is worth more than a non-certified one. In the near future, the aesthetical quality certification will be able to be standardised by international and national standardising rules.

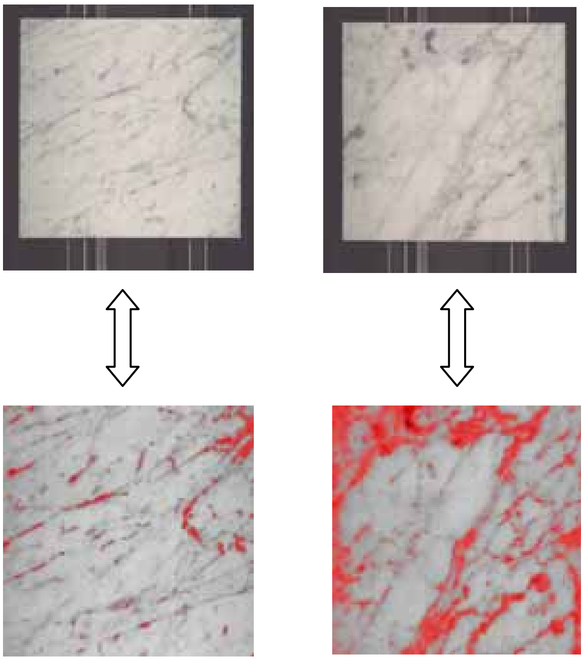


Figure 117. Morphological identification of dark phase of images of White Carrara Marble (class C and C/D): class C/D has more frequent and bigger dark veins.

Control of origin denomination

The aesthetical characterisation proved to be very efficient in quality selection of the final product. The latter means that it is possible to distinguish between tiles of the same quarry and of the same block. Furthermore, distinguishing among different stone types is even simpler. A slightly different case is that of similar stone types, but of different origin; for example two limestones, one Italian and one Chinese. Normally, the market attributes different selling prices to different products, even if they are similar stone types, and usually, the cheaper a tile costs to produce the less its market price is. The temptation of selling the cheaper product under the same name of the more expensive one is analogous to the difficulty of unmasking the fraud.

Here, the aesthetical characterisation intervenes and allows to identify if a product corresponds to the name it is marketed with. In fact, the aesthetical characterisation of a product is an essential factor for its name protection. The set of variation ranges of its parameters and functions, which allowed the selection of its quality class, immediately shows if the doubtful product is what it claims to be.

Therefore the capability of easily discriminating among products of different or similar stone types, allows a certification not only of the quality, but the denomination of origin as well (Figure 118). This is a point of strategic importance in the global market. In fact, the request of protection for typical product names is continuously growing and many times it is necessary to obtain it by law. CEN TC246 published the official names of most European stones marketed. Again, this certification means an increase of value.

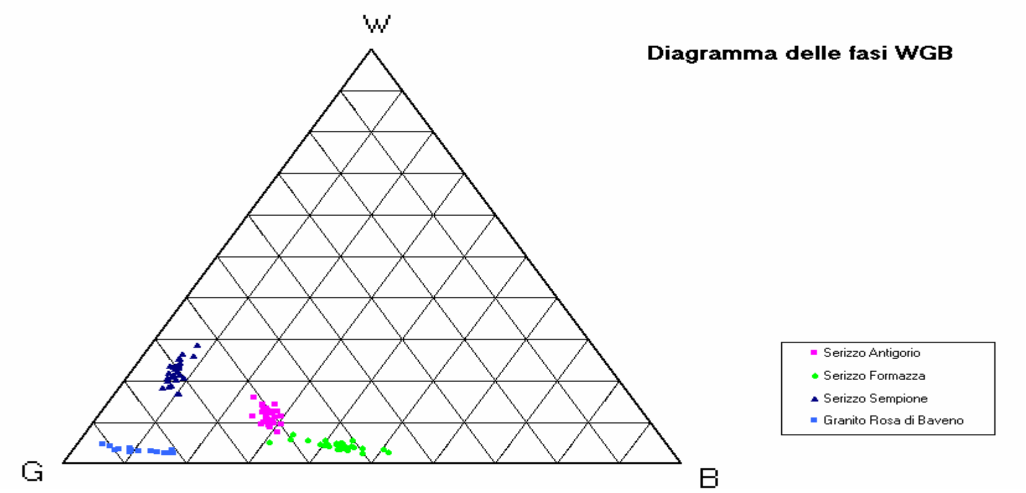


Figure 118. Optical-mineralogical ternary phase diagrams. Samples of Serizzo Antigorio, Sempione, Formazza and of Rosa Baveno.

Other uses

Even if product classification is an immediate and powerful application of aesthetical characterisation, many other uses are possible, some with interesting economic value.

Figure 119. Different ways of placing tiles of Kashmire White.

Virtual stock and its applications

As it was previously presented, there is a need for acquiring and processing a digital image when aesthetical characterisation is to be performed. This image is stored and can be retrieved for different purposes. An interesting application emerges when it is impossible for the customer to see the stone merchandise, as in the case of stone products because they are immediately packaged and stocked. But if a simple camera takes and saves the image of every slab/tile produced, in a specific database (Figures 119 and 120), it is very easy for the customer to see the merchandise, just by recovering the corresponding images on the database.

Moreover, if an ink-jet printer marks any slab/tile produced with a corresponding number, the customer can control any product element. In practice he is able to virtually see what he is buying, but he can also control physically the correctness of the virtual representation. This is the basic principle of the “virtual stock”, entirely based on images.

Figure 120. Image recording system for industrial tile production.

Figure 121. Simulation of tile matching for flooring

Moving further, it is possible to imagine other applications such as the following:

- The substantial support to e-commerce, by substituting the classic sample image, representative just of itself, with complete merchandise images;
- The possibility of knowing which tile is contained in which package. This improves the flexibility towards the customer that can choose among packages;
- The possibility for the customer to “simulate” his own application of tiles (floor, cladding) with true materials, before buying them. Simulations can be made with alternative materials, too;
- The possibility for the customer to test combinations of different materials and, again, to choose what he prefers;
- The final aesthetical result of a work, a floor for example, is strongly linked to the way of matching and orientating the slab/tiles because of colour and patterns variability (Figure 121). The skilled worker for such work is rare, and the virtual stock gives a chance to the designer to assure the best aesthetical result according to his taste. The designer can choose the exact combination of elements to be placed under way. Thus the worker has a laying plan where each tile is numbered and exactly located on the laying surface.

The above applications are also relevant to the application of automatic selection, but apply in general on the basis of the unprocessed image.

Efficiency control of processing tools

When recording the aesthetical quality of the industrial production, a variation in the processing line is reflected on product properties. Therefore, as in the case of ceramics, the temporal control of image analysis parameters provides useful information on production optimisation. This is quite clear in the case of polishing tools and systems. The surface roughness has very clear effect on the reflected image. Thus, it is possible to control the efficiency of the process of surface finishing and estimate, for example, the polishing tools working life (Figure 122).

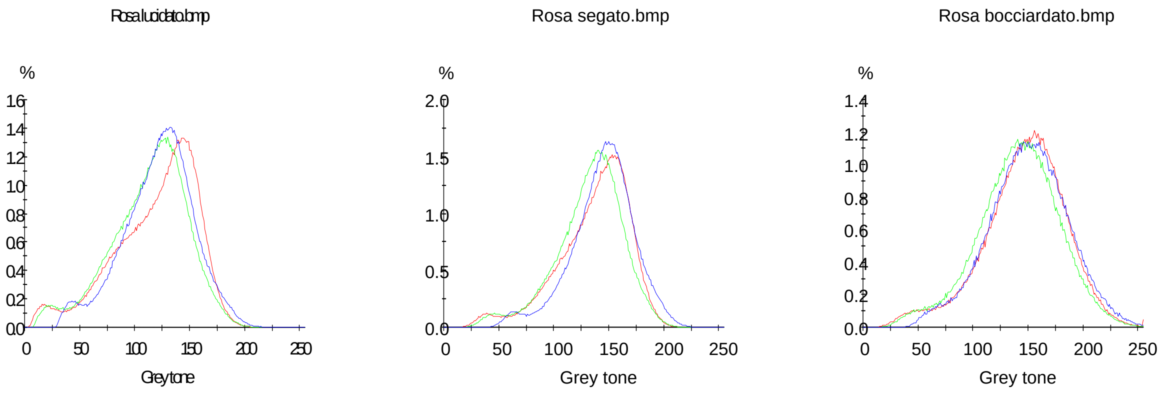


Figure 122. RGB histogram of Rosa Baveno samples with different surface finishing (polished, sawn and hammered)

Non-destructive characterisation

New research applications are in progress, many of which are dealing with the non-destructive process of image characterisation. In fact, many stone characterisations tests are destructive and/or based on samples, which normally are different from the final product. It is clear that a standard destructive test produces a characterisation that cannot be attributed to a whole product for many reasons:

- it pertains to a sample destructed, thus not included into the product;
- it generally needs a particular specimen form, which is different from that of the finished product; therefore it is difficult to measure a property, for example resistance, for a selling product element.

It is difficult for the specimen to originate from the same blocks that the final product will be produced from; as a matter of fact it originates from stone pieces different from the ones that produce the final blocks. Many of the above considerations also apply in the case of non-destructive properties. The characterisation of those properties directly on the selling products should be of great interest. The studies under way aim to take non destructive measurements, such as image analysis, on the whole industrial production and correlate them with the property of interest.

2.2.6. Conclusions

The evolution of the whole production cycle, from quarrying to marketing, can benefit very much from the correct use of Image Analysis. In fact, the basic problem of the natural variability of stone material properties, both physical/mechanical and aesthetical, can be controlled, not only subjectively, but nowadays objectively. Image Analysis is, as well a powerful method for instrument and tool evaluation objectively and efficiently.

Synthetically, these results contribute in reducing the uncertainty margins in any decision or choice from the deposit evaluation to the processing choices and to commercial product types. By reducing uncertainty an economic optimisation in general, is achieved. Economic optimisation accounts for the improvement of the volumetric and/or economic recovery of the resource, starting from deposit, banks, bulk stones or blocks, up to the economic enhancement of finished products recovery, typically tiles. Image Analysis allows justifying and optimising such production decisions/choices (cuttings, wastes, selection, etc).

The economic improvement can mean the automation of production lines, by reducing total costs by a specific manpower reduction and by a better exploitation of laboratories. Typically, the tile automatic selection system allows the minimisation of employees to the selection and production lines over three shifts. A higher control of the production process results in better equipment efficiency and higher recovery of useful material.

Finally, the economic improvement leads to higher product added value. It increases profits because of higher unitary value or because of larger amounts sold. Such improvement derives from product qualification/certification, but also by an efficient e-commerce.

Image Analysis, however, has many other applications aimed always to product qualification, but still needs to be fully tested. Broadly speaking it is time to process the electro-magnetic waves not only in the visible spectrum and explore more than just the aesthetical or visible properties. In effect, Image Analysis deals with non-destructive tests and measurements, which can be made on commercial products. This is the reason why image analysis will prevail to conventional destructive tests and measurements, which are limited to specific forms and dimensions of specimens, different from those of the commercial products.

3

Sampling strategies from deposit to finished product

KOSTAS LASKARIDIS, KLAUS GERMANN

3.1. Basic issues in rock sampling

Sampling is the scientific selection process applied to a large mass or group – a population – in order to identify parts of it – the samples – which reflect the characteristics of the parent population within acceptable limits of accuracy, precision and cost effectiveness.

Representative samples and their characteristics are the basis for the geological and economical evaluation of mineral deposits and their products. Sampling of ore deposits and ore bodies, for example, aims to the estimation of average mineral grades, and in addition, to the assessment of the prevailing mineralogical composition and ore fabrics. An adequate number of small samples may be sufficient in carrying out this task. The primary composition of the ore body is in this case only of minor importance for the quality of the final product, the pure metal.

In deposits of industrial minerals and rocks, however, a far larger number of characteristics has to be determined from samples of standardized dimensions in order to describe the average quality of the mineral deposit, and these inherent properties are decisive for the quality and marketability of the final product. These facts make sampling of industrial rocks a particularly difficult and responsible task for which rules or norms are hardly available.

To investigate possible variations of rock-mechanical parameters due to rock anisotropy, sampling of the rock mass has to be carried out in three perpendicular directions. As schematically shown in Figure 123, undisturbed rock samples (marble in this case) should be recovered in situ or from rock blocks by core drilling.

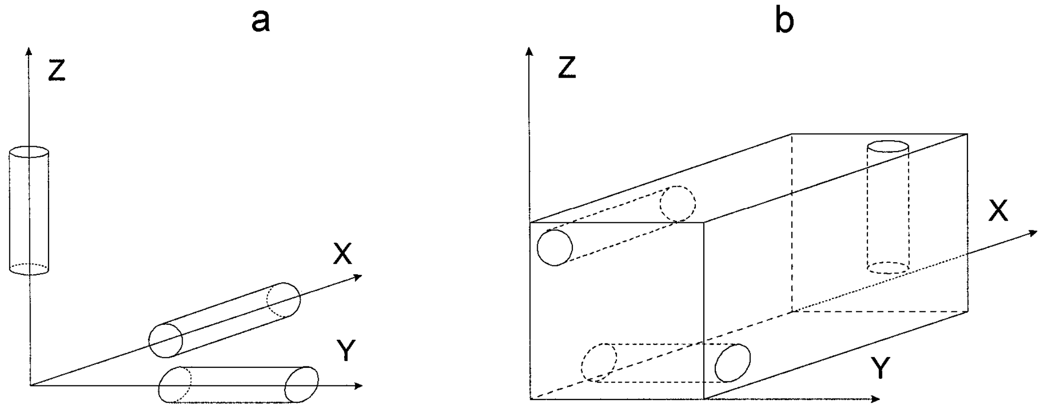


Figure 123. Schematic representation of core drilling directions in sampling marble for laboratory mechanical characterization. a) directions of in situ core drilling; b) directions of rock block core drilling ("Technical Specifications" Iabichino, 1998)

Testing the variability of dimension stones properties requires a wide variety of different sample sizes and shapes and a varying number of sub-samples which are standardized for most of the laboratory tests (Table 32). The choice of tests to be carried out is determined by the intended uses of the stone, and the number of tests (and samples) depends on the lithological variability or continuity of the rock mass.

In conclusion, any sample-based true quality control cannot be achieved for a deposit or quarry of dimension stone without understanding the geological reasons for the quality variations (magmatic zonation, metamorphic banding, sedimentary bedding, supergene zonation) and related dimensions and gradients. An evaluation of the geological factors at the target site, therefore, should include (Harben and Purdy 1991):

- Rock type mapping to determine lithological continuity
- Structural analysis and zonal boundary mapping to determine consistency
- Joint (discontinuity) system analysis

It is only on this geological basis that a sampling plan which facilitates the three-dimensional representation of the stone quality pattern can be designed.

Table 32. Sizes, shapes and numbers of dimension stone samples to be used in standardized laboratory test.

Test	Standard Norm	Sample Size lxwxh (mm)	Sample Shape	Min. Number of Samples
Petrographic study	E DIN 52101 (EN 13383-2)	min. 150x90x30	Slab (hand specimen)	
Geotechnical testing	E DIN 52101 (EN 13383-2)	min. 300x200x200	Block	
Water absorption coefficient	EN 1925	70x70x70 70(50)x70(50)	Cube Cylinder	6

Compressive strength	EN 1926	70x70x70 70x70	Cube Cylinder	5
Real and apparent density; total and open porosity	EN 1936	Volume min. 25 ml Surface to volume ratio 0,1-0,2 mm-1	Cylinder, cube, prism	6
Resistance to salt crystallization	EN 12370	40x40x40	Cube	6
Frost resistance	EN 12371	50x50x300	Prism	7
Flexural strength under constant moment	EN 13161	h: 25 – 100 l: 6xh w: 50 – 3xh	Prism	10
Breaking load at dowel hole	EN 13364	Identity test: 200x200x30 Application test: 200x200x20-65 300x300x>65-80	Slab	3-5
Water absorption at atmospheric pressure	EN 13755	Volume min. 60 ml 50(70)x50(70)x50(70) Surface to volume ratio 0,1-0,2 mm-1	Cylinder, cube, prism	6
Resistance to ageing by SO2 action	EN 13919	120x60x10	Slab	7
Resistance to ageing by thermal shock	PrEN 14066	200x200x20	Slab	7

3.2. Stages of stone exploration and production

Sampling will be needed during the following stages of Dimensional Stone exploration and production:

- Regional reconnaissance exploration
- Pre-feasibility and feasibility studies of specific targets (potential quarry sites)
- Quarry planning and development
- Quality control of the deposit during quarrying and quarry extension
- Quality control of the rough blocks
- Quality control of the semi-finished and finished product

The number and size of samples and the quality features to be determined will be considerably in each of these exploration and production stages. For example, quality control of deposit or rough blocks is particularly sampling-intensive.

3.3. Sampling during a regional reconnaissance program and pre-feasibility study

The criteria to be investigated during early phases of the evaluation of Dimensional Stone deposits should make possible a general evaluation of the aesthetic properties, the marketability of the stone and the general characteristics of the deposit:

- Location of the deposit
- Determination of the rock type
- Definition of commercial quality:
    - Colour of the stone
    - Texture of the stone
- Properties of the deposit (size, shape, dimension)

Sampling can be restricted to taking a few selected samples, which represent the average rock type and its properties, and to field inspection documented in sketches and photographs. Considering the sampling scheme (Webster and Oliver, 1990 for a presentation of the main sampling schemes), data locations usually will not be spread evenly over the area of interest as it is often the case in earth science applications. Sampling of outcrops, quarry faces or boreholes will be carried out, depending on accessibility and availability. Clustered locations may be sampled to characterise short range variability. Detailed testing of physical and chemical parameters and systematic sampling are left for the following phases which include consideration of realistically assumed quarrying, processing, marketing, legal and environmental factors.

3.4. Sampling in a stone deposit or quarry

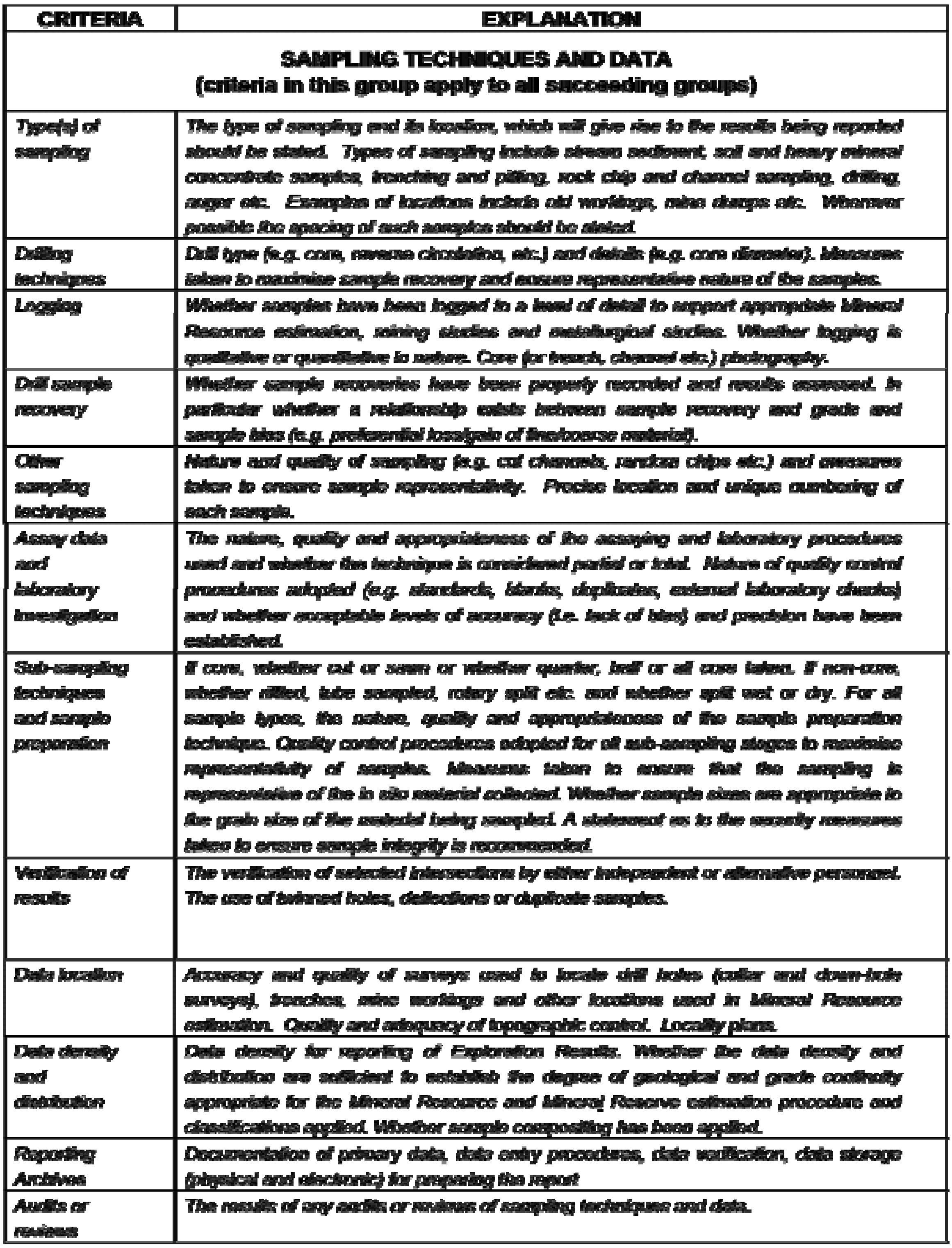
Harben and Purdy (1991) have summarised some essential facts for sampling Dimensional Stone deposits. In an initial statement they underline the fact that the most rigorous laboratory testing program will provide little if any true quality control if representative samples are not obtained from the quarry with an understanding of the geological variations within the deposit. Only then, they underline, can quality control be implemented from the start during the quarrying process to assure a steady supply of the job specified material.

The recommended sampling sequence, which has served well in the past, would be the following:

1. Reviewing existing installations and identifying key geological elements:
    - colour range, texture, finish
    - structural imperfections, surface conditions
    - typical finished slab size
2. Association of the information from step 1 along with the colour, texture and size ranges for a specified project, with the quarry area and the development plan, in order to identify sampling locations.
3. Obtaining representative quarry blocks from specified areas:
    - Labelling of orientation and sample location
    - Sawing of blocks into slabs for testing and finishing
    - Selection of slabs for sample preparation and testing according to standards

- Establishing job specific test programmes
- Construction of a mock-up of the finished installation

Table 33. First group: “Sampling Techniques and Data” of Table 1 of “The Reporting Code”(2001)



CRITERIA	**EXPLANATION**
SAMPLING TECHNIQUES AND DATA (criteria in this group apply to all succeeding groups)	
Type(s) of sampling	*The type of sampling and its location, which will give rise to the results being reported should be stated. Types of sampling include stream sediment, soil and heavy mineral concentrate samples, trenching and pitting, rock chip and channel sampling, drilling, auger etc. Examples of locations include old workings, mine dumps etc. Wherever possible the spacing of such samples should be stated.*
Drilling techniques	*Drill type (e.g. core, reverse circulation, etc.) and details (e.g. core diameter). Measures taken to maximise sample recovery and ensure representative nature of the samples.*
Logging	*Whether samples have been logged to a level of detail to support appropriate Mineral Resource estimation, mining studies and metallurgical studies. Whether logging is qualitative or quantitative in nature. Core (or trench, channel etc.) photography.*
Drill sample recovery	*Whether sample recoveries have been properly recorded and results assessed. In particular whether a relationship exists between sample recovery and grade and sample bias (e.g. preferential loss/gain of fine/coarse material).*
Other sampling techniques	*Nature and quality of sampling (e.g. cut channels, random chips etc.) and measures taken to ensure sample representivity. Precise location and unique numbering of each sample.*
Assay data and laboratory investigation	*The nature, quality and appropriateness of the assaying and laboratory procedures used and whether the technique is considered partial or total. Nature of quality control procedures adopted (e.g. standards, blanks, duplicates, external laboratory checks) and whether acceptable levels of accuracy (i.e. lack of bias) and precision have been established.*
Sub-sampling techniques and sample preparation	*If core, whether cut or sawn or whether quarter, half or all core taken. If non-core, whether riffled, tube sampled, rotary split etc. and whether split wet or dry. For all sample types, the nature, quality and appropriateness of the sample preparation technique. Quality control procedures adopted for all sub-sampling stages to maximise representivity of samples. Measures taken to ensure that the sampling is representative of the in situ material collected. Whether sample sizes are appropriate to the grain size of the material being sampled. A statement as to the security measures taken to ensure sample integrity is recommended.*
Verification of results	*The verification of selected intersections by either independent or alternative personnel. The use of twinned holes, deflections or duplicate samples.*
Data location	*Accuracy and quality of surveys used to locate drill holes (collar and down-hole surveys), trenches, mine workings and other locations used in Mineral Resource estimation. Quality and adequacy of topographic control. Locality plans.*
Data density and distribution	*Data density for reporting of Exploration Results. Whether the data density and distribution are sufficient to establish the degree of geological and grade continuity appropriate for the Mineral Resource and Mineral Reserve estimation procedure and classifications applied. Whether sample compositing has been applied.*
Reporting Archives	*Documentation of primary data, data entry procedures, data verification, data storage (physical and electronic) for preparing the report*
Audits or reviews	*The results of any audits or reviews of sampling techniques and data.*

4. Quantification of the availability and accessibility of the material for a specified project in the quarry production benches, development area, and in the block inventory:

- Mapping quarry exposures
- Sample trenching and key cuts
- Core drilling
- Establishing a quarry block inventory

When reporting on industrial minerals resources and reserves in accordance with "The Reporting Code" of IMM et al., 2001, the guidelines summarised in Table 33, should also be considered persuasive.

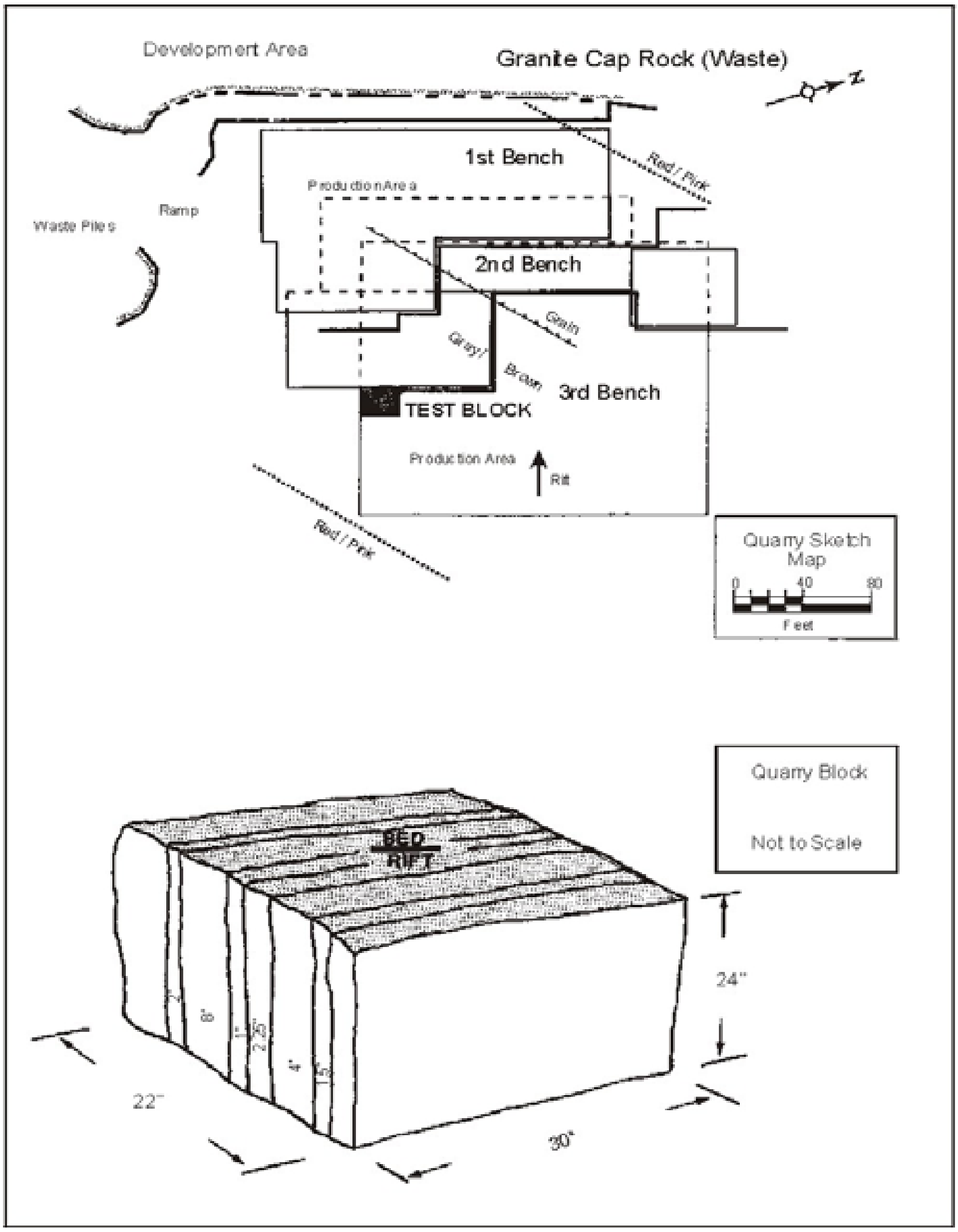


Figure 124. Quarry sketch map with location of the test block and quarry block with orientation mark and slab thickness needed for standard ASTM tests (from Harben & Purdy(1991)

The quarry block samples should be extracted intact/undisturbed from the rock mass using the stone natural discontinuities (cleavage, bedding, joints). According to Harben and Purdy (1991) a specimen block at least 22x24x30 inches (= 56x61x76 cm) should be selected from a potential production area (Figure 124). This block should be located on and orientated to the quarry map and marked accordingly. It should also be marked top/bottom, north/south, with the rift/bed direction noted (Figure 124). Powers (1994) emphasizes, that the best sample is a block from which slabs 0,3 m^2 or larger can be sawed. DIN 52101 (withdrawn since 1999-03) proposed a minimum size of the sample blocks of 30x20x20 cm (Table 32).

Sample size is also depending on the size of the final product. In the case of tiles as the intended product, the samples to be characterised in view of the average natural pattern types (colour, texture, size and shape of mineralogical components) must be adapted to the product size, e.g. 30x30 cm.

Samples taken in this way are subjected to a variety of physical-mechanical tests of the “initial type”, which define the characteristics of the raw material being or to be subsequently worked (Table 32). Further testing is carried out “during the work” to define the characteristics that the market product must have.

3.5. Evaluation of rough blocks

The rough blocks produced in the quarry can be considered as systematic samples. Visual inspection of these block samples must be carried out with regard to colour and discolouration of the stone, its texture and the presence of mechanical defects as e.g. hairline cracks, the orientation of the cutting planes with respect to the textures, and its weight, size and shape. This information is needed for marketing and selling the block as a product as well as for its following processing. Specifications for the investigation of rough blocks of natural stone are given in prEN 1467, 1994:

- Visible hairline cracks and other defects in the stone material must be indicated at the blocks.
- The agreed commercial quality must be fulfilled by the rough block stone; selected characteristics of the stone have to be certified according to the European Norms.
- The natural stone type must be denominated.
- The block is to be marked with respect to its main rift/bed direction.

Specific quality demands on granite rough blocks have been defined by Nelles (1996):

- Size and shape of the block must be optimally adapted to the intended use.
- The block must be free of natural and mechanical defects as e.g. veins, joints, hairline or blasting cracks, large pores, reflecting (ore) minerals
- Geologically and mineralogically induced in-homogeneities in colour, texture and structure should be absent,
- Standardized minimum requirements regarding physical-technical characteristics must be fulfilled.

3.6. Quality control of semi-finished and finished products

Specifications of semi-finished products (rough slabs) of natural stone (prEN 1468, 1994) provide for the determination of the following requirements:

- Thickness, plane ness
- Quality
- Surface state

The numerically dominant stone products are trimmed slabs and tiles. The first goal of quality control of these finished products is to classify every tile into quality-constant batches according to the following specifications:

- Dimension
- Surface state quality (e.g. quality of polish, planeness of cut planes, defects; Primavori (2002) gives an overview on surface treatment of ornamental/dimension stone)
- Lithological quality (colour: global colour analysis, homogeneity, patterns; texture, size and shape of components)

Quality control of semi-finished and finished stone products is based on visual inspection which still relies mainly on human vision. In the ideal case, each semi-finished and finished product would have to be inspected individually on the production line in real time, a task which is far beyond human capabilities. Visual inspection tools have been developed, for this reason using efficient automated machine vision, as presented in Chapter 2. In the meantime, a wide variety of non-contact visual inspection systems for quality control is available for ceramic tiles and also for dimension stone tiles (Bruno et al. 1999, Lebrun 2001). The image acquisition and stone classification with these machine vision systems is achieved without any sampling operation. The algorithms used must be fast enough to follow the production rates and the system must be designed to cover the size range of standard tiles.

Among the machine vision systems developed for the needs of the stone industry are the following:

- The European COSS project (Bruno et al., 1999) resulted in a system which is able to characterize the visual appearance of ornamental stones by applying digital image analysis techniques. Characterization in this case means the objective reliable measurement of the visual properties of the ornamental stone (colour, texture, shape and dimension of their components) and the identification of variability tolerances with respect to accepted standards. 30x30 cm polished tiles have been used in developing and testing the system.

- MARCO (developed with the collaboration of MICA Laboratory, University of Liège, and distributed by DMO, Belgium) is an on-line quality control system for dimension stones which can check surface state quality, colour homogeneity and dimension. The inspected area is 50x50 cm, and the system can accept any type of surface finish from rough sawn to polished finish.

- MASC, the Marble Slab Clusterer, is an associated activity of the Technology Transfer Node (TTN) named TETRApc (TEchnology TRAnsfer in Parallel Computing) aiming at identifying the aesthetic properties of dimension stones in the form of slabs or tiles, as they are evaluated by human experts who presently cluster slabs or tiles at the end of the processing chain.

In conclusion, it can be stated that quality control at the end of the processing chain of dimension stone does no longer depend on any manual sampling strategy when machine vision systems can be applied.

4

Characterisation and standards

4.1. Introduction

This chapter is divided into three main parts: the first part (paragraph 4.2) gives general information on the standardisation activities, the principles of European standardisation according to the European Committee for Standardisation (CEN); the second part (paragraph 4.3) presents the progress of the preparation of European standards in the field of Natural Stones and its reflex on the implementation of Construction Product Directive and CE marking of stone construction products; the third part (namely 4.4) correlates the existing European standards in the field of Natural Stones with the existing National standards in the CEN members countries and it also presents the list of ASTM standards on Natural Stones.

4.1.1. Presentation of standardisation activities, CEN and European standardisation

Standardisation aims to produce quality criteria for the stone market. The term “market” includes the producers, the customers, public administrators, educational institutions, testing houses and the representatives of public interest in general. The rules for the production of standards are given in guides prepared by International organisations for standardisation. These guides define the following items:

- Organisations authorized to participate to the standardisation process
- Practical ways to perform the standardisation work
- Possible content of standards.

Standardisation

The principles governing the standardisations activities are the following:

- Voluntary

- Consensus
- Public and open to everybody
- Coherence
- Current state of technology
- Primacy of International Standardisation.

The benefits of the standardisation process for the interested parties are summarised into the following:

- Simplification of the growing variety of products and procedures in human life
- Variety control and efficient use of materials, energy and human resources
- Compatibility and interchangeability of data communication
- Safety, health and protection of life and environment
- Reduction of the degree of market uncertainty
- Protection of consumers and community interests
- Elimination of trade barriers.

The role played by the entrepreneurs in the standardisation process refers mainly to the voluntary participation in standards development, observation of the standardisation formation and application of standards. In addition to that, the benefits and consequences for the enterprises are summarised into the following:

- Influence on the standards contents
- Additional information on new developments and the contents of future standards
- Access to International/European Normative documents
- Meeting competitors and other interested bodies on neutral ground.

Standards

A Standard is defined as a document established in a consensus and approved by a recognised organisation. This document applies for common and recurrent use, is based on consolidated results in science, technology and experience and aims to the promotion of optimum community benefits. The use of standards provides the basis for technological cooperation and mutual understanding, describes the technology state, indicates ways to comply with basic safety requirements and represents the basis for certification and marking. The Standards should have the following characteristics:

- Easy understandable and used
- Impartial
- Planned
- Broadly based.

The Standards aim to suit the purpose for their existence along with the following items:

- Simplification
- Compatibility (interfaces) and interchangeability (dimensional, functional)
- Health, safety (security) and protection of the environment (general interest)
- Consumers protection
- Mutual understanding and communication
- Free trade (elimination of technical trade barriers).

The Standards vary mainly according to the target application, their contents and the technical approach they propose. In addition to that, the European Standards are tools especially designed to:

- reduce uncertainty and levels of risk in the market
- meet the manufacturers needs
- harmonise common requirements
- bolster new legal measures concerning the transparency of specifications and tendering procedures for public procurement
- technically foster the interconnection and interoperability of the “Member States” national networks, transport, telecommunications, energy or even water.

4.1.2. European standardisation

The European standardisation system comprises of many partners and associates such as:

- CEN
- CENELEC (European Committee for Electrotechnical Standardisation)
- ETSI (European Telecommunications Standards Institute)
- EFTA (European Free Trade Association)

CEN is a multi-sector organisation while CENELEC and ETSI are responsible for electrotechnical and telecommunications Standards respectively. CEN, CENELEC and ETSI have coordination structures for general policy (JPG), information technology (ICTSB) and technical liaison (JCG). The European standardisation helps in the elimination of technical barriers to trade in E.U via an effective and legitimate method of self-regulation and in ensuring the competitiveness of the European industry, both within the internal market and beyond its borders.

The National members are the integral part of the European standardisation system and there are also many affiliates and organisations in liaison:

- ISO (International Organisation for Standardization)
- IEC (International Electrotechnical Organization)
- ITU (International Telecommunication Union)
- WTO (World Trade Organisation)

4.1.3. CEN organisation

CEN is an international association set up to manage the cooperation among the National standards organisations of European countries, with the objective to adopt – through consensus and transparency - standards that are voluntary. CEN is a non-profit organisation under Belgium law, founded in 1961 with legal entity since 1976. CEN’s management centre is at Brussels and it comprises over 3000 trade and professional organisations in liaison. CEN constitutes from the EU-15 National representatives, Czech Republic, Malta and the following European countries: Cyprus, Croatia, Bulgaria, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia and Turkey. CEN’s corresponding organisations are also present in Bosnia Herzegovina, Ukraine, FYROM, Egypt and Thailand. The development of the European Standards is achieved mainly through the following routes:

- Questionnaire based on a reference document (usually ISO)

- Work processed under Vienna Agreement with ISO
- Work allocated to Technical Committees (or ASBs).

In the case of the Questionnaire, the following questions are always needed to be answered:

- What do I want? (proposal)
- Can I do it? (planning, evaluation of interest, possibility of consensus, resources)
- Shall I put it on paper? (drafting)
- Does it suit to everybody? (consensus building)
- Any comments? (CEN enquiry)
- Does everybody accept that? (formal vote)
- When do I make it available? (adoption)
- Is it still valid? (review)

4.2. European Standardisation in Natural Stones field

4.2.1. The European Standardisation rules

In the context of the formation of the European internal market, a harmonisation of the different technical regulations and specifications in use in the different European countries is needed in order to remove trade barriers. The ECC Resolution of 7th May 1985 decided a new approach to this problem that is moved away from the concept of Directives that included detailed technical specifications. Instead the approach provided:

- Legislative harmonisation by means of Directives should be limited to the essential requirements, these being obligatory and formulated in general terms.
- Establishment of the technical specifications necessary for the Directives implementation should be entrusted to the voluntary Standards organisations.
- A presumption of conformity should be made with the essential requirements for products manufactured according to harmonised European standards (EN).

The organisation competent to adopt the harmonised standards technically needed to facilitate achievement of conformity to these directives is the European Committee for Standardisation (CEN). The procedures for the drafting and adoption of European Standards are as follows:

- STAGE 1: The National Members of CEN agree on the development of a set of European Standards with precise scopes, titles and target dates for completion.
- STAGE 2: A Technical Committee (TC) is created in order to prepare working drafts of this set of standards.
- STAGE 3: Once each working draft has been approved by the TC, it is proposed as a draft European Standard (pr EN) and circulated within the CEN National Members for a six-month public enquiry in order to collect possible technical comments.
- STAGE 4: A final text is then prepared by the TC, taking into account the technical comments received at the public enquiry stage.
- STAGE 5: The approval of the final text of each pr EN (in the three languages versions, namely English, French and German) is done by formal vote of the Members. If the voting result is positive the European Standard (EN) is adopted.
- STAGE 6: Once a European Standard has been adopted, Members must implement it by giving it the status of a national standard and by withdrawing any conflicting pre-existing national standards.

Stages 3 to 5 of this procedure can be substituted by the Unique Acceptance Procedure (UAP). The UAP, which aims to achieve a rapid approval of an EN, combines the CEN enquiry and formal vote in a six-month voting period. This procedure should only be applied if it is reasonable to suppose that the document is acceptable at a European level in order to prevent further delays. In case of amendments to an EN, the TC can decide to shorten the UAP to a four-months voting period. Finally, it must be reminded that in the frame of European standardisation, besides the *harmonised standards*, there are also the *supporting standards* (standards concerning test methods mentioned in harmonised standards). All other European standards are *voluntary standards*.

4.2.2. European Standardisation in the Building Sector

The Building Sector has the Directive 89/106/EEC "Construction products" (CPD) as its reference Directive. According to this Directive, construction products should be placed on the market only if they are suitable for the intended use. In addition to that, these products should satisfy the specific characteristics that the works in which they are to be incorporated, assembled, applied or installed. These characteristics refer mainly to the following items:

- Mechanical resistance and stability
- Safety in case of fire
- Hygiene, health and environmental safety
- Safety in use
- Protection against noise
- Energy economy and heat retention.

According to CPD, all construction products suitable for the intended use must bear the CE mark and be accompanied by an attestation of conformity. The Construction Products Directive indicates two main ways for the attestation of conformity:

- Certification of the product's conformity by an approved certification body (*System 1*),
- Declaration of the product's conformity by the manufacturer.

The declaration of conformity must be based on the results of initial type testing of the product and on factory production control. There are three different possibilities for the declaration of conformity, which differ mainly in the way these tasks are carried out:

- Initial type testing and factory production control carried out by the manufacturer, with certification of the system by an approved certification body (*System 2*);
- Initial type testing of the product by an approved laboratory and factory production control carried out by the manufacturer (*System 3*);
- Initial type testing and factory production control carried out by the manufacturer (*System 4*).

The characteristics to be controlled on construction products for CE marking and the system for the attestation of conformity are given in the mandates issued by the European Commission to CEN for the drafting of harmonised standards. These mandates refer to the classes of construction products for which the following two conditions apply:

- Likely to be subject to technical barriers to the trade
- Product characteristics have a direct effect on enabling the gratification of one or more essential requirements.

Each mandate concerns an end-use in the works (e.g. roof coverings, floorings, etc) and has three technical annexes. *Annex 1* is a list of the families of products under the mandate. *Annex 2* lists the products characteristics to be controlled for CE marking for each family. *Annex 3* indicates the system to be followed for the attestation of conformity. When a mandate has been issued, each CEN technical committee in charge of the standardisation of a construction product under mandate must develop harmonised standards. Each harmonised standard must define test methods and requirements for all the characteristics listed in the mandate. It must have a clause entitled “Evaluation of conformity” that specifies the procedures for initial type testing and factory production control and an Annex Z entitled “Attestation of conformity” that specifies all information which shall accompany the CE marking. The CE marking for a family of construction products will became effective only when the harmonised standards for this family are available.

4.2.3. European Standards and Draft European Standards on Stone Construction Products

Some of the CEN Technical Committees which are drafting standards for the Building sector in the framework of the CPD 89/106/EEC deal with stone products. Some indicative Standards are listed below:

- CEN TC 125 "Masonry" whose Workgroup 1 has a Task Group dealing with stone products for masonry;
- CEN TC 128 "Roof covering products for discontinuous laying" whose Sub Committee 8 deals with slate and stone products for roofing;
- CEN TC 178 "Paving units and kerbs" whose Workgroup 2 deals with stone products for paving;
- CEN TC 246 "Natural stones" in which all other stone building products (claddings, slabs for floors and stairs, modular tiles, Dimensional Stone works) are considered.

After the adoption of the first group of European Standards on stone construction products in March 1999, many other standards have been adopted during the following years. However, a part of the standardisation work done in this field is still in the form of draft European Standards at different stages of completion (either at public enquiry stage or between enquiry and vote or at vote). A brief account of the Standards and draft Standards prepared both by CEN TC 246 "Natural Stones" and by other CEN Technical Committees is given. As CEN TC 246 was structured into three Workgroups (namely WG1 “Terminology and classification”, WG2 “Test methods” and WG3 “Product specifications”) the drafts prepared by each Workgroup are separately treated.

Standards prepared by TC 246 WG1

Workgroup 1 (Terminology and classification) has prepared two draft Standards, both adopted already as European standards. The first Standard (EN 12440 "Denomination of Natural Stone") adopted in October 2000, provides the criteria for the designation of stones and establishes that the name could refer to the place of origin or to some special stone characteristics, but geographical names not related with the actual country of origin and company names shall be avoided. The Standard suggests that together with the stone name the following data should also be given:

- Petrographic name from the scientific classification obtained by petrographic examination;
- Visual appearance, particularly referring to colour range;
- Place of origin, also giving the quarry place.

The list of Natural Stones produced in Europe is an informative annex of the standard.

The second Standard (EN 12670 "Terminology of Natural Stones") adopted in December 2001 comprises of two parts:

- A glossary with definitions of petrographic and trade terms used for different stones and of main terms concerning exploitation, working, characterisation and utilisation in buildings of natural stones;
- Scientific classification of igneous, metamorphic and sedimentary rocks.

Standards and draft Standards prepared by TC 246 WG 2

The eleven Standards listed in Table 34 have already been adopted as European Standards.

Table 34. Adopted European Standards on Natural Stones test methods.

Standard Number	Description
EN 1925	Natural Stones test methods - Determination of water absorption coefficient by capillarity
EN 1926	Natural Stones test methods - Determination of compressive strength
EN 1936	Natural Stones test methods - Determination of real density, apparent density, total and open porosity
EN 12370	Natural Stones test methods - Determination of resistance to salt crystallisation
EN 12372	Natural Stones test methods - Determination of flexural strength under concentrated load
EN 12407	Natural Stones test methods – Petrographic description of Natural Stones
EN 12371	Natural Stones test methods - Determination of frost resistance
EN 13161	Natural Stones test methods - Determination of flexural strength under constant moment
EN 13364	Natural Stones test methods - Determination of breaking load at dowel hole
EN 13755	Natural Stones test methods - Determination of water absorption at atmospheric pressure
EN 14231	Natural Stones test methods - Determination of the slip resistance by means of the pendulum tester

Table 35 lists draft standards that are at formal vote stage while Table 36 lists draft standards that are between enquiry and formal vote. Finally Table 37 gives a list of draft standards that have been recently sent to CEN CMC for the enquiry.

Table 35. Draft European Standards on Natural Stones test methods at formal vote stage.

Standard Number	Description
prEN 13373	Natural Stones test methods - Determination of geometric characteristics
prEN 13919	Natural Stones test methods - Determination of resistance to ageing by SO2 action in presence of humidity
prEN 14066	Natural Stones test methods - Determination of resistance to ageing by thermal shock

Table 36. Draft European Standards on Natural Stones test methods between enquiry and formal vote.

Standard Number	Description
prEN 14146	Natural Stones test methods - Determination of dynamic elastic modulus
prEN 14147	Natural Stones test methods - Determination of resistance to ageing by salt mist
prEN 14157	Natural Stones test methods - Determination of the abrasion resistance
prEN 14158	Natural Stones test methods - Determination of rupture energy
prEN 14205	Natural Stones test methods - Determination of Knoop microhardness

Table 37. Draft European Standards on Natural Stones test methods in preparation for the enquiry.

Standard Number	Description
prENWI 24611	Natural Stones test methods - Determination of thermal linear expansion coefficient
prENWI 24612	Natural Stones test methods - Determination of sound speed propagation
prENWI 24618	Natural Stones test methods - Determination of the static elastic modulus in uniaxial compression

Draft Standards prepared by TC 246 WG 3

Workgroup 3 has submitted six draft Standards, namely the requirements for rough blocks, rough slabs and finished products, as voluntary standards to the enquiry. While the standards were revised in preparation for formal vote, European Commission issued the Mandates M 119 "Flooring" and M 121 "Wall and ceiling finishes" (obviously applicable to stone products with the corresponding end uses). The TC 246 therefore decided to change the specifications concerning products for flooring and cladding into harmonised standards while the other three standards (Table 38), concerning products not covered by the said mandates, will remain voluntary standards. The three candidate harmonised standards required the following changes and additions:

- Definition of test methods and requirements for all the characteristics listed in Annex 2 of the relevant mandate(s)
- Addition of the clause "Evaluation of conformity"

- Addition of Annex Z “Attestation of conformity” that summarises the characteristics to be controlled and the procedures to be followed for the attestation of conformity and CE marking.

The redrafted versions of these standards were thoroughly discussed and amended during the last plenary meeting of CEN TC 246 in May 2002. At the end they were unanimously approved and will presently be submitted to a four-month UAP period (due to the addition of the Annex Z they cannot be submitted to formal vote). The amended versions of the three voluntary product standards have been prepared by the Secretariat of CEN TC 246 and are submitted to an internal enquiry among TC members (deadline September 15, 2002). After that, the final versions will be submitted to the formal vote. It can be foreseen that by March 2003 both the UAP on harmonised standards and the formal vote on voluntary standards will end and that these standards will be adopted as European Standards by June 2003.

Table 38. Draft European Standards on stone products requirements.

Standard Number	Description
A. Harmonised draft standards	
prEN 1469	Natural Stones products – Slabs for cladding – Requirements
prEN 12057	Natural Stones products – Modular tiles – Requirements
prEN 12058	Natural Stones products – Slabs for floors and stairs – Requirements
B. Voluntary draft standards	
prEN 1467	Natural stone products - Rough blocks – Requirements
prEN 1468	Natural stone products - Rough slabs – Requirements
prEN 12059	Natural stone products - Dimensional stone work – Requirements

Standards and draft Standards prepared by other CEN Technical Committees

The European Standard EN 771-6/2000 “Specification for masonry units. Part 6: Natural stone masonry units” prepared by CENTC 125 has been adopted as voluntary standard in August 2000. CEN TC 128 SC8 (“Slate and stone products for roofing”) has finished its work programme comprising a two part standard (prEN 12326 “Slate and stone products for discontinuous roofing and cladding: Part 1: Product specification and Part 2: Test Methods). Part 2 is now an adopted European Standard (EN 12326-2:2000 Slate and stone products for discontinuous roofing and cladding. Part 2: Test Methods) while Part 1 is a candidate harmonised standard and will presently be submitted to UAP. The three draft standards on stone products for external paving prepared by TC 178 WG 2 have been adopted as harmonised European Standards (Table 39) in December 2001.

Table 39. European harmonised Standards on stone products for external paving adopted in December 2001

Standard Number	Description
EN 1341/2001	Slabs of Natural stones for external paving: Requirements and test methods
EN 1342/2001	Sets of Natural Stones for external paving: Requirements and test methods
EN 1343/2001	Kerbs of Natural Stones for external paving: Requirements and test methods

4.2.4. CE Marking for Stone Construction Products

In December 2001 the harmonised European Standards on stone products for external paving have been adopted. Twenty-one months after this adoption (that is in September 2003) the CE marking for these products will come in force. After that date it will not be possible to place products for external paving on the stone market without CE marking. The marking can be affixed in voluntary form a year before the coming into effect of the obligation (that is September 2002). The main tasks related to the CE marking are briefly summarised below. The system to be followed for the attestation of conformity is System 4 (declaration of conformity by the manufacturer on the basis of the results of initial type testing and factory production control both carried out by the manufacturer itself). Table 40 gives the characteristics to be controlled in the initial type testing of stone products for external paving. These characteristics are divided into two categories: essential characteristics, that is characteristics which shall accompany the CE marking, and other characteristics that are important to the trade and may also be included on the labels provided that they are separated from the CE marking characteristics.

Initial type testing shall be carried out at the first application of the corresponding standards or when a new product type is developed and whenever a significant change occurs in the raw material or the production process. On the basis of the initial type testing results for determination of the essential characteristics the manufacturer shall prepare the declaration of conformity which authorises the affixing of the CE marking. The latter will be affixed only on finished products but initial type testing can also be performed on samples taken from the raw material used to manufacture the product. For factory production control a sampling plan for the testing of finished products shall be defined and the results shall be recorded and available for inspection. Alternative test methods to the reference methods given in the corresponding standard can be used but only if the correlation of their results to the results of the reference tests is documented and available for inspection. The responsibility of the manufacturer on the declared values is clearly stated: a finished product is accepted only if the test results for any of the specimens as far as the essential characteristics are concerned, are equal or better than the declared values.

Table 40. Initial type testing of slabs, sets and kerbs for external paving: Control characteristics.

A – Essential characteristics	Test method
Flexural strength (excluding sets)	EN 12372
Compression strength (only for sets)	EN 1926
Slip/skid resistance (excluding kerbs)	EN 14231
Abrasion resistance (excluding kerbs)	prEN14157
Frost resistance	EN12371
B - Other characteristics	**Test method**
Petrographic name	EN 12407
Water absorption at atmospheric pressure	EN 13755

For the other stone construction products it is not yet possible to give so detailed information until the corresponding harmonised standards are approved. It is likely that the harmonised product standards prepared by CENTC 246 will be approved at UAP and consequently published and adopted by June 2003. Therefore, the CE marking of stone products for cladding and flooring will come in force by March 2005. In that case, the system for the attestation of conformity will be System 4. Tables 41 and 42 present the characteristics to be controlled in initial type testing of stone products for flooring and cladding respectively.

Table 41. Characteristics to be controlled in initial type testing of slabs and modular tiles for floor and stairs.

A - Essential characteristics	Test method
Petrographic name	EN 12407
Flexural strength	EN 12372 or EN13161
Slip resistance (excluding risers)	EN 14231
Frost resistance (*)	EN12371
Resistance to SO_2 actions (*)	prEN13919
Thermal shock resistance (*)	prEN14066
(*) only for external use	
B - Other characteristics	**Test method**
Visual appearance	Comparison with a reference sample
Water absorption at atmospheric pressure	EN13755
Water absorption by capillarity	EN1925
Apparent density and open porosity	EN1936
Abrasion resistance (excluding risers)	prEN14157

Table 42. Characteristics to be controlled in initial type testing of slabs and modular tiles for cladding.

A - Essential characteristics	Test method
Petrographic name	EN 12407
Flexural strength	EN 12372 or EN13161
Resistance to fixing (only for slabs to be mechanically fixed)	EN13364
Apparent density and open porosity	EN1936
Frost resistance (*)	EN12371
Resistance to SO_2 actions (*)	prEN13919
Thermal shock resistance (*)	prEN14066
(*) only for external use	
B - Other characteristics	**Test method**
Visual appearance	Comparison with a reference sample
Water absorption at atmospheric pressure	EN13755
Water absorption by capillarity	EN1925

4.2.5. Conclusions

During the last four years many European standards on stone construction products have been adopted. Most of them are voluntary or supporting standards; however, in December 2001 three more harmonised standards concerning stone products for external paving have been adopted. Many other draft standards are at UAP or formal vote stage. It can, therefore, be foreseen that by the year 2005 the CE marking of all stone construction products will come in force.

4.3. Presentation of existing standards

4.3.1. Introduction

In order to facilitate the comprehension of the existing situation the present chapter has been divided into three sections:

- *Section 4.3.2* : list of European standards studied by CEN (including their drafting status),
- *Section 4.3.3*: tables of correspondence between the European and the National standards (implementation of European standards at a National level by the National standardisation bodies). This section is sub-divided in Table 40 “Correspondence of general standards” (terminology, design, execution, etc), Table 41 “Correspondence of test methods standards” and Table 42 “Correspondence of product standards”.
    - *Section 4.3.4*: List of existing National standards (number and title in the National language(s) and in English) of some European countries and North America (ASTM Standards).

4.3.2. List of European standards studied by CEN

The list is sub-divided into three Sections: general, test methods and product standards (Table 43).

Table 43. European Standards studied by CEN

EN or prEN Number (mm/yy of publication)	Title in English	Status of drafting (original number of work item)
Section 1: General (terminology, etc.)		
12440 (Oct 2000)	Natural Stones - Denomination criteria	Published (WI 246029)
12670 (Dec 2001)	Natural Stones - Terminology	Published (WI 246004)
Section 2: Test methods		
1925 (Mar 1999)	Natural Stones test methods - Determination of water absorption coefficient by capillarity	Published (WI 246006)
1926 (Mar 1999)	Natural Stones test methods - Determination of compressive strength	Published (WI 246007)
1936 (Mar 1999)	Natural Stones test methods - Determination of real density and apparent density and of total and open porosity	Published (WI 246005)

12370 (Mar 1999)	Natural Stones test methods - Determination of resistance to salt crystallisation	Published (WI 246034)
12371 (Oct 2001)	Natural Stones test methods - Determination of frost resistance	Published (WI 246009)
12372 (Mar 1999)	Natural Stones test methods - Determination of flexural strength under concentrated load	Published (WI 246008)
12407 (May 2000)	Natural Stones test methods - Petrographic examination	Published (WI 246013)
13161 (Oct 2001)	Natural Stones test methods - Determination of flexural strength under constant moment	Published (WI 246037)
13364 (Nov 2001)	Natural Stones test methods - Determination of breaking load at dowel hole	Published (WI 246010)
13755 (Dec 2001)	Natural Stones test methods - Determination of water absorption at atmospheric pressure	Published (WI 246036)
13373	Natural Stones test methods - Determination of geometric characteristics on units	Under publication (WI 246031)
13919	Natural Stones test methods - Determination of resistance to ageing by SO_2 action in presence of humidity	Under publication (WI 246033)
14066	Natural Stones test methods - Determination of thermal shock resistance	Under publication (WI 246016)
14146	Natural Stones test methods - Determination of dynamic elastic modulus (by measuring the fundamental resonance frequency)	Under approval (WI 246035)
14147	Natural Stones test methods - Determination of resistance to ageing by salt mist	Under approval (WI 246032)
14157	Natural Stones test methods - Determination of the abrasion resistance	Under approval (WI 246014)
14158	Natural Stones test methods - Determination of rupture energy	Under approval (WI 246019)
14205	Natural Stones test methods - Determination of Knoop hardness	Under approval (WI 246015)
14231	Natural Stones test methods - Determination of the slip resistance by means of the pendulum tester (friction)	Published (WI 246017)
14581	Natural Stones test methods - Determination of thermal dilatation coefficient	Under study (WI 246011)
14579	Natural Stones test methods - Determination of sound speed propagation	Under study (WI 246012)
14580	Natural Stones test methods - Determination of static elastic modulus	Under study (WI 246018)

	Natural Stones test methods - Determination of radiation	(WI to be approved by TC 246)
Section 3: Product standards (and assimilated)		
1467	Natural Stones products – Rough blocks – Specifications	Under publication (WI 246020)
1468	Natural Stones products – Rough slabs – Specifications	Under publication (WI 246021)
1469	Natural Stones products – Slabs for cladding – Specifications	Under publication (WI 246024)
12057	Natural Stones products – Modular tiles - Specifications	Under publication (WI 246022)
12058	Natural Stones products – Slabs for floors and stairs – Specifications	Under publication (WI 246028)
12059	Natural Stones products – Dimensions stone work – Specifications	Under publication (WI 246025)
	Natural Stones products – Kitchen and vanity tops	(WI to be approved by TC 246)

4.3.3. *Tables of correspondence between European and National standards*

Table 44 presents the General standards (Terminology, Design, Execution, etc) according to EU and National level Directives.

Table 44. General Standards

National Standards	CEN TC 246 EN on terminology, denomination , etc				
	12670 Terminology	12440 Denomination	Natural Stones selection	Design	Execution
AENOR (ES)	UNE EN 12670	UNE EN 12440			
AFNOR (FR)		NF EN 12440	NF P B10-601		NF P 98-335
BSI (UK)	BSI EN 12670	BSI EN 12440			
COSMT (CZ)					
DIN (DE)	DIN EN 12670	DIN EN 12440			
DS (DK)	DS EN 12670	DS EN 12440			
ELOT (GR)					
IBN/BIN (BE)	NBN EN 12670	NBN EN 12440	B 17-001		
IPQ (PT)					
SEE (LU)					
NEN (NL)					

NSAI (IR)					
NSF (NW)	NS EN 12670 SS 3002	NS EN 12440			
ON (AT)	ON EN 12670	ON EN 12440	ON EN	ON EN	ON EN
SFS (SF)					
SIS (SW)	SS EN 12670 SS 22 10 02	SS EN 12440			
SNV (CH)					
STRI (IS)					
UNI (IT)	UNI 8458, 9379	UNI EN 12440			UNI Under publication

Table 45 lists the major test methods standards according to CEN.

Table 45. a. Test Methods Standards

	CEN TC 246 ENs					
National Standards	1925 Water absorption by capillarity	1926 Compressive strength	1936 Density and porosity	12370 Salt crystallisation	12371 Frost resistance	12372 Flexural strength concentrated
AENOR (ES)	UNE EN 1925	UNE EN 1926	UNE EN 1936	UNE EN 12370	UNE EN 12371	UNE EN 12372
AFNOR (FR)	NF EN 1925	NF EN 1926	NF EN 1936	NF EN 12370	NF EN 12371	NF EN 12372
BSI (UK)	BSI EN 1925	BSI EN 1926	BSI EN 1936	BSI EN 12370	BSI EN 12371	BSI EN 12372
COSMT (CZ)						
DIN (DE)	DIN EN 1925	DIN EN 1926	DIN EN 1936	DIN EN 12370	DIN EN 12371	DIN EN 12372
DS (DK)	DS EN 1925	DS EN 1926	DS EN 1936	DS EN 12370	DS EN 12371	DS EN 12372
ELOT (GR)		ELOT 750	ELOT 748			
IBN/BIN (BE)	NBN EN 1925	NBN EN 1926	NBN EN 1936	NBN EN 12370	NBN EN 12371	NBN EN 12372
IPQ (PT)	NP EN 1925	NP EN 1926	NP EN 1936	NP EN 12370		NP EN 12372
SEE (LU)						
NEN (NL)						
NSAI (IR)						
NSF (NW)	NS EN 1925	NS EN 1926	NS EN 1936	NS EN 12370	NS EN 12371	NS EN 12372
ON (AT)	ON EN 1925	ON EN 1926	ON EN 1936	ON EN 12370	ON EN 12371	ON EN 12372
SFS (SF)						

SIS (SW)	SS EN 1925	SS EN 1926	SS EN 1936	SS EN 12370	SS EN 12371	SS EN 12372
SNV (CH)						
STRI (IS)						
UNI (IT)	UNI EN 1925	UNI EN 1926	UNI EN 1936	UNI EN 12370	UNI EN 12371	UNI EN 12372

Table 45. b. Test Methods Standards

National Standards	CEN TC 246 ENs					
	12407 Petrographic description	13161 Flexural strength const.	13364 Dowel hole resistance	13373 Geomechanical characteristics	13755 Water absorption at atmospheric pressure	13919 SO_2 resistance
AENOR (ES)	UNE EN 12407	UNE EN	UNE EN	UNE 22170 UNE 22180	UNE EN	UNE EN
AFNOR (FR)	NF EN 12407	NF EN 13161	NF EN 13364	NF EN	NF EN 13755	NF EN
BSI (UK)	BSI EN 12407	BSI EN 13161	BSI EN 13364	BSI EN	BSI EN 13755	BSI EN
COSMT (CZ)						
DIN (DE)	DIN EN 12407	DIN EN 13161	DIN EN 13364	DIN EN	DIN EN 13755	DIN EN
DS (DK)	DS EN 12407	DS EN 1926	DS EN 13364	DS EN	DS EN 13755	DS EN
ELOT (GR)		ELOT 749				
IBN/BIN (BE)	NBN EN 12407	NBN EN 13161	NBN EN 13364	NBN EN	NBN EN 13755	NBN EN
IPQ (PT)		NP EN	NP EN	NP EN		NP EN
SEE (LU)						
NEN (NL)						
NSAI (IR)						
NSF (NW)	NS EN 12407	NS EN 13161	NS EN 13364	NS EN	NS EN 13755	NS EN
ON (AT)	ON EN 12407	ON EN 13161	ON EN 13364	ON EN13373	ON EN 13755	ON EN 13919
SFS (SF)						
SIS (SW)	SS EN 12407	SS EN 13161	SS EN 13364	SS EN	SS EN 13755	SS EN
SNV (CH)						

STRI (IS)						
UNI (IT)	UNI EN 9724-1	UNI EN	UNI EN	UNI EN	UNI EN	UNI EN

Table 45. c. Test Methods Standards.

National Standards	CEN TC 246 ENs					
	14066 Thermal shock	14146 Dynamic elastic modulus	14147 Ageing by salt mist	14157 Abrasion resistance	14158 Rupture energy	14205 Knoop hardness
AENOR (ES)	UNE EN	UNE EN	UNE EN	UNE EN	UNE 22178 UNE 22188	UNE EN
AFNOR (FR)	NF EN	NF EN	NF EN	NF EN	NF EN	NF EN
BSI (UK)	BSI EN	BSI EN	BSI EN	BSI EN	BSI EN	BSI EN
COSMT (CZ)						
DIN (DE)	DIN EN	DIN EN	DIN EN	DIN 52108	DIN EN	DIN EN
DS (DK)	DS EN	DS EN	DS EN	DS EN	DS EN	DS EN
ELOT (GR)						
IBN/BIN (BE)	NBN EN	NBN EN	NBN EN	NBN EN	NBN EN	NBN EN
IPQ (PT)	NP EN	NP EN	NP EN	NP EN	NP EN	NP EN
SEE (LU)						
NEN (NL)						
NSAI (IR)						
NSF (NW)	NS EN	NS EN	NS EN	NS EN	NS EN	NS EN
ON (AT)	ON EN 14066	ON EN 14146	ON EN 14147	ON EN 14157	ON EN 14158	ON EN 14205
SFS (SF)						
SIS (SW)	SS EN	SS EN	SS EN	SS EN	SS EN	SS EN
SNV (CH)						
STRI (IS)						
UNI (IT)	UNI EN	UNI EN	UNI EN	UNI EN	prU32.07.248	UNI 9724-6

Table 45. d. Test Methods Standards.

National Standards	CEN TC 246 and TC 178, 128/SC 8 ENs					
	14231 Slip resistance	14579 Sound speed propagation	14580 Static elastic modulus	14581 Thermal dilate. coefficient	EN tests on paving/roofing elements	Other test methods
AENOR (ES)	UNE EN	UNE EN	UNE 22177 UNE 22187	UNE EN		(1)
AFNOR (FR)	NF EN	NF EN	NF EN	NF EN		
BSI (UK)	BSI EN	BSI EN	BSI EN	BSI EN		
COSMT (CZ)						
DIN (DE)	DIN EN	DIN EN	DIN EN	DIN EN		
DS (DK)	DS EN	DS EN	DS EN	DS EN		
ELOT (GR)						
IBN/BIN (BE)	NBN EN	NBN EN	NBN EN	NBN EN	NBN EN 12326-2	
IPQ (PT)	NP EN	NP EN	NP EN	NP EN	NP EN 1324	(2)
SEE (LU)						
NEN (NL)						
NSAI (IR)						
NSF (NW)	NS EN	NS EN	NS EN	NS EN		
ON (AT)	ON EN 14231	ON EN 14579	ON EN 14580	ON EN		
SFS (SF)						
SIS (SW)	SS EN	SS EN	SS EN	SS EN		
SNV (CH)						
STRI (IS)						
UNI (IT)	UNI EN	UNI EN	UNI 9724-8	UNI EN		(3)

(1) UNE 22171, 22173, 22181, 22183, 22190-1/2/3

(2) NP 116, 311, 312, 313, 314,

(3) UNI 10813, 10859, 10921, 10922, 10923, 10925, 9724-4

Table 46. a. Standards for products.

National Standards	CEN TC 246 ENs					
	1467 Rough blocks	1468 Rough slabs	1469 Cladding	12057 Modular tiles	12058 Slabs for floor and stairs	12059 Dimensional stone work
AENOR (ES)	UNE EN	UNE EN	UNE EN	UNE EN	UNE EN	UNE EN
AFNOR (FR)	NF EN	NF EN	NF EN	NF EN	NF EN	NF EN
BSI (UK)	BSI EN	BSI EN	BSI EN	BSI EN	BSI EN	BSI EN
COSMT (CZ)						
DIN (DE)	DIN EN	DIN EN	DIN EN	DIN EN	DIN EN	DIN EN
DS (DK)	DS EN	DS EN	DS EN	DS EN	DS EN	DS EN
ELOT (GR)		ELOT EN	ELOT EN			
IBN/BIN (BE)	NBN EN	NBN EN	NBN EN	NBN EN	NBN EN	NBN EN
IPQ (PT)	NP EN	NP EN	NP EN	NP EN		NP EN
SEE (LU)						
NEN (NL)						
NSAI (IR)						
NSF (NW)	NS EN	NS EN	NS EN	NS EN	NS 3003, 3004	NS 3006
ON (AT)	ON EN 1467	ON EN 1468	ON EN 1469	ON EN 12057	ON EN 12058	ON EN 12059
SFS (SF)						
SIS (SW)	SS EN	SS EN	SS EN	SS EN	SS EN	SS EN
SNV (CH)						
STRI (IS)						
UNI (IT)	UNI EN	UNI EN	UNI EN	UNI EN	UNI EN	UNI EN

Table 46. **b**. Standards for products

National Standards	CEN TC 178 Paving, TC 125 Masonry, TC 128/SC8 Roofing					
	1341 Slabs for paving	1342 Sets for paving	1343 Kerbs for paving	771-6 Stone units for masonry	12326-1 Slates for roofing	Other product standards
AENOR (ES)	UNE EN 1341	UNE EN 1342	UNE EN 1343	UNE EN 771-6	UNE EN 12326-1	UNE EN
AFNOR (FR)	NF EN	NF EN	NF EN	NF EN	NF EN	NF EN

BSI (UK)	BSI EN 1341	BSI EN 1342	BSI EN 1343	BSI EN	BSI EN 12326-1	BSI EN
COSMT (CZ)						
DIN (DE)	DIN EN	DIN EN	DIN EN	DIN EN	DIN EN	DIN EN
DS (DK)	DS EN	DS EN	DS EN	DS EN	DS EN	DS EN
ELOT (GR)						
IBN/BIN (BE)	NBN EN	NBN EN	NBN EN	NBN EN	NBN EN	NBN EN
IPQ (PT)	NP EN	NP EN	NP EN	NP EN	NP 51	NP EN
SEE (LU)						
NEN (NL)						
NSAI (IR)						
NSF (NW)	NS EN	NS 3005	NS EN	NS EN	NS 3003, 3004	NS 3006
ON (AT)	ON EN 1341	ON EN 1342	ON EN 1343	ON EN		
SFS (SF)						
SIS (SW)	SS EN	SS EN	SS EN	SS EN	SS EN	SS EN
SNV (CH)						
STRI (IS)						
UNI (IT)	UNI EN 1341 (1)	UNI EN 1342 (1)	UNI EN 1343 (1)			(2)

(1) UNI 2712, 2713, 2714, 2715, 2716, 2717, 2718

(2) UNI 9725, 9726

4.3.4. List of existing National standards

Table 47. List of AENOR (Spanish standards UNE)

UNE Number (year of publication)	Spanish title	English title	Note
Part 1. General (terminology, etc.)			
UNE EN 12440	Piedra natural - Denomination de la piedra natural	Natural Stone - Denomination criteria	Published in Spanish
UNE EN 12670	Piedra natural - Terminología	Natural Stone - Terminology	Under publication
Part 2. Test methods			

UNE EN 1925 (1999)	Métodos de ensayo para piedra natural - Determinación del coeficiente de absorción de agua por capilaridad‡.	Natural Stone test methods - Determination of water absorption coefficient by capillarity.	Published in Spanish
UNE EN 1926 (1999)	Métodos de ensayo para piedra natural - Determinación de la resistencia a la compresión	Natural Stone test methods - Determination of compressive strength.	Published in Spanish
UNE EN 1936 (1999)	Métodos de ensayo para piedra natural.Determinación de la densidad real y aparente y de la porosidad abierta y total.	Natural Stone test method - Determination of real density and apparent density, and of total and open porosity.	Published in Spanish
UNE EN 12370 (1999)	Métodos de ensayo para piedra natural.Determinación de la resistencia a la cristalización de sales.	Natural Stone test methods - Determination of resistance to salt crystallisation.	Published in Spanish
UNE EN 12371	Piedra natural.Resistencia a las heladas	Natural Stone test methods - Frost resistance	Under publication
UNE EN 12372 (1999)	Métodos de ensayo para piedra natural - Determinación de la resistencia a la flexión bajo carga concentrada.	Natural Stone test methods - Determination of flexural strength under concentrated load.	Published in Spanish
UNE EN 12407 (2001)	Métodos de ensayo para piedra natural.Estudio petrográfico.	Natural Stone test methods - Petrographic examination	Published in Spanish
UNE EN 13161	Métodos de ensayo para piedra natural - Determinacion de la resistencia a la flexión a momento constante	Natural Stone test methods - Determination of flexural strength under constant moment	Published in Spanish
UNE EN 13364	Métodos de ensayo para piedra natural - Determinación de la carga de rotura para anclajes	Natural Stone test methods - Determination of breaking load at dowel hole	Under publication
UNE EN 13755	Metodos de ensayo para piedra natural - Determinación de la absorción de agua a presión constante	Natural Stone test methods - Determination of water absorption at atmospheric pressure	Under publication
UNE 22170 (1985)	Granitos ornamentales - Caracteristicas generales	Ornamental granites - General Characteristics	Will be EN 13373
UNE 22171	Granitos ornamentales - Tamaño de grano	Ornamental granites - Grain size	No existing EN on this subject
UNE 22173 (1985)	Granitos ornamentales - Resistencia al desgaste por rozamiento	Ornamental granites - Resistance to wear by friction	No existing EN on this subject
UNE 22174 (1985)	Granitos ornamentales - Resistencia a las heladas	Ornamental granites - Resistance to frosting	Will be EN 12371

UNE 22177 (1985)	Granitos ornamentales - Módulo elástico	Ornamental granites - Modules of elasticity	Under study EN 14580
UNE 22178 (1985)	Granitos ornamentales - .Microdureza Knoop	Ornamental Granites - Microhardness Knoop.	Will be EN 14205
UNE 22179 (1985)	Granitos ornamnetales - Resistencia al choque	Ornamental Granites - Impact strength	Will be EN 14158
UNE22183 (1985)	Mármoles y calizas ornamentales - Resistencia al desgaste por rozamiento	Ornamental marbles and limestones - Resistance to wear by friction	Will be 14157
UNE 22184 (1985)	Mármoles y calizas ornamentals - Resistencia a las heladas	Ornamental marbles and limestones - Frost resistance	Will be EN 12371
UNE 22187 (1985)	Mármoles y calizas ornamentals - Módulo elástico	Ornamental marbles and limestones - Modules of elasticity	Under study 14580
UNE 22188 (1985)	Mármoles y calizas ornamentales - Microdureza Knoop	Ornamental marbles and limestones- Microhardness Knoop	Will be EN 14205
UNE 22189 (1985)	Mármoles y calizas ornamentals - Resistencia al choque	Ornamental marbles and limestones. Impact strength	Will be EN 14158
UNE EN 12326-2	Productos de pizarra para tejados inclinados y revestimientos - Parte2.Métodos de ensayo	Slate products for discontinuous roofing and cladding - Part 2 Test Methods	Published in Spanish

Part 3. Product standards (and assimilated)

UNE 22180 (1985)	Mármoles y calizas ornamentales - Características generales	Ornamental marbles and limestones - General Characteristics	Will be EN 1467. 1468, etc
UNE 22181 (1985)	Mármoles y calizas ornamentales Clasificación	Ornamental marbles and limestones – Classification	Will be EN 1467. 1468, etc
UNE EN 1341 (2000)	Baldosas de piedra natural para uso como pavimento - Requisitos y métodos de ensayo.	Slabs of Natural Stones for external paving - Specifications	Published in Spanish
UNE EN 1342 (2000)	Adoquines de piedra natural para su uso como pavimento - Requisitos y métodos de ensayo.	Sets of Natural Stone for external paving - Requirements and test methods	Published in Spanish
UNE EN 1343 (2000)	Bordillos de piedra natural para su uso como pavimento- Requisitos y método de ensayo	Kerbs of Natural Stones for external paving - Requirements and test methods	Published in Spanish

UNE EN 771-6 (2001)	Especificación de piezas para fábrica de albañilería.- Parte 6 Piezas de piedra natural		Published in Spanish
UNE 221901 (1998)	Productos de pizarra para tejados inclinados y revestimientos - Especificaciones de producto		Will be UNE EN 12326-1

Table 48. List of AFNOR (French standards NF)

NF number (publication year)	French title	English title	Note
Part 1. General (terminology, etc.)			
NF EN 12440 (2000) (B10-623)	Pierres naturelles - Critères de dénomination	Natural Stones - Denomination criteria	Published in French
XP B10-601 (1995)	Produit de carrières – Pierres naturelles- Prescription générales d'emploi des pierres naturelles	Quarry products – Natural Stones – General criteria for the use of Natural Stones	Published in French
P98-335 (1993)	Chaussées urbaines – Mise en oeuvre des pavés et dalles en béton, des pavés de terre cuite et des pavés et dalles en pierre naturelle	Urban paving – Execution of paving with concrete or clay or Natural Stones products	Published in French
Part 2. Test methods			
NF EN 1925 (1999) (B10-613)	Méthodes d'essai pour pierres naturelles - Détermination du coefficient d'absorption d'eau par capillarité	Natural Stones test methods - Determination of water absorption coefficient by capillarity	Published in French
NF EN 1926 (1999) (B10-614)	Méthodes d'essai pour pierres naturelles - Détermination de la résistance en compression	Natural Stones test methods - Determination of compressive strength	Published in French
NF EN 1936 (1999) (B10-615)	Méthodes d'essai pour pierres naturelles - Détermination des masses volumiques réelle et apparente et des porosités ouverte et totale	Natural Stones test method - Determination of real density and apparent density, and of total and open porosity	Published in French
NF EN 12370 (1999) (B10-619)	Méthodes d'essai pour pierres naturelles - Détermination de la résistance par un essai de cristallisation des sels	Natural Stones test methods - Determination of resistance to salt crystallisation	Published in French

NF EN 12371 (2002) NB10-513 (1991)	Méthodes d'essai pour pierres naturelles - Détermination de la résistance au gel Produits de carrières – Pierre naturelles Essai de gel	Natural Stones test methods - Determination of frost resistance Quarry products – Natural Stones – Frost test	Under publication in French Published in French
NF EN 12372 (1999) (B10-621)	Méthodes d'essai pour pierres naturelles - Détermination de la résistance à la flexion sous charge centrée	Natural Stones test methods - Determination of flexural strength under concentrated load	Published in French and English
NF EN 12407 (2000) (B10-622)	Méthodes d'essai pour pierres naturelles - Examen pétrographique	Natural Stones test methods - Petrographic examination	Published in French
NF EN 13161 (2002) (B10-...)	Méthodes d'essai pour pierres naturelles - Détermination de la résistance en flexion sous moment constant	Natural Stones test methods - Determination of flexural strength under constant moment	Under publication in French
NF EN 13364 (2002)	Méthodes d'essai pour pierre naturelle - Détermination de l'effort de rupture au niveau du goujon de l'agrafe	Natural Stones test methods - Determination of the breaking load at dowel hole	Under publication in French
NF EN 13755 (2002) (B10-...)	Méthodes d'essai pour pierres naturelles - Détermination de l'absorption d'eau à la pression atmosphérique	Natural Stones test methods - Determination of water absorption at atmospheric pressure	Under publication in French

Table 49. List of BSI (English standards BS)

BSI number (publication year)	English (BSI) title	English title	Note
Part 1. General (terminology, etc.)			
BS EN 12440 (2001)	Natural Stones - Denomination criteria	Natural Stones - Denomination criteria	Adoption of EN
BS EN 12670 (2002)	Natural Stones -Terminology	Natural Stones - Terminology	Adoption of EN
Part 2. Test methods			
BS EN 1925 (1999)	Natural Stones test methods Determination of water absorption coefficient by capillarity	Natural Stones test methods-Determination of water absorption coefficient by capillarity	Adoption of EN
BS EN 1926 (1999)	Natural Stones test methods-Determination of compressive strength	Natural Stones test methods-Determination of compressive strength	Adoption of EN

BS EN 1936 (1999)	Natural Stones test methods-Determination of real and apparent density and total and open porosity	Natural Stones test methods-Determination of real and apparent density and total and open porosity	Adoption of EN
BS EN 12370 (1999)	Natural Stones test methods-Determination of resistance to salt crystallisation	Natural Stones test methods-Determination of resistance to salt crystallisation	Adoption of EN
BS EN 12371 (2002)	Natural Stones test methods-Determination of frost resistance	Natural Stones test methods-Determination of frost resistance	Adoption of EN
BS EN 12372 (1999)	Natural Stones test methods-Determination of flexural strength under concentrated load	Natural Stones test methods-Determination of flexural strength under concentrated load	Adoption of EN
BS EN 12407 (2000)	Natural Stones test methods Petrographic examination	Natural Stones test methods-Petrographic examination	Adoption of EN
BS EN 13161 (2002)	Natural Stones test methods-Determination of flexural strength under constant moment	Natural Stones test methods-Determination of flexural strength under constant moment	Adoption of EN
BS EN 13364 (2002)	Natural Stones test methods-Determination of the breaking load at dowel hole	Natural Stones test methods-Determination of the breaking load at dowel hole	Adoption of EN
BS EN 13755 (2002)	Natural Stones test methods-Determination of water absorption at atmospheric pressure	Natural Stones test methods-Determination of water absorption at atmospheric pressure	Adoption of EN
BS EN 12326-2	Slate and stone products for discontinuous roofing and cladding - Part 2: Test Methods	Slate and stone products for discontinuous roofing and cladding - Part 2: Test Methods	Adoption of EN
Part 3. Product standards			
BS EN 1341	Slabs of Natural Stone for external paving – Requirements and test methods	Slabs of Natural Stone for external paving – Requirements and test methods	Adoption of EN
BS EN 1342	Sets of Natural Stone for external paving – Requirements and test methods	Sets of Natural Stone for external paving – Requirements and test methods	Adoption of EN
BS EN 1343	Sets of Natural Stone for external paving – Requirements and test methods	Sets of Natural Stone for external paving – Requirements and test methods	Adoption of EN

Table 50. List of DIN German standards

DIN Number (publication year)	German title	English title	Note
Part 1. General (terminology, etc.)			
DIN EN 12440 (2000)	Naturstein - Kriterien für die Bezeichnung	Natural Stones - Denomination criteria	Published in German
DIN EN 12670	Naturstein - Terminologie	Natural Stones - Terminology	Published in German
Part 2. Test methods			
DIN 52102 (1988)	Prüfung von Naturstein und Gesteinskörnungen - Bestimmung von Dichte, Trockenrohdichte, Dichtigkeitsgrad und Gesamtporosität	Determination of absolute density, dry density, compactness and porosity of Natural Stones and mineral aggregates	Published in German
DIN 52104-1 (1982)	Prüfung von Naturstein - Frost-Tau-Wechsel-Versuch; Verfahren A bis Q	Testing of Natural Stones: freeze-thaw cyclic test; methods A to Q	Published in German
DIN 52104-2 (1982)	Prüfung von Naturstein; Frost-Tau-Wechsel-Versuch; Verfahren Z	Testing of Natural Stones: freeze-thaw cyclic test; method Z	Published in German
DIN 52108 (1988)	Prüfung anorganischer nichtmetallischer Werkstoffe - Verschleißprüfung mit der Schleifscheibe nach Böhme; Schleifscheiben-Verfahren	Testing the abrasive wear of inorganic non-metallic materials using the Böhme disk abrader	Published in German
DIN EN 1925 (1999)	Prüfverfahren von Naturstein - Bestimmung des Wasseraufnahme_ Koeffizienten infolge Kapillarwirkung	Natural Stones test methods - Determination of water absorption coefficient by capillarity.	Published in German
DIN EN 1926 (1999)	Prüfverfahren von Naturstein - Bestimmung der Druckfestigkeit	Natural Stones test methods - Determination of compressive strength.	Published in German
DIN EN 1936 (1999)	Prüfung von Naturstein - Bestimmung der Reindichte, der Rohdichte, der offenen Porosität und der Gesamtporosität	Natural Stones test method - Determination of real and apparent density and total and open porosity.	Published in German
DIN EN 12370 (1999)	Prüfverfahren für Naturstein - Bestimmung des Widerstandes gegen Kristallisation von Salzen	Natural Stones test methods - Determination of resistance to salt crystallisation.	Published in German

DIN EN 12371 (2002)	Prüfverfahren für Naturstein - Bestimmung des Frostwiderstandes	Natural Stones test methods - Determination of frost resistance	Published in German
DIN EN 12372 (1999)	Prüfverfahren für Naturstein - Bestimmung der Biegefestigkeit unter Mittellinienlast	Natural Stones test methods - Determination of flexural strength under concentrated load.	Published in German
DIN EN 12407 (2000)	Prüfverfahren von Naturstein - Petrographische Prüfung	Natural Stones test methods - Petrographic examination	Published in German
DIN EN 52100-2 (1990)	Naturstein und Gesteinskörnungen; Gesteinskundliche Untersuchungen; Allgemeines und Übersicht	Petrographic examination of natural stones and mineral aggregates; general	Published in German
DIN EN 13161 (2002)	Prüfverfahren für Naturstein - Bestimmung der Biegefestigkeit unter Drittellinienlast	Natural Stones test methods - Determination of flexural strength under constant moment	Published in German
DIN EN 13364 (2002)	Prüfung von Naturstein - Bestimmung der Ausbruchlast am Ankerdornloch	Natural Stones test methods - Determination of the breaking load at dowel hole	Published in German
DIN EN 13755 (2002)	Prüfverfahren für Naturstein - Bestimmung der Wasseraufnahme unter atmosphärischem Druck	Natural Stones test methods - Determination of water absorption at atmospheric pressure	Published in German

Table 51. List of ELOT (Greek standards)

ELOT number (publication year)	Greek title	English title	Note
Test methods			
ELOT 748 (1988)	Προσδιορισμός της πυκνότητας των φυσικών λίθων – Φαινόμενη πυκνότητα, απόλυτη πυκνότητα, βαθμός πυκνότητας, ολικό πορώδες	Determination of absolute density, dry bulk density, compactness and porosity	Published in Greek Translation of DIN 52102
ELOT 749 (1988)	Φυσικοί λίθοι – Δοκιμή αντοχής σε εφελκυσμό από κάμψη	Natural Stones test methods - Determination of tensile strength by bending.	Published in Greek Translation of DIN 52112
ELOT 750 (1988)	Φυσικοί λίθοι – Δοκιμή αντοχής σε θλίψη	Natural Stones test methods - Determination of compressive strength.	Published in Greek Translation of DIN 52105

Table 52. List of IBN/NBN (Belgian standards)

NBN number (publication year)	Flamish title/French title	English title	Note
Part 1. General (Terminology, etc.)			
NBN EN 12440 (2001)	Natuursteen – Benamingscriteria Pierres naturelles - Critères de dénomination	Natural Stones - Denomination criteria	Published in French and English
NBN EN 12670 (2002)	Natuursteen – Terminologie Pierre naturelle - Terminologie	Natural Stones - Terminology	Published in English
NBN B 17-001 (1999)	Natuursteen - Vorstbestendigheid: waterimpregneringsmethoden - Vorstdooicycli – Gebruikscriteria Pierres naturelles - Gélivité: imprégnations d'eau - Cycles de gel - dégel - Critères d'emploi	Natural Stones - Frost resistance: water impregnations - Freeze - thaw cycles - Criteria for use	Published in Flamish and English
Part 2. Test methods			
NBN EN 1925 (1999)	Beproevingsmethoden voor natuursteen - Bepaling van de waterabsorptiecoëfficiënt door capillaire werking Méthodes d'essai pour pierres naturelles - Détermination du coefficient d'absorption d'eau par capillarité	Natural Stones test methods - Determination of water absorption coefficient by capillarity	Published in French and English
NBN EN 1926 (1999)	Beproevingsmethoden voor natuursteen - Bepaling van de druksterkte Méthodes d'essai pour pierres naturelles - Détermination de la résistance en compression	Natural Stones test methods - Determination of compressive strength	Published in French and English
NBN EN 1936 (1999)	Beproevingsmethode voor natuursteen - Bepaling van de werkelijke dichtheid, de schijnbare dichtheid en van de totale poreusheid Méthodes d'essai pour pierres naturelles - Détermination des masses volumiques réelle et apparente et des porosités ouverte et totale	Natural Stones test method - Determination of real density and apparent density and total and open porosity	Published in French and English

NBN EN 12326-2 (2000)	Producten van lei en andere natuursteen voor overlappende dakbedekkingen en buitenmuurbekledingen - Deel 2: Beproevingsmethoden Ardoises et éléments en pierre pour toiture et bardage pour pose en discontinu - Partie 2: Méthodes d'essais	Slate and stone products for discontinuous roofing and cladding - Part 2: Methods of test	Published in French and English
NBN EN 12370 (1999)	Beproevingsmethoden voor natuursteen - Bepaling van de weerstand tegen kristallisatie van zouten Méthodes d'essai pour pierres naturelles - Détermination de la résistance par un essai de cristallisation des sels	Natural Stones test methods - Determination of resistance to salt crystallisation	Published in French and English
NBN EN 12371 (2002)	Beproevingsmethoden voor natuursteen - Bepaling van de vorstbestandheid Méthodes d'essai pour pierres naturelles - Détermination de la résistance au gel	Natural Stones test methods - Determination of frost resistance	Published in French and English
NBN EN 12372 (1999)	Beproevingsmethoden voor natuursteen - Bepaling van de buigsterkte bij geconcentreerde belasting Méthodes d'essai pour pierres naturelles - Détermination de la résistance à la flexion sous charge centrée	Natural Stones test methods - Determination of flexural strength under concentrated load	Published in French and English
NBN EN 12407 (2000)	Beproevingsmethoden voor natuursteen - Petrografisch onderzoek Méthodes d'essai pour pierres naturelles - Examen pétrographique	Natural Stones test methods - Petrographic examination	Published in French and English
NBN EN 13161 (2002)	Beproevingsmethoden voor natuursteen - Bepaling van de buigsterkte onder een constant moment Méthodes d'essai pour pierres naturelles - Détermination de la résistance en flexion sous moment constant	Natural Stones test methods - Determination of flexural strength under constant moment	Published in French and English

NBN EN 13364 (2002)	Beproevingsmethoden voor natuursteen - Bepaling van de breekkracht bij een deuvelgat Méthodes d'essai pour pierre naturelle - Détermination de l'effort de rupture au niveau du goujon de l'agrafe	Natural Stones test methods - Determination of the breaking load at dowel hole	Published in French and English
NBN EN 13755 (2002)	Proeven voor natuursteen - Bepaling van waterabsorptie bij atmosferische druk Méthodes d'essai pour pierres naturelles - Détermination de l'absorption d'eau à la pression atmosphérique	Natural Stones test methods - Determination of water absorption at atmospheric pressure	Published in French and English

Table 53. List of IPQ (Portuguese standards NP)

NP number (publication year)	Portuguese title	English title	Note
Part 2. Test methods			
NP 116 (1962)	Materiais de construção - Determinação da condutibilidade térmica pelo processo da placa quente.	Building materials - Determination of thermal conductivity by the warm-plate method.	Published in Portuguese
NP 309 (1962)	Ladrilhos - Ensaio de desgaste	Tiles - Abrasion wear test.	Withdrawn standard
NP 311 (1962)	Ardósia - Soletos - Ensaio de absorção de água.	Slate - Roofing slates - Determination of water absorption.	Published in Portuguese
NP 312 (1962)	Ardósia – Soletos - Ensaio de imersão e secagem.	Slate. Roofing slates. Immersion in water and drying test.	Published in Portuguese
NP 313 (1962)	Ardósia. Soletos - Ensaio de imersão em ácido	Slate. Roofing slates. Acid immersion test.	Published in Portuguese
NP 314 (1962)	Ardósia. Ardósia para peças resistentes. Ensaio de flexão.	Slate. Slates for load-bearing elements. Flexural strength test	Published in Portuguese
NP EN 1925 (2000)	Métodos de ensaio para pedra natural - Determinação do coeficiente de absorção de água por capilaridade.	Natural Stones test methods - Determination of water absorption coefficient by capillarity	Published in Portuguese

NP EN 1926 (2000)	Métodos de ensaio para pedra natural - Determinação da resistência à compressão	Natural Stones test methods - Determination of compressive strength	Published in Portuguese
NP EN 1936	Métodos de ensaio para pedra natural - Determinação das massas volúmicas real e aparente e das porosidades total e aberta.	Natural Stones test methods - Determination of real density and apparent density and of total and open porosity	Published in Portuguese
NP EN 12370	Métodos de ensaio para pedra natural - Determinação da resistência à cristalização de sais.	Natural Stones test methods - Determination of resistance to salt crystallisation	Published in Portuguese
NP EN 12372	Métodos de ensaio para pedra natural - Determinação da resistência à flexão sob carga centrada.	Natural Stones test methods - Determination of flexural strength under concentrated load	Published in Portuguese
Part 3 Product standards			
NP 51 (1962)	Ardósia - Soletos de ardósia para peças resistentes Classificação e características.	Slates - Roofing slates and slates for load-bearing elements - Classification and characteristics.	Published in Portuguese

Table 54. List of NSF (Norwegian standards NS)

NS number (publication year)	Norwegian title	English title	Note
Part 1. General (Terminology, etc.)			
NS 3002 (1967)	Naturstein-Terminologi	Natural Stones-Terminology	NS 3002 to be withdrawn
NS EN 12440 (2001)	Naturstein-Kriterier for betegnelse	Natural Stones-Denomination criteria	Implemented as Norwegian standard
NS EN 12670 (2002)	Naturstein-Terminologi	Natural Stones-Terminology	To be translated into Norwegian
Part 2. Test methods			
NS EN 1925 (1999)	Prøvingsmetoder for naturstein-Bestemmelse av kapillær vannabsorpsjonskoeffisient	Natural Stones test methods-Determination of water absorption coefficient by capillarity	
NS EN 1926 (1999)	Prøvingsmetoder for naturstein-Bestemmelse av trykkfasthet	Natural Stones test methods-Determination of compressive strength	

NS EN 1936 (1999)	Prøvingsmetoder for naturstein-Bestemmelse av netto- og bruttodensitet, total og åpen porøsitet	Natural Stones test methods-Determination of real density and apparent density and total and open porosity	ENs implemented as Norwegian Standards NS-EN
NS EN 12370 (1999)	Prøvingsmetoder for naturstein-Bestemmelse av motstand mot saltkrystallisasjon	Natural Stones test methods-Determination of resistance to salt crystallisation	
NS EN 12371 (2002)	Prøvingsmetoder for naturstein-Bestemmelse av frostmotstand	Natural Stones test methods-Determination of frost resistance	
NS EN 12372 (1999)	Prøvingsmetoder for naturstein-Bestemmelse av bøyefasthet ved konsentrert last	Natural stone test methods-Determination of flexural strength under concentrated load	
NS EN 12407 (2000)	Prøvingsmetoder for naturstein-Petrografisk undersøkelse	Natural stone test methods-Petrographic examination	
NS EN 13161 (2002)	Prøvingsmetoder for naturstein-Bestemmelse av bøyestrekkfasthet under constant moment	Natural stone test methods-Determination of flexural strength under constant moment	
NS EN 13364 (2002)	Prøvingsmetoder for naturstein-Bestemmelse av styrken ved forankringspunkter	Natural stone test methods-Determination of the breaking load at dowel hole	
NS EN 13755 (2002)	Prøvingsmetoder for naturstein-Bestemmelse av vannabsorpsjon ved atmosfærisk trykk	Natural stone test methods-Determination of water absorption at atmospheric pressure	
Part 3. Product standards			
NS 3003 (1967)	Naturstein-Plater og lister for gulv og terrasser	Natural Stones - Slates and lists for floors and terrace	to be withdrawn
NS 3004 (1967)	Naturstein-Trinn for utvendige trapper	Natural Stones - Steps for outdoor stairs	to be withdrawn
NS 3005 (1967)	Plater, bruddheller og gatestein av naturstein	Natural Stones - Slates, flagstones and paving stones	to be withdrawn
NS 3006 (1967)	Kantstein av naturstein	Natural Stones - Curb stones	to be withdrawn

Table 55. List of OENORM (Austrian standards ON)

ON Number (publication year)	German title	English title	Note
Part 1. General (terminology, etc.)			

ON EN 12440 (2000)	Naturstein - Kriterien für die Bezeichnung	Natural Stones - Denomination criteria	Published in German
ON EN 12670	Naturstein - Terminologie	Natural Stones - Terminology	Published in German

Part 2. Test methods

ON EN 1925 (1999)	Prüfverfahren von Naturstein - Bestimmung des Wasseraufnahme koeffizienten infolge Kapillarwirkung	Natural Stones test methods - Determination of water absorption coefficient by capillarity.	Published in German
ON EN 1926 (1999)	Prüfverfahren von Naturstein - Bestimmung der Druckfestigkeit	Natural Stones test methods - Determination of compressive strength.	Published in German
ON EN 1936 (1999)	Prüfung von Naturstein - Bestimmung der Reindichte, der Rohdichte, der offenen Porosität und der Gesamtporosität	Natural Stones test method - Determination of real density and apparent density, and of total and open porosity.	Published in German
ON EN 12370 (1999)	Prüfverfahren für Naturstein - Bestimmung des Widerstandes gegen Kristallisation von Salzen	Natural Stones test methods - Determination of resistance to salt crystallisation.	Published in German
ON EN 12371 (2002)	Prüfverfahren für Naturstein - Bestimmung des Frostwiderstandes	Natural Stones test methods - Determination of frost resistance	Published in German
ON EN 12372 (1999)	Prüfverfahren für Naturstein - Bestimmung der Biegefestigkeit unter Mittellinienlast	Natural Stones test methods - Determination of flexural strength under concentrated load.	Published in German
ON EN 12407 (2000)	Prüfverfahren von Naturstein - Petrographische Prüfung	Natural Stones test methods - Petrographic examination	Published in German
ON EN 13161 (2002)	Prüfverfahren für Naturstein - Bestimmung der Biegefestigkeit unter Drittellinienlast	Natural Stones test methods - Determination of flexural strength under constant moment	Published in German
ON EN 13364 (2002)	Prüfung von Naturstein - Bestimmung der Ausbruchlast am Ankerdornloch	Natural Stones test methods - Determination of the breaking load at dowel hole	Published in German
ON EN 13755 (2002)	Prüfverfahren für Naturstein - Bestimmung der Wasseraufnahme unter atmosphärischem Druck	Natural Stones test methods - Determination of water absorption at atmospheric pressure	Published in German

Part 3. Product standards

ON EN 1467		Natural Stone products – Rough blocks – Requirements	
ON EN 1468		Natural Stone products – Rough slabs – Requirements	
ON EN 1469		Natural Stone products – Slabs for cladding – Requirements	

ON EN 12057		Natural Stone products – Modular tiles – Requirements
ON EN 12058		Natural Stone products – Slabs for floors and stairs – Requirements
ON EN 12059		Natural Stone products – Dimensional stone work – Requirements
ON EN 1341	Platten aus Naturstein fur Aussenbereiche – Anforderungen und Prufverfaren	Slabs of Natural Stone for external paving – Requirements and test methods
ON EN 1342	Pflastersteine aus Naturstein fur Aussenbereiche – Anfordwerungen und Prufverfaren	Sets of Natural Stone for external paving – Requirements and test methods
ON EN 1343	Bordsteine aus Naturstein fur Ausserbereiche – Anforderungen und Prufverfaren	Sets of Natural Stone for external paving – Requirements and test methods

Table 56. List of SIS (Swedish standards SS)

SS number (publication year)	Swedish title	English title	Note
Part 1. General (Terminology, etc.)			
SS EN 12440 (2001)	Natursten – Benämning	Natural Stones-Denomination criteria	Adoption of EN
SS EN 12670 (2002)	Natursten - Terminologi	Natural Stones-Terminology	Adoption of EN
SS 22 10 02 (1984)	Nutursten for byggnader – Terminologi, toleranser och ytbehanding	Natural Stones for buildings – Terminology, tolerances and surface finishing	
Part 2. Test methods			
SS EN 1925 (1999)	Natursten – Bestämning av vattenabsorptionstal via kapillaritet	Natural Stones test methods- Determination of water absorption coefficient by capillarity	Adoption of EN
SS EN 1926 (1999)	Natursten – Bestämning av tryckhållfasthet	Natural Stones test methods- Determination of compressive strength	Adoption of EN
SS EN 1936 (1999)	Natursten – Bestämning av densitet och porositet	Natural Stones test methods- Determination of real density and apparent density and total and open porosity	Adoption of EN

SS EN 12370 (1999)	Natursten – Bestämning av inverkan av salkristallisering	Natural Stones test methods- Determination of resistance to salt crystallisation	Adoption of EN
SS EN 12371 (2002)	Provningsmetoder för natursten – Bestämning av frostmotstånd	Natural Stones test methods- Determination of frost resistance	Adoption of EN
SS EN 12372 (1999)	Natursten – Bestämning av böjhållfasthet vid trepunktsbelastning	Natural Stones test methods- Determination of flexural strength under concentrated load	Adoption of EN
SS EN 12407 (2000)	Natursten – Petrografisk undersökning	Natural Stones test methods- Petrographic examination	Adoption of EN
SS EN 13161 (2002)	Provningsmetoder för natursten – Bestämning av böjdraghållfasthet med fyrpunktsbelastning	Natural Stones test methods- Determination of flexural strength under constant moment	Adoption of EN
SS EN 13364 (2002)	Provningsmetoder för natursten – Bestämning av utspjälkningshållfasthet vid dubbhål	Natural Stones test methods- Determination of the breaking load at dowel hole	Adoption of EN
SS EN 13755 (2002)	Provningsmetoder för natursten – Bestämning av vattenabsorption vid atmosfärtryck	Natural Stones test methods- Determination of water absorption at atmospheric pressure	Adoption of EN
Part 3. Product standards			
SS 83 34 11 (1982)	Fönsterbänkar av natursten	Window shelves of Natural Stones	

Table 57. List of UNI (Italian standards UNI)

UNI Number (publication year)	Italian title	English title	Note
Part 1. General (Terminology, etc.)			
UNI 8458 (1983)	Edilizia. Prodotti lapidei. Terminologia e classificazione	Building. Natural building stones. Terminology and classification	
UNI 9379 (1989)	Edilizia. Pavimenti lapidei. Terminologia e classificazione..	Building. Stone elements for flooring. Terminology and classification.	
UNI EN 12440	Pietre naturali - Criteri di denominazione	Natural Stones – Denomination criteria	Under publication in Italian
UNI EN 12670	Pietre naturali- Terminologuia	Natural Stones – Terminology	Under publication in Italian

UNI …	Esecuzione delle pareti ventilate	Execution of ventilated facades	Under publication

Part 2. Test methods

Draft U3207.248 (1994)	Materiali lapidei. Determinazione della resistenza all'urto.	Natural Stones. Determination of the impact resistance.	Published as draft standards, will be EN 14148
UNI EN 1925 (2000)	Metodi di prova per pietre naturali - Determinazione del coefficiente di assorbimento d'acqua per capillarità.	Natural Stones test methods - Determination of water absorption coefficient by capillarity.	Published in Italian
UNI EN 1926 (2000)	Metodi di prova per pietre naturali - Determinazione della resistenza a compressione.	Natural Stones test methods - Determination of compressive strength.	Published in Italian
UNI EN 1936 (2001)	Metodi di prova per pietre naturali - Determinazione delle masse volumiche reale e apparente e della porosità totale aperta.	Natural Stones test method - Determination of real density and apparent density and total and open porosity.	Published in Italian
UNI EN 12370 (2001)	Metodi di prova per pietre naturali - Determinazione della resistenza alla cristallizzazione dei sali.	Natural Stones test methods - Determination of resistance to salt crystallisation.	Published in Italian
UNI EN 12372 (2001)	Metodi di prova per pietre naturali - Determinazione della resistenza a flessione sotto carico concentrato.	Natural Stones test methods - Determination of flexural strength under concentrated load.	Published in Italian
EN 12407 (2001)	Metodi di prova per pietre naturali - Esame petrografico.	Natural Stones test methods - Petrographic examination	Published in Italian
UNI 9724-2 (1990)	Materiali lapidei - Determinazione della massa volumica apparente e del coefficiente di imbibizione.	Stone materials - Determination of the volume mass and adsorption coefficient.	Published in Italian, see also EN 1936
UNI 9724-4 (1990)	Materiali lapidei - Confezionamento sezioni sottili e lucide.	Stone materials - Preparation of thin and polished sections.	No existing EN on this matter
UNI 9724-6 (1990)	Materiali lapidei - Determinazione della microdurezza Knoop.	Stone materials - Determination of the Knoop microhardness	Will be EN 14205
UN I 9724-8 (1990)	Materiali lapidei. Determinazione del modulo elastico semplice (monoassiale).	Stone materials - Determination of the elastic modulus (monoaxial).	Will be EN WI 018

UNI 10813 (1999)	Beni culturali - Materiali lapidei naturali ed artificiali - Verifica della presenza di microrganismi fotosintetici su materiali lapidei mediante determinazione spettrofotometrica UV/Vis delle clorofille a, b e c.	Cultural heritage - Natural and artificial stones - Check the presence of photoautotrophic micro-organisms on stone materials by UV/Vis spectrophotometric determination of chlorophyll a, b e c.	No existing EN on this matter
UNI 10859 (2000)	Beni culturali - Materiali lapidei naturali ed artificiali - Determinazione dell'assorbimento d'acqua per capillarità..	Cultural heritage - Natural and artificial stones - Determination of water absorption by capillarity.	No existing EN on this matter
UNI 10921 (2001)	Beni culturali - Materiali lapidei naturali ed artificiali - Prodotti idrorepellenti - Applicazione su provini e determinazione in laboratorio delle loro caratteristiche.	Cultural heritage - Natural and artificial stones - Water repellents - Application on samples and determination of their properties in laboratory.	No existing EN on this matter
UNI 10922 (2001)	Beni culturali - Materiali lapidei naturali ed artificiali - Allestimento di sezioni sottili e sezioni lucide di materiali lapidei colonizzati da biodeteriogeni.	Cultural heritage - Natural and artificial stones - Preparation of thin and polished sections of stone colonised by biodeteriogens	No existing EN on this matter
UNI 10923 (2001)	Beni culturali - Materiali lapidei naturali ed artificiali - Allestimento di preparati biologici per l'osservazione al microscopio ottico.	Cultural heritage - Natural and artificial stones - Preparation of biological specimens for the observation by light microscopy	No existing EN on this matter
UNI 10925 (2001)	Beni culturali - Materiali lapidei naturali ed artificiali - Metodologia per l'irraggiamento con luce solare artificiale.	Cultural heritage - Natural and artificial stones - Method for artificial solar light test.	No existing EN on this matter

Part 3. Product standards

UNI EN 1341 (2002)	Lastre di pietra naturale per pavimentazioni esterne - Requisiti e metodi di prova.	Slabs of Natural Stones for external paving - Specification.	Published in Italian
UNI EN 1342 (2002)	Cubetti di pietra naturale per pavimentazioni esterne - Requisiti e metodi di prova.	Sets of Natural Stones for external paving - Requirements and test methods	Published in Italian
UNI EN 1343 (2002)	Cordoli di pietra naturale per pavimentazioni esterne - Requisiti e metodi di prova.	Kerbs of Natural Stones for external paving - Requirements and test methods.	Published in Italian
UNI 2712 (1945)	Manufatti lapidei stradali. Cordoni di pietra.	Stone road construction materials. Stone kerbs.	
UNI 2713 (1945)	Manufatti lapidei stradali - Bocchette di scarico, di pietra..	Stone road construction materials. Stone drain holes.	

UNI 2714 (1945)	Manufatti lapidei stradali. Risvolti di pietra, per ingressi carrai.	Stone road construction materials. Stone kerbs for passageways for vehicles.	
UNI 2715 (1945)	Manufatti lapidei stradali. Guide di risvolto, di pietra, per ingressi carrai.	Stone road construction materials. Stone kerb guides for passageways for vehicles.	
UNI 2716 (1945)	Manufatti lapidei stradali - Scivolo di pietra, per ingressi carrai.	Stone road construction materials - Stone ramps for passageways for vehicles.	
UNI 2717 (1945)	Manufatti lapidei stradali. Guide di pietra.	Stone road construction materials - Stone guides.	
UNI 2718 (1945)	Manufatti lapidei stradali - Masselli di pietra, per pavimentazione.	Stone road construction materials. Paving stones	Will be withdrawn
UNI 4692 (1961)	Edifici scolastici - Manufatti di marmo per servizi igienici.	School buildings - Marble items for lavatories.	
UNI 9725 (1990)	Prodotti lapidei - Criteri di accettazione.	Natural Stones - Acceptance criteria	
UNI 9726 (1990)	Prodotti lapidei (grezzi e lavorati) - Criteri per l' informazione tecnica.	Natural Stones (raw and worked products) - Criteria for technical information.	

Table 58. List of ASTM (North America standards)

ASTM number (publication year)	ASTM title	Note
Part 1. General (Terminology, etc.)		
ASTM C119-01 (2001)	Terminology relating to Dimensional Stone	
ASTM C 1242-00 (2002)	Guide for design, selection and installation of stone anchors and anchoring systems	
ASTM C1496-01 (2001)	Guide for assessment and maintenance of exterior Dimensional Stone masonry wall and facades	
Part 2. Test methods		
ASTM C97-96e1	Test methods for absorption and bulk specific gravity of Dimensional Stones	
ASTM C99-87 (conf. 2000)	Test method for modulus rupture of Dimensional Stones	
ASTM C120-00 (2000)	Test methods of flexure testing of slate (modulus of rupture, modulus of elasticity)	

C1352-96 (1996)	Test method for flexural modulus of elasticity of Dimensional Stones
ASTM C121-90 (conf. 1999)	Test method for water absorption of slate
ASTM C170-90 (conf. 1999)	Test method for compressive strength of Dimensional Stones
ASTM C217-94 (conf. 1999)	Test method for weather resistance of slate
ASTM C241-90 (conf. 1997)	Test method for abrasion resistance of stone subjected to foot traffic
ASTM C880-98 (1998)	Test method for flexural strength of Dimensional Stones
ASTM C1201-91 (conf. 1996)	Test method for structural performance of exterior Dimensional Stones cladding system by uniform static air pressure difference
ASTM C1353-98 (1998)	Test method using the Taber abraser for abrasion resistance of Dimensional Stones subjected to foot traffic
ASTM C1354-96 (1996)	Test method for strength of individual stone anchorages in Dimensional Stones

Part 3. Product standards

ASTM C406-00 (2000)	Specification for roofing slate
ASTM C503-99e1 (1999)	Specification for marble Dimensional Stones (exterior)
ASTM C568-99 (1999)	Specification for limestone Dimensional Stones
ASTM C615-99 (1999)	Specification for granite Dimensional Stones
ASTM C616-99 (1999)	Specification for quartz-based Dimensional Stones
ASTM C629-99 (1999)	Specification for slate Dimensional Stones

5

Durability: a characterisation challenge for the optimisation of stone applications

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5.1. Introduction and definition

The purpose of this chapter is to discuss various durability aspects of natural stones, e.g. how to define durability and which properties should be examined for different applications. Which are the needs for improvement?

Durability is often considered as the resistance of building stones towards climatic variations, like weathering, mechanical stresses and frost action. However, such a definition will only cover a part of the entire durability concept.

"Durability of a building, assembly, component, product or construction, in general, is its capability to maintain its intended serviceability over at least a specified time".

Defined in this way, durability can not be seen as something absolute. Instead, it is more appropriate to consider it as the time period during which the required operations will not fall below certain prescribed limits. Durability is thus closely connected to "Service life" or "Performance over lifetime"

Similar to other building, and civil engineering materials/products/constructions, the real challenge is to achieve a reasonable product quality, a quality that corresponds to the needs and specifications. The first step towards this goal is to develop guidelines on how to characterize stone properties for each application. Different set-ups of properties are important for each application. What and how to test and how to interpret the results and combine experience with laboratory testing?

One major obstacle towards this goal is the lack of a lot of documented experience from the performance of existing buildings. Such references are generally the best for the preparation of relevant specifications for different applications in different climates and thus expanding the market of a stone type. There is also a lack of correlation analysis between field performance, exposure sites and laboratory test (e.g. accelerated ageing test). Such experience is crucial in order to be able to assess test results and give guidance for specific stone types.

This chapter focuses on finished products and elaborates durability aspects within the areas of properties physical, aesthetical and biological properties. It can always be argued that many more properties should be taken into account or a different division should be made. However, the importance of this chapter is to give an overview of the current situation and to form a basis for a discussion on how to characterise and evaluate stone durability/performance in the future in a cost efficient way. Various durability problems will be exemplified in the following text. Durability properties will be described in the following, along with the present means of characterisation linked to durability, the common practice today and the identification of possible need for improvement.

5.2. Durability against freeze-thaw action (including salt)

Freeze-thaw resistance is certainly the most important issue to consider when specifying stone for external use. If frost damage occurs, it is so destructive that the affected stone elements are generally smashed to pieces, threatening the service life of the whole building (Figures 125, 126). Unfortunately, freeze-thaw resistance is also one of the most difficult stone properties to evaluate. In fact, freezing in a porous material, like natural stone, is a complex phenomenon, which is not yet fully understood and there is certainly a need for additional research in this area. It includes several various mechanisms that sometimes interact with each other.

Figure 125. Quoin units in masonry destroyed by frost action

In very general terms, the factors which will determine if a stone element exposed to frost will be damaged or not can be classified as follows:

- climate
- minimal temperature
- rate of freezing
- rainfall level
- position of the stone in the building
- behaviour of stone towards frost action, being for the most part determined by
- porosity related properties
- mechanical properties

In the past, it was only through experience that durability against the freeze-thaw action could be evaluated. Nowadays, experience is still a valuable tool, but used rarely, since this information is scarcely available. For example, there is no long-term experience concerning the behaviour of all imported stones from countries outside Europe in the various European climates. Consequently, laboratory tests are more preferable.

Many efforts have been made worldwide in the development of laboratory tests capable of predicting the in-situ behavior of porous building materials exposed to freeze-thaw conditions. But so far, none of the many tests proposed and even standardised can be considered as fully reliable. Some reasons for this could be the following:

- It has been shown in the literature that at least three different mechanisms could induce stresses in the pore structure of a material while freezing. In function with the climatic conditions, type of material and position of the material in the building, one or more of these mechanisms can be generated. That is why a universal test method applicable for every material in every position under every climate cannot exist. Specific situations have to be taken into account.

- The different direct freeze-thaw tests can be distinguished as either omni-directional or unidirectional, depending on the fact that all the faces or only one face of the tested samples are submitted to cooling. Applying the same cycles to the same samples saturated in the same way will give completely different results between omni- and unidirectional freezing. For natural stone, some national standards, as in France, use the omni-directional freezing, while other countries, like Belgium, prefer the unidirectional method.

- Besides the way of freezing, the success of a test method depends on the method used to impregnate specimens with water. Here also, some big differences do exist between several countries: immersion in water (France, Germany), impregnation under vacuum (Belgium). In reality, the degree of water saturation of a product depends on the water supply and the drying conditions it encounters (i.e. the climate and the position of the product in the building) and on the water absorption and drying properties of the product itself (i.e. porosity and permeability related properties).

- The climate to be simulated in a freeze-thaw test can be derived from climatic data describing the nature and occurrence of raining periods and temperature oscillations around the freezing point. But not only the level to which the temperature drops down but also the speed at which it falls, is important. Moreover, the duration of temperature below zero is important. Finally, depending on the heat behind the exposed face of a product, the ice front may penetrate either only to a certain depth or throughout the entire material. It is also possible that thawing occurs to some depth after renewed freezing has occurred. In this situation, the liquid water in the pores of the zone in between may come under high pressure and this can lead to splintering. Some test methods take this phenomenon into account, others do not.

Besides these observations, which are common to any building material, the following difficulties have to be overcome in the particular case of natural stone:

- "natural stone" is a generic denomination gathering a large number of materials with a very broad variation of characteristics. Developing one frost test suitable for all types must take this into account. For example, the method for water impregnation must be suitable for granites with a very low porosity as well as for very porous limestone.
- unlike manufactured materials, which are designed for one specific use, natural stone has many applications in a building and one type of stone can be suitable for several of them. Consequently, a frost test for natural stone must have one or more varying parameter (impregnation level and/or number of cycles) to allow the simulation of the different stresses on the material in function of its use.

Figure 126. Pedestal of a statue cracked by the frost

Figure 127. Beginning of scaling on a flooring slab after one winter

For a given climate, a classification for the intensity of the frost action on the different external parts of a building can be the following (from the highest to the lowest):

- paving and floorings
- elements in direct contact with the floor (base courses, plinths, etc.)
- non vertical parts in elevation and all elements sticking out of the facade (cornices, mouldings, windowsills, etc.)
- solid masonry units (not ventilated wall, that is with no possibility of drying from the back-face of the stone units)
- wall cladding units or cavity wall units with ventilation allowing the drying from the inner face.

Nevertheless, there exist many different laboratory test methods, standardised or not, which give, with a variable level of reliability, an estimation of the frost resistance of natural stone elements for external applications.

These tests can be grouped in three categories:

- freeze/thaw tests (or direct tests)
- crystallisation tests
- tests which evaluate other characteristics of the stone, upon which the frost resistance is dependant

5.2.1. The freeze/thaw tests (direct tests)

Freeze/thaw tests are certainly the most used tests among the other categories. Their principle is to monitor the stone performance in conditions which simulate the causes of decay, i.e. the succession of freeze/thaw cycles. Usually, these frost tests involve the following operations:

- impregnating the specimen with water:
  - by soaking them during a fixed period of time
  - by capillary absorption
  - under atmospheric depression (vacuum)
- subjecting them to cycles of freezing in air and thawing in water (or in air)
- characterising damages:
  - visually
  - by measuring the loss of mass
  - by measuring the changes in mechanical strength (generally flexural strength)
  - by measuring the changes in sound speed propagation or resonance frequency

By varying preliminary water impregnation level or the number of cycles, these tests can simulate different degrees of severity of frost action. They can also be related to different levels of stress induced to stone by freezing and thawing and in relation to the type of application in the building.

Regarding the great number of different test methods of this kind, there is an urgent need to harmonize at European level a direct frost test for natural stone and to develop the related guidelines for product specifications.

Figure 128. samples in a frost chamber

Figure 129. increasing damages on specimens of the same type of stone after the same number of freeze-thaw cycles but with increasing impregnation rates

5.2.2. The crystallisation tests

The mechanical action of the crystallisation process exerts pressure on the pores of the material which is similar to the one generated by the formation and growing of the ice, during freezing. This is the reason why the crystallisation tests have been developed and used since many years to assess the frost durability of building materials in general, and particularly ornamental natural stones and aggregates for concrete. For example, this method is standardised and often used in United Kingdom for the evaluation of the durability of limestone, instead of the freeze-thaw cycles.

The principle involves subjecting samples to cycles of soaking in salt solution and drying. The result is usually expressed as a weight loss of the samples after a certain number of cycles. Some studies [1] have shown that the severity of the test was increased by the following factors:

- an increase in the solution concentration
- a decrease in the soaking temperature
- an increase in the drying rate

By varying one or more of these factors, the severity of the test can be adapted to the expected use of the stone.

5.2.3. Tests which evaluate the characteristics of the stone on which the frost resistance is dependant

As it was mentioned before, the frost resistance of a porous material is mainly governed by properties related to porosity: open porosity, pore size distribution, mean pore diameter, pore connectivity, etc.

For example, it is well known that the presence of big and non-capillary pores in the porosity of a material will prevent excessive stresses from appearing during the formation and growing of ice in the freezing material. This is why natural stone with a very low capillary saturation rate are generally very frost resistant.

Based on these observations, some criteria have been proposed to assess the frost resistance, only by measuring one or more of specific pore properties, like the proportion of small pores or the mean pore diameter. This kind of information can also be deduced from capillary absorption tests, and particularly from the determination of the saturation coefficient, i.e. the amount of pore space that will be filled by soaking in water for a given period of time, expressed as a percentage of the total pore space. Similar to this characteristic is the Hirschwald coefficient or the GC-factor.

In spite of the very detailed and scientific approach, one can say that until now, these methods have not been widely used yet in the case of natural stones and that their standardisation at European level is not to be expected in near future.

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[1] Price C. A. “The use of the sodium sulphate crystallisation test for determining the weathering resistance of untreated stone”, in Proc. of the RILEM/UNESCO Symposium, Paris, 1978.

5.3. Durability against mechanical stresses

The mechanical stresses can, in general terms, be divided into natural and human induced stresses.

5.3.1. Natural induced stresses

Natural induced stresses can be wind loads, the weight of the stone element itself or the impact from flying objects. One durability characteristic is the resistance against wind load, which scarcely is tested directly but often assessed indirectly by flexural strength or break load at dowel holes tests. These tests reflect the maximum static load before cracking. However, this is not the case when a true wind load is acting on facade cladding in a dynamic way and on the entire area of the stone.

In many places in Europe, the resistance against wind load is simulated in the laboratory as a direct loading on a façade clad. In contrast to testing of compressive and flexural strength, the force is applied on a much larger area of the test specimen, thus simulating the wind. The load is static. The resistance against flying objects can be assessed the same way as described below for hard body impact. Regardless of the variability of tests, the property of interest is tested on new and dry samples. The durability aspect is therefore not assessed throughout the service life of the finished product. There is a need to complement the existing standards with such testing procedures and information.

5.3.2. Human induced mechanical stresses

Human induced mechanical stresses can shortly be described as the abrasive action on flooring and paving stone units, when people walk on the stone, drive or in any other way wear the stone surface. The static and dynamic forces acting upon the stones when hard items fall on them or when a load is applied on them is also included in this durability group. The three most common cases of durability aspects are discussed. Durability/resistance against abrasion can be measured in many ways. The two predominant test methods are the Böhme and the Wide wheel (which is presented in page 95).

The Böhme test is principally a test where a stone plate is abraded on a rotating disc, with a define load and a defined abrasive (Figure 131). The durability is principally evaluated as the decrease in thickness/volume. This test has a long tradition and several other abrasion tests correlate very well with it. Almost all references of abrasion durability results sited in catalogues etc can be correlated with the Böhme test. The Wide Wheel (also called modified Capon test) is principally a test where a stone plate is mounted vertically forced, by a counterweight, towards a rotating wheel (7 cm wide) and mainly abraded by the action of an abrasive flowing down in the slot between the test specimen and the wheel. The durability is evaluated as the width of the abrade groove into the stone.

Regardless of the test result and the different ways of interpreting them, there is also a need for assessing the esthetical aspects. However, this is not included in the standards. Despite the same abrasion value, different stones can look extremely different when directly in use. Some stone types get dirty very quickly. Others abrade in an even rate but look very nice meanwhile. The needs regarding this durability aspect is thus to achieve complementary information on esthetical aspects during abrasion tests.

The durability/resistance against different loads acting upon a stone tile, paving unit or similar is normally measured by testing the flexural strength and, in cases, also the compressive strength. These tests are straightforward and have mainly proven satisfactory, especially so the flexural strength.

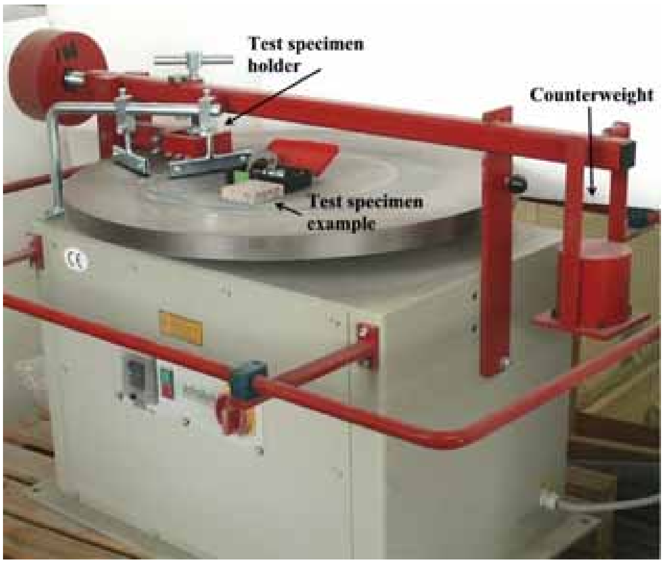


Figure 130. Böhme abrasion test device

Figure 131. Test rig for break load at dowel hole

The major drawback is that stones in real use are often wet though all tests are done on dry samples. The correlation between wet and dry strength depends on many things and no simple correlation coefficient can be defined to fit all stone types. Another major draw back is that some stone types, e.g. marble and limestone loose strength when dried during the conditioning phase before the actual testing.

Finally, these tests do not tell much about the dynamic stability of the stones. This is, in fact, more related to durability, e.g. long-term dynamic loading. The need regarding strength and durability against long-term loading is to develop the existing standard methods so they can take into account the wet/moist strength, dynamic loading and also evaluate the conditioning effects on different stone types.

The durability/resistance against hard body impact is a property that is not frequently tested. The reason for this is not clear since it is fairly obvious that many paving units and flooring tiles are partly or totally broken for some reason. It is also an important property to evaluate for lower parts of a façade where, many objects such as bicycles, bottles, stones during demonstrations etc. can fall onto and/or hit the stone claddings.

There are many uncertainties associated with testing of the resistance against impact. Concerning flooring and paving units the substrate plays an essential role for the possibility to resist impact without cracking. It can also be discussed what type of impact body the test should specify. There is a need to develop a link between testing of the durability/resistance against hard body impact and the possibility to assess the results and dimension the building component thereafter.

5.4. Durability against changes of the surface appearance

Rock weathering consists of a number of processes. Knowledge of the weathering state of buildings and of the properties of stones caused by weathering is the basis for the explanation of the complex weathering process and causes of damage and therefore important for planning and execution of either restoration concepts or prevention of damage.

Pollution: The literature includes many papers on causes of stone damage (Amoroso and Fassina, 1983). However, recent research has been dominated by three topics: air pollution, salts and bio-caused deterioration. Most research has focused on the traditional pollutants: sulphur oxides, nitrogen oxides, and carbon dioxide. All of them are soluble in water giving an acidic solution, which casts them capable of reacting with calcareous materials such as limestone, marble, calcareous matrix and lime mortar. The effect of acidic pollutants on stone material depends on the immediate environment of the stone.

Air pollution is the major source of the soluble salts: sulphates and nitrates. Other sources include soil salts, which may be carried into masonry by rising damp; salts blown by the sea or desert wind; de-icing salt etc. The growth of salt crystals within the pores of stone can generate stresses that are sufficient to overcome the stone's tensile strength and cause damage. The deterioration of many of the world's monuments can be attributed to salts. Salt damage includes two mechanisms: the crystallisation of salt from a solution, and the hydration of salt (re-crystallization). Any salt is capable of causing crystallisation damage, whereas hydration damage can be caused only by salts that can exist in more than one hydration state. Sodium chloride is only capable of crystallisation damage, while sodium sulphate (which can exist as either the anhydrous salt thenardite Na_2SO_4 or decahydrate mirabilite $Na_2SO_4 \cdot 10H_2O$) can cause both crystallisation damage and hydration damage. Salt damage also occurs in indoors environments due to hygroscopic action of the salts.

Surface treatments:
Over the past 20 years surface treatments have become increasingly used in order to alleviate damage due to chemical and physical impact on the stone material. The main reasons for the application of water repellents are found to be:

- enhancement of maintenance of appearance: colour, texture, reflectance and resistance to graffiti, mould growth and staining
- prevention of direct deterioration due to chemical and physical effects, e.g. acid attack (to prevent decay due to wet deposition), erosion/abrasion, soiling, salt crystallisation and freeze-thaw damage
- prevention of biological degradation.
- limitation of contact with or ingress of water, liquids (wine, coffee, oil, etc) and gases. Waterproofing (prevent wet spots, keep the structure dry and limit heat losses), damp proofing, methane/radon/isotope barriers, floor protection.
- Improvements in safety, e.g. anti-slip/skid, road/floor markings and anti-static treatments.

The main reason for treatment with water repellent is to prevent the penetration of water and the assessment of the method performance should also include:

- resistance against the attack of pollutants
- resistance against the biological growth
- damage occurring after treatment and the relation between treatment and damage. It should be stressed that effectiveness of a treatment should be controlled on the "system" (e.g. impregnated clinker on heated floor, coated facades with/without isolation, sun/ shadow impact on the stone material).

The effectiveness of treatment with water repellent can last for more than 30 years. However, they may be considerable differences in effectiveness within one building depending on e.g. macro- and micro-climatic differences, material in-homogeneities or its different performance/shape/finishing and last but not least choice of water repellent and failure in application of the impregnation material. Not well-performed treatment may lead to high moisture content behind the surface and cause splintering due to frost damage.

Stone surface finishing has not yet been investigated. It may influence the tendency to absorb water and to be affected by pollutants. The most common types; polished (e.g. may be effective against water retention or dust but could be more prone to acidic attack which results in much more visible discoloration/spot or stain), ground, polished, flamed, bush hammered are mostly chosen due to the aesthetical point of view. It should be pointed out that neither surface treatment nor surface finishing prevent dry deposition of pollutants on the stone material. In cases of porous materials it should be combined with consolidation often a water-based polymer that penetrates deep into the porous stone decreasing permeability but allowing "breathing". However, the modification of the pore structures by applied protective agents should be analysed in more detail.

Laboratory tests: Basic investigations on factors, processes characteristics of weathering of natural stones could be performed by using following tests:

- corrosion tests; simulation of acid rain; SO_2/NO_2 exposure (Malaga et al, 2000),
- salt crystallisation tests, efflorescence (Arnold and Zehnder, 1989, 1996; Böhm, 2001)
- efficiency of protective agents (van Hees et al, EU project "Surface treatments")

Analyses and instrumentation

- Microscopy (optical, SEM/EDX, ESEM) of stone samples; prisms, scratched samples, thin sections, gives best and most cost effective results of the effects.
- The quantitative and qualitative analyses of corrosion products, sulphates, nitrates, chlorides and oxalates may be performed by leaching samples in ultra-pure water and analysed by Ion Chromatography (using a Dionex DX-100 instrument with an IonPac column).
- Effectiveness of impregnation materials could be analysed by checking porosity changes (surface area and porosity distribution) by e.g. nitrogen adsorption measuring unit; by colour and ocular surface analyses (Figures 132-134).

Useful tests for resistance against staining of flooring tiles can e.g. be ISO 2812-1 Part 3 Spotting test. The wet cleaning is also done after a standard. In this case the Swedish standard SS-184164 and ISO 4628-1 were used for the visual evaluation.

Needs/thoughts

The laboratory test results represent an essential tool for damage investigation and especially for simulation of the susceptibility of the material. Results available in the literature represent mostly the successfully completed laboratory experiments and field tests. There is a need of publication of “failed results” in order to avoid doubling of experimental work, inappropriate applications and wrong methodology.

The tests presented in the literature help to distinguish among rocks of different susceptibility to weathering. However, each of the tests is concerned with one particular physical/chemical property of the rock. The total response of the rock to weathering can only be determined by considering all the results together. No individual test is sufficient to properly classify the rock relative to its expected behaviour during use and exposure to weathering. A combination of tests that consider various rock properties should normally be used. However, classifications are still based on the ability of the rock to pass each of the tests.

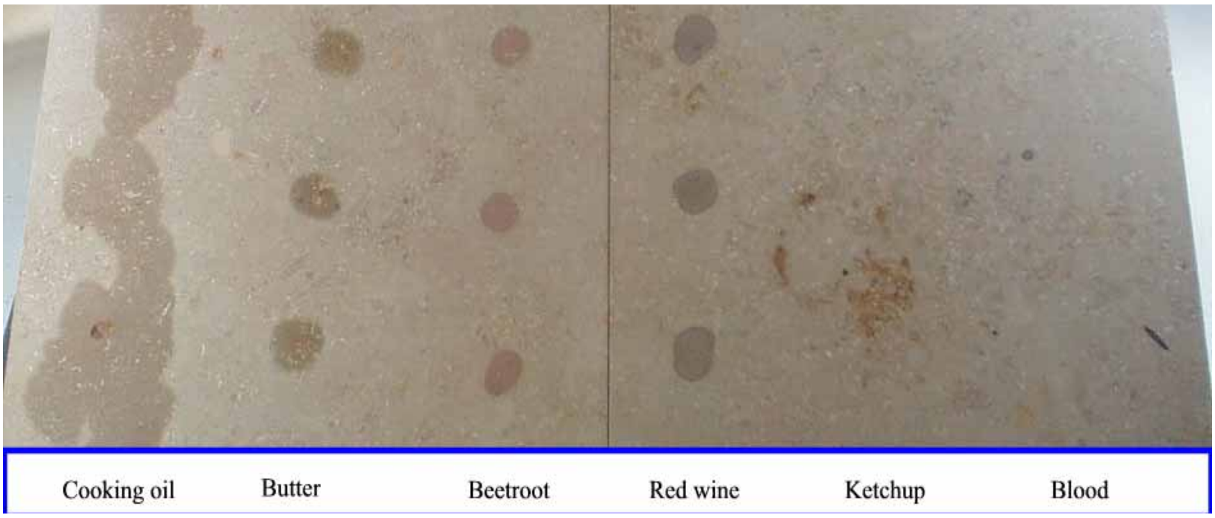


Figure 132. Picture stain test of limestone after cleaning

Figure 133. Picture of soap treated limestone after cleaning

Figure 134. Picture of stain test. Limestone with surface impregnated by perm-coat

It is always instructive to learn what property the various tests actually measure, and how close the results of the various tests are to each other. Different multivariate statistical techniques exist which can group the tests according to their effect on the sample. From the correlation of the results the future damage formation can be derived.

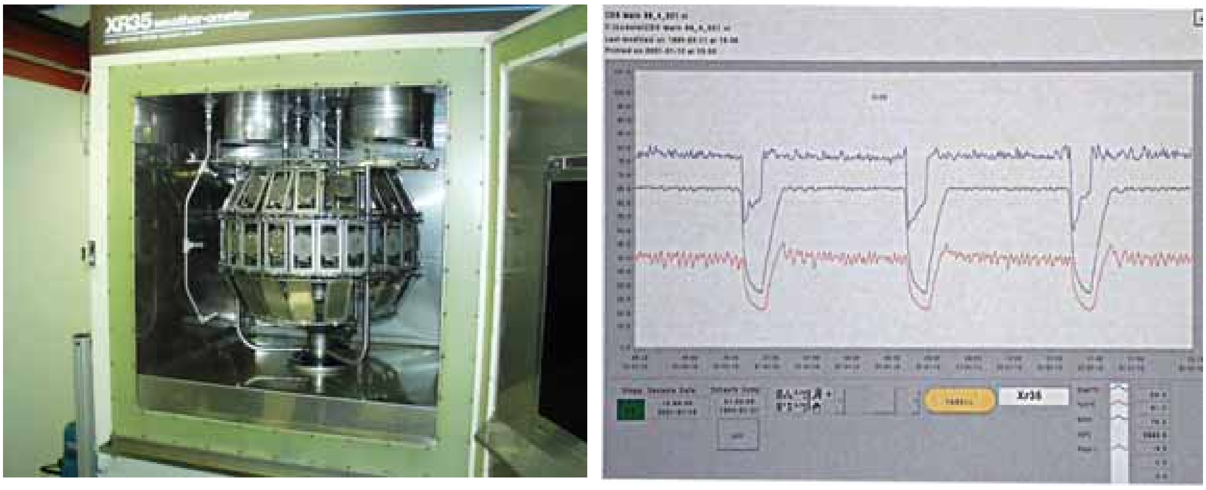
Figure 135. Discolouration of façade element due to staining from Copper studs and pollution

Figure 136. Graffiti

Resistance towards Graffiti (Figure 136) is different for different stones and surface finishing. The resistance can be improved by the application of surface protection or impregnation. However, the durability may decrease by using a poor chemical or application technique.

Figure 137. Photo of test specimens with and without surface coating (anti-graffiti protection). It is important not to change the appearance of the stone surface by the coating agent, neither immediate after application or in the long-run. The centre specimens are uncoated. Left down is coated before weathering test and Top left after the test – the resulting change in appearance is uncontrolled. The samples to the right are coated with a different chemical. A slight change initially which doesn't change through time

Testing of the durability of surface protecting agents can e.g. be done in a weather-o-meter where different climates can be simulated (Figure 138).



a) b)

Figure 138. a) Weather-o-meter and b) graphs of temperature and rH cycles. Light, temperature, water (including salt) and relative humidity are controlled

Figure 139. Permanent surface coating. Clearly visible and changing the appearance radically

Figure 140. Splintering due to dense coating, probably due to moisture saturation behind the surface maybe in combination with frost action

5.5. Durability against micro-climatic influences (temperature, moisture, etc)

The micro-climate, within or directly surrounding constructions, influences properties such as temperature movements, moisture and salt transport that are crucial for the durability. Moisture and temperature variations can initiate swelling and shrinkage in the stone. This can induce formation of cracks and voids along grain boundaries causing permanent expansion (Figures 141-143). A consequence of this may be strength loss and deformation if the expansion is heterogeneous. Moisture and temperature gradients can initiate water transport through diffusion, capillary transport and permeability. Changes in the microclimate, caused by changes in insulation or heating, may change the moisture content in the transport directions and thus change the service life of the construction.

Water in liquid state can transport salt in solution that may concentrate in certain positions such as were water transport mechanism change from capillary to diffusion. Salt deposition may occur as efflorescence on the surface or sub-efflorescence below the surface causing scaling of the surface. With change in moisture content the salt can crystallize and dissolve or change volume through hydration to dehydration reactions.

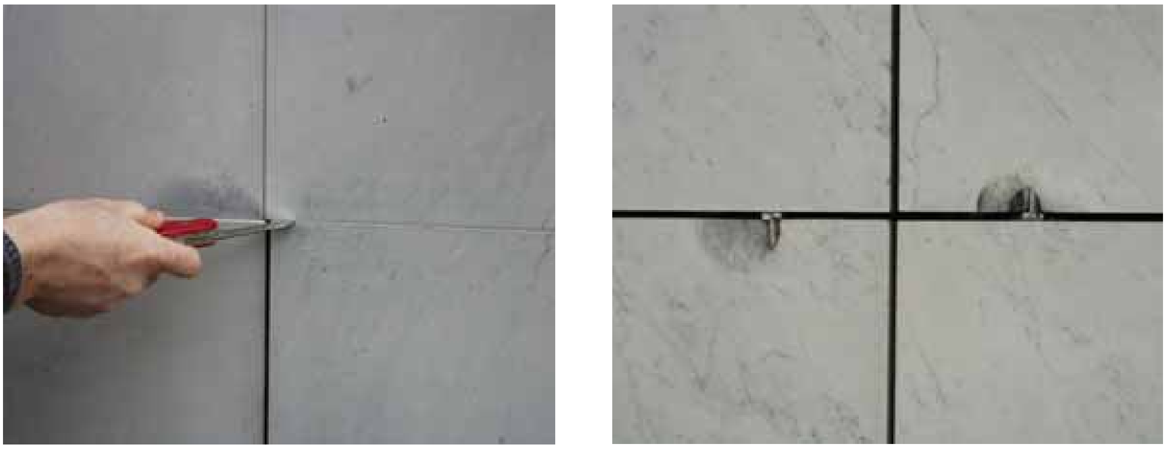


Figure 141. Thermal and hygric expansion may close the dilatation joints and cause cracking

Figure 142. Damage caused by thermal dilatation

Figure 143. Thermal and moisture gradients in may give bowing of marble, regardless of the thickness

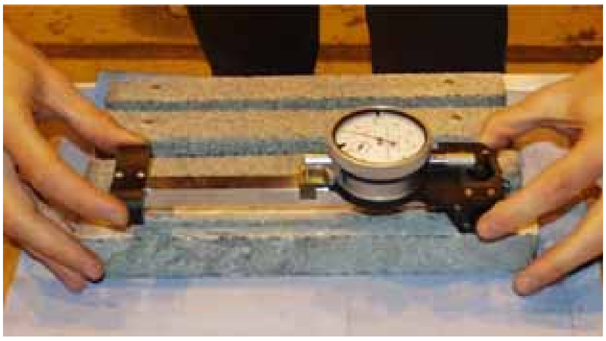


Figure 144. Testing of expansion due to temperature andmoisture influence

Figure 145. Laboratory testing for the bowing potential of marble (NORDTEST, draft method)

Figure 146. Testing deterioration of internal structure and hence the strength. To the left a Schlerometer and to the right Ultrasonic velocity test

5.6. Durability against biological activity

Durability against biological activity can be described as the effect on the stone material of the development and growth of micro and macro organisms. Biological activity induces stresses either directly with mechanical action (endolithic growing structures, root expansion, boring organisms etc.) or indirectly due to the chemical reactions linked to their metabolic activity (production of acids, chelants, etc.). The mechanisms which operate on stones when a living organism is dwelling on it are also included in this durability group.

The durability against biological activity is strictly dependent from that ones previously reported, in fact the starting of any biological activity is successive to the physical-chemical and mechanical weathering of the stone surface. These factors induce modifications in its finishing quality (cleaning, polishing and protective treatments) and progressive increasing of its roughness and porosity. Only after that these alterations have become effective the reproductive bodies (seeds, spores, conidi and propaguli), transported by the air and rain, can settle and find suitable conditions to anchorage themselves on the surface and develop using the minimal nutritive factors deposited by the environment (soiling of the surface).

Once these preliminary conditions have been realised the other chief factor is the rock's "bio-receptivity". The concept of bio-receptivity was introduced by Guillitte, (1985) as the aptitude of a material to be colonised by one or several groups of living organisms. Otherwise, the mere occurrence of organisms on stone surfaces does not automatically imply destructive action but in some cases could be considered: as only aesthetic detrimental appearance; perceived aesthetically pleasing or credit these with a protective role against weather induced aggression. The bio-receptivity must be related with the totality of material properties that contribute to the establishment, anchorage and development of flora and/or fauna. In stony material it relates mainly with surface roughness, moisture content, chemical composition (principal and trace elements) and with the structure-texture (porosity, grain size) of the rock.

The kind of microorganisms, type of ecological succession and level of the contaminants are dependent not only on the lithotype but also on the climatic localization and geographical exposure of the material concerned. Taking into consideration the level of potential weathering effects for stone materials the most potentially dangerous microorganisms are the crustose lichens followed by the photoautotrophes (algae and cyanobacteria) and last by etherotrophes (actinomycetes, micro-fungi and bacteria). Other problematic groups exist as well such as: weeds and higher plants, birds and small mammalians, molluscs and crustacea (Figure 147). But all these can have worse effects (even at high level) only in particular conditions (stones in caves or under sea level) or interesting the integrity of the whole structure as in the case of the root system growing in joints and crevices between stone slabs.

Figure 147. A fortress in Lisbon with biological growth (lichens on surface and weeds in joints

Figure 148. Formation of biological patinas on the parts of the building submitted to direct rainfall

The development of coloured biological patinas or encrustations is the more diffuse phenomenon (Figure 148). These patinas are mainly formed where rain runs off, maintaining moist in the stone material and are formed by mixed population in which the photoautotropic component is prevailing. The colour can range from brilliant green to black as a function of the growing cycle and the season and its thickness can reach several millimetres if left undisturbed. These microorganisms can weaken the stone superficial grain cohesion and increase its porosity through the emission of organic acids dissolving the stone mineral structure. The durability against biological activity is not yet used/tested. Only during the last year, laboratory tests have been started to evaluate the bio-receptivity of a stone material. This could be considered an indirect test to evaluate the stone durability against biological activity.

One can assess the bio-receptivity of a material to an organism by artificially inoculating the material with the diaspores of the organism itself and placing them under optimal environmental conditions (growth chamber). Thus a specific "Bio-receptivity Index" could be determined for a stone material related to its susceptibility to bio-deterioration. A multidisciplinary team must operates to conduct integrated studies, as standard as possible, choosing the most suitable parameters for measuring the bio-receptivity either for quantify the microbial mass or to characterise the stony material. Regardless of the test results and the different ways of interpreting them, there is also a need for assessing the esthetical aspects. The needs as regards this durability aspect is thus to achieve complementary information on bio-receptivity properties during recommended tests.

A major drawback is that these studies are always indicatives, as many types of colonisation are part of an ecological mechanism and not all the organisms present on exposed stone surfaces can develop in artificial conditions, even if they are very close to those present in nature. Hence the test made with a single organism or few isolated strains can become either impossible or completely atypical. In fact, the results reported in few lab experiments can be considered pertinent only for the stones used, the organisms tested and the incubation conditions applied. Thus a recommended procedure should be established at a European level.

5.7. Durability aspects in European product standards and tests; requirements, test methods and evaluation

According to the Directive 89/106/EEC "Construction products" (CPD), construction products may be placed on the market only if they are suitable for the intended use. This means that they must have such characteristics that the works in which they are to be used, assembled, applied or installed, can, if properly designed and built, satisfy the following essential requirements:

- Mechanical resistance and stability;
- Safety in case of fire;
- Hygiene, health and the environments;
- Safety in use;
- Protection against noise;
- Energy economy and heat retention.

The satisfaction of the essential requirements must be maintained during the service life of the building; therefore the durability aspects must be considered in any harmonized standard concerning construction products. In the mandates issued by the European Commission for the execution of standardisation work, it is recalled that “the standard shall include a definition of the durability in terms of performance of the declared values of the products characteristics as well as suitable methods for its evaluation against the actions of weathering, freeze-thaw, de-icing salts, etc., as relevant”. For this reason CEN TC 246 Natural Stones has included in his work programme five work items on durability. Two of them have already been adopted as European Standards, the others are either at formal vote stage or after enquiry (see table).

The European Standards and draft European Standards concerning test methods on durability of natural stones are:

- EN 12370: 1999 Determination of resistance to salt crystallisation
- EN 12371:2001 Determination of frost resistance
- prEN 13919 Determination of resistance to ageing by S02 action in presence of humidity
- prEN 14066 Determination of resistance to ageing by thermal shock
- prEN 14147 Determination of resistance to ageing by salt mist

Even if, durability requirements should be dealt within the framework provided by the directives in the harmonized European Standards, pre-normative research in the field of durability of natural stones is of the utmost interest for the next generation of European standards. CEN TC 246 especially needs numerical parammeters apt to establish natural stones durability indexes or classes be made available from the research.

5.8. Concluding discussion

Many things can be concluded from the above. Much information concerning weathering, protection and consolidation to prolong the service life, can be obtained from the huge amounts of projects on the cultural heritage. However, when we talk about the cultural heritage, we infer much longer service life than is usual for modern buildings. The latter are scarcely designed for more than 50 years, whereas the former are anticipated to exist for several hundred years.

The main objective in this chapter is to discuss the service life of modern stone building components concerning their first generation of application. It wouldn’t be realistic to cover the second generation of application, i.e. demounting and reuse for other applications or similar applications in another construction/building. Demounted building components of stone have to undergo renewed testing for each purpose.

A useful and constructive work towards greater durability can be the development of a database with information and service records and consequently produce a State-of-the-art project concerning documented experience (based on travelling, interviews, literature search etc.), a compilation on damages due to rock failure, misuse, construction problems (poor design), poor craftsmanship etc.

A macro- and micro-climatic index for Europe and building constructions has to be developed. This requires a co-ordination concerning field exposure sites in several places in Europe. Guidelines for requirements and testing for climatic influence on stone building components can thereafter be written.

Finally there is a need to:

- Develop methodologies for mathematical modelling of test results and to transfer these into designed building components
- Design of Testing Methodology primarily based on the new EN for each area of application (Relevant testing for each purpose)
- Test components and their use, e.g. FEM, in order to create safer and more economical stone constructions
- Development of the lacking material constants
- Development of guidelines for the use of safety factors for different purposes/applications of stones
- Development of guidelines for test results in order to both stone producers and entrepreneurs/architects can understand
- Review of test methods and their relevance to real stone operating conditions.

All these aspects are lacking in European harmonization work of standards. The standards are produced to characterize stones as such and they are not very useful for designing specific building components. Another major shortcoming is that the standards do not take into account the change of properties through time, i.e. the durability.

A maintenance handbook should be produced and delivered to each building when natural stones are used. The handbook can be based on manuals i.e. that follow when a new car is acquired, and include technical specifications for general maintenance on different levels, i.e. one for the building owner and one more detailed for the care-taker. The book should contain information about the stone types, quarry, producer, location on/in the building, construction info. The kind of maintenance that should be used, if anti-graffiti protection will be used, the kind that can be recommended for this stone type, etc. Today a lot of misuse and poor maintenance cause problems in the future. The building owner doesn't know how to carry out everyday cleaning or how to clean stains graffiti etc. Different varieties of very poor protection chemicals flood the market without any reference about their performance - a big problem that causes damages and a bad reputation.

References

Agliardi, F., Crosta, G., and Zanchi, A. “Structural constraints on deep-seated slope deformations kinematics”, Engineering Geology, Vol.59 (2001) pp. 83-102.

Albuquerque, T., Sousa, J., Pereira, H., 1999: Kriging with external drift and soft kriging in the characterisation of a marble region. Proceedings of APCOM `99, 28th Intern. Symp. on Computer Application in the Minerals Industries, pp. 249 – 256, Colorado.

Arbeitskreis Naturstein, 1997: Geotechnische Untersuchungen zur Neuaufschließung und Erweiterung von Gewinnungsstätten der Natursteinindustrie – Empfehlung. geotechnik 20, pp.117-125.

Badge, M.N., Raina, A.K., Chakraborty, A.K., Jethwa, J.L., 2002: Rock mass characterisation by fractal dimension. Engineering Geology, 63, pp. 141-155.

Barton, N., Lien, R., Lunde, J., 1974: Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, 6, pp. 183-236.

Barton; N.R.; “A review of the shear strength of filled discontinuities in rock. Norwegian Geoth. Inst. Publ., Vol. 105, 1974.

Barton, N.R., and Choubey, V.; “The shear strength of rock joints in theory and practice”. Rock Mech. 10 (1-2).(1977). pp 1-54.

Bell, F.G., (1993), “Engineering Geology”, Blackwell Science Publications.

Bienawski, Z.T., 1989, Deere, D.U., 1989Hoek, E. and E. T Brown, “ Engineering Rock Mass Classifications”, John Willey and Sons, New York Rock Quality Designation (RQD) After Twenty Years, US Army Corps of Engineers “Underground Excavations in Rock”, Institution of Mining and Metallurgy, 1998.

Blyth, F. G. H., and Freitas, M.H.; “A Geology for Engineers”, Edward Arnold, 1986.

Bourque, H. J. and Associates, 1999: Dimensional Stone Feasibility Study: Development Potential in Michigan’s Upper Peninsula (www.deq.state.mi.us/gsd/DSFS/DSFSReport.pdf).

Brown, E. T. (ed.). “Rock characterisation, testing and monitoring: International Society for Rock Mechanics suggested methods”, Pergamon Press, (1981).

Carreon-Freyre, D., Cojean, R., and Rocchini, J.F; “Caractérisation géométrique des réseaux de fracturation en carriére de roches ornementales. Application à l´optimisation de l´exploitation”. Bulletin De Lássociation Internationales de Géologie de Língénieur, París, nº 54 (1996), pp. 45-58.

Chilés, J.-P, Gentier, S., 1993: Geostatistical modelling of a single fracture. In: Soares, A. (Ed.), Geostaistics Troia `92, Kluwer Academic Publishers.

Coggan, J.S., Stead, D., and Eyre, J.M; “Evaluation of techniques for quarry slope stability assessement”, Trans. Instn Min. Metall. (Sect B: Apll.earth sci.), Vol. 107, September-December 1998, pp. 139-147.

COSS project “Characterisation of Ornamental Stone Standards by image analysis of slabs” Final Report – EC Standards, Measurement and testing programme - Contract Number: SMT4-CT95-2028.

Crassoulis, G., Kapenis, A., Thoraval, A., Ferrero, M., Germann, K., Iabichino, G., Gardenato, M., Dell´Antone, F., 1999: Development of an integrated computer-aided design and planning methodology for underground marble quarries. In: I. Paspaliaris, M. Taxiarchou and A. Adjemian, G. Katalagarianakis, Eurothen `99 – Proceedings of the 2nd Annual Workshop, 380 -384, National Technical University, Athens.

Crassoulis, G., Kapenis, A., Thoraval, A., Ferrero, M., Germann, K., Iabichino, G., Gardenato, M., Dell´Antone, F., 1999: Development of an integrated computer-aided design and planning methodology for underground marble quarries. In: I. Paspaliaris, M. Taxiarchou And A. Adjemian, G. Katalagarianakis, Eurothen 2000 – Proceedings of the 3rd Annual Workshop, 342 – 361, National Technical University, Athens.

Crassoulis, G., Kapenis, A., Thoraval, A., Ferrero, M., Germann, K., Iabichino, G., Gardenato, M., Dell´Antone, F., 2000: Development of an integrated computer aided design and planning methodology for underground marble quarries. In: I. Paspaliaris, M. Taxiarchou and A. Adjemian, G. Katalagarianakis, Eurothen 2000 – Proceedings of the 3rd Annual Workshop, 342 – 361, National Technical University, Athens.

Deere, D.U & Deere, D.W., 1988: The rock quality designation (RQD) index in practice. In: L. Kirkaldie (ed.), Rock Classification Systems for Engineering Purposes. ASTM Spec. Publ. 984: 91-101.

Deposits Features of Tranovalto Marbles, IGME and LEONARDO ENGINEERING s.r.l., May 1997.

Esbert, R. M., Ordaz, J., Alonso F., J. and Montoto, M., (1997), “Manual de diagnosis y tratamiento de materiales pétreos y cerámicos”, Col-legi d’Aparelladors i Aquitectes Técnics, Ed., Barcelona, Spain.

European Standard EN 12440 – October 2000 – “Natural Stone – Denomination criteria” - ©2000 CEN European Committee for Standardization, Ref.No.12440.2000 E.

European Standard Draft prEN 771-6 - CEN/TC 125 – May 2001 – “Specification for masonry units - Part 6: Natural stone masonry units”.

European Standard Draft prEN 12059 - CEN/TC 246 - July 2002 – "Natural stone products – Dimensional stone work - Requirements".

European Standard Project prEN XXXX - CEN/TC 178/WG 5- 22nd May 2002 – "Specification for tactile paving surface indicators".

European Standard Project prEN 1469 - CEN/TC 246 DOC. N. 366 - April 2002 – "Natural stone – Finished products, slabs for cladding –Specifications".

European Standard Project prEN 12057 - CEN/TC 246 DOC. N. 367 - April 2002 – "Natural stone – Finished products, modular tiles – Specifications".

European Standard Project prEN 12058 - CEN/TC 246 DOC. N. 368 - April 2002 – "Natural stone – Finished products, slabs for floors and stairs – Specifications".

European Standard Project prEN 12326-1 - CEN/TC 128/SC 8 DOC 394 – 19 February 2002 – "Slate and stone products for discontinuous roofing and cladding and internal wall lining - Part 1: Product specification".

Germann, K., Koch-Moeck, M., Crassoulis, G., Kazatsanidis L., Thoraval, A., Ferrero, M., Iabichino, G., Gardenato, M., Dell´Antone, F., 2001: Development of an integrated computer-aided design and planning methodology for underground marble quarries. In: I. Paspaliaris, M. Taxiarchou And A. Adjemian, G. Katalagarianakis, Eurothen 2001 – Proceedings of the Fourth Annual Workshop, 187 – 236, National Technical University, Athens.

Ferrer, M. and González de Vallejo, L. I.(Ed.). "Manual de campo para la descripción y caracterización de macizos rocosos en afloramientos".Instituto Tecnológico y Geominero de España. (1999). ISBN 84-7840-387-6.

Fookes, P. G., Gourley, C. S., and Ohikere, E., (1998). Rock weathering in engineering time. Quaterly J. of Engng. Geology, 21, 33-57.

Germann, K., Koch-Moeck, M., Crassoulis, G., Kazatsanidis, L., Thoraval, A., Ferrero, M., Iabichino, G., Gardenato, M. & Dell'Antone, F., 2001: Development of an integrated computer aided design and planning methodology for underground marble quarries. In: I. Paspaliaris, M. Taxiarchou, A. Adjemian & G. Katalagarianakis (eds.), Proceedings of the Fourth Annual Workshop (EUROTHEN 2001), 207-236, Athens, NTUA.

Goovaerts, P. 1997: Geostatistics for Natural Resources Evaluation. 483 pp., New York etc., Oxford University Press.

Hadjigeorgiou, J., Grenon, M., and Lessard, J.F.; "Defining in-situ block size". CIM Bulletin. May (1998). pp 72-75.

Hall, A., 1996: Igneous Petrology. 2nd Edition, 551 pp., Longman, Harlow.

Halsey, D.P., Mitchell, D.J., and Dews, S.J. (1998) "Influence of climatically induced cycles in physical weathering. Quaterly journal of Engineering Geology, Vol 31, pp.359-367.

Harben P., Purdy, J., 1991: Dimensional Stone evaluation. From cradle to gravestone. Industrial Minerals Febr. 1999, pp. 47-61.

Heliot, D., 1988: Generating a blocky rock mass. Int. J. Rock Mech. Min. Sci & Geomech. Abstr. 25:/3: 127 -138.

Hill, S. E. and Rosebaum, M.S. (1998) "Assesing the significant factors in a rock weathering system". Journal of Engineering Geology, Vol 31, pp. 85-94.

Hobbs, B. E. et. al., 1976: An Outline of Structural Geology ,p.576, 1976.

Hoek, E., and Bray, J.W.; "Rock slope engineering, 3rd edn". (London: IMM, 1981).

Houlding, S.W., 2000: Practical Geostatistics, 160 pp., with CD-ROM, Heidelberg etc., Springer.

Huang, Q., and Angelier, J.; "Fracture spacing and its relation to bed thickness", Geol. Mag., 126, pp 355-362.

Hudson, J.A.; "Rock mechanics principles in engineering practice". Construction Industry Research and Information Association, (1989), pp. 72.

Iliev, I. G. (1967) "An Attempt to estimate the degree of weathering of intrusive rocks from their physico-mechanical properties. Proceed. 1st Cong. Int. Soc. For Rock Mechanics, Libson, 1, 109.114.

Institution of Mining and Metallurgy (IMM), European Federation of Geologists, Geological Society of London & Institute of Geologists of Ireland, 2001: Code for Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves (The Reporting Code), 34 pp.

http://www.miro.co.uk/docs/thereportingcode.pdf

Irfan, T.Y. and Dearman, W.R. (1978). Engineering classification and index properties of weathered granite. Bull. Int. Assoc. Engng. Geology, No. 17, 79-90.

Judson, S., and Richardson, S. M.; "Earth , An Introduction to Geologic Change", Prentice Hall Englewood Cliffs. (1995).

Kearey, P. (ed.), (1995), "The Encyclopedia of the Solid Earth Sciences", Blackwell Science.

Kirsten, H.A.D. (1988), "Discussion on Q-System", Rock classification for Engineering Purposes, ASTM STP 984, pp. 85-88.
Lemy, F., Hadjigeorgiou, J., Cote, P. & Malkdague, X., 2001: Image analysis of drill core. Trans. Instn. Min. Metall (Sect. A: Min. Technol.), 110: A172-177.

López Jimeno, C., (Ed.).; "Manual de rocas ornamentales". Consejo Superior de Colegios de Ingenieros de Minas de España. (1986). ISBN: 84-605- 4597- 7.

Lorenz, W., Gwosdz, W., Thoms, H., 2000: The UN International Framework Classification for Reserves/Resources applied to mineral construction materials. Erzmetall 53 (2000), 26 – 30.

Lu, P., Latham, J.-P., 1999: Developments in the assessment of in-situ block size distributions of rock masses. Rock Mech. Rock Engng. 32: 29 – 49

Luodes, H., Selonen, O. & Pääkkönen, K., 2000: Evaluation of Dimensional Stone in gneissic rocks – a case history from southern Finland. Engineering Geology 52: 209-223.

Lutgens, F.K., and Trabuck, E.J.; "Fundation of Earth Sciences". Prentice Hall, Ic. (1996). ISBN: 0-02-37281-3.

Matsukura, Y., and Takahashi, K. (1999) "A new technique for rapid and non-destructive measurement of rock-surface moisture content; preliminary application to weathering studies of sandstone blocks". Engineering Geology, Vol. 55, pp.113-120.

Mononen, S. Söderholm B., Tammenmaa, J. & Ärmänen, E., 1998: Multicolor Dimensional Stone evaluation by integration of geomethods. Helsinki University of Technology, Department of Materials Science and Rock Engineering, Laboratory of Engineering Geology and Geophysics, Research Report TKK-IGE-A-22, 57 pp. + 10 appendices. ISBN 951-22-3977-9, ISSN 0785-9732.

www.hut.fi/Units/Rock/Abstracts/tkk-ige-a-22.html

Montgomery, C.W., and Dathe, D.; "Earth, Then and Now", Brown Publ. (1994).

Müller, F. 2001: Gesteinskunde. 6th Edition, 276 pp., Ebner Verlag, Ulm. ISBN 3-87188-122-8

Nelles, P., 1996: Die Granit-Natursteingewinnung weltweit. Erzmetall 49: 286-299

Nelles, P.L., 1996: Die Granit-Natursteingewinnung weltweit (Granite mining worldwide). Erzmetall 5/96: 286 – 299.

Ollier, C., (1984), "Weathering", Longman.

Palmström, A., 1982: The volumetric joint count – A useful and simple measure of the degree of rock mass jointing. Proc. 4th Congress Int. Assoc. Eng. Geology, New Delhi, vol. 2, 221-228.

Palmström, A., 2000: Blocks size and block size distribution. Paper presented at the Workshop on the "Reliability of classification systems", GeoEng2000 Conference, Melbourne.

http://www.rockmass.net/Block%20size%20measurements1.pdf

Paradis, S., Townsend, J. and Simandl, G.J. (1999): Sedimentary Rock-hosted Opal; in Selected British Columbia Mineral Deposit Profiles, Volume 3, Industrial Minerals, G.J.

Simandl, Z.D. Hora and D.V. Lefebure, Editors, British Columbia Ministry of Energy and Mines.

Pereira, H.G., Brito, G., Albuquerque, T., Ribeiro, J., 1993: Geostatistical estimation of a summary recovery index for marble quarries. In: Soares, A. (Ed.), Geostaistics Troia `92, 1029 – 1040, Kluwer Academic Publishers.

Peschel, A., 1977: Natursteine. 390 pp., VEB Deutscher Verlag für Grundstoffindustrie, Leipzig.

Power, W. R., 1994: Stone, Dimension. In: D. D. Carr (Ed.), Industrial Minerals and Rocks, 6th Edition, 987 – 1001, Society for Mining, Metallurgy, and Exploration, Littleton, Col.

Press, F., and Siever, R.;”Understanding Earth”, Freeman. (1994).

Quick, G., 2002: CSIRO Guide to the Specification of Dimensional Stone, Discovering Stone, No.1: 8 – 21. Abridged version: http://www.dbce.csiro.au/inno-web/0402/stone.htm

Raymond, L.A.: “Petrology: The study of Igneous, Sedimentary, Metqamorphic rocks”. Wm. C. Brown Communications, Inc. (1995). ISBN: 0-697- 00190-3.

Reading, H.G., (Ed).; “Sedimentary Environments: Processes, Facies and Stratigraphy”. Blackwell science (1998). ISBN: 0-632-03627-3.

Report on the investigations of the Illo calcite marble deposit in 1996 - 2000, claim areas Illo and Illo 2 (6398-1 and 6834-1).

Sandia National Laboratories, Hydraulic Fracturing Stress Measurements in Test Hole ESF-AOD-HDFR1, Thermal Test Facility, Exploratory Studies Facility, TDIF 305878, DTN: SNF37100195002.001, January 1997.

Selley, R. C., 2000: Applied Sedimentology. 480 pp., Academic Press, San Diego.

Selonen, O., Luodes, H. & Ehlers, C., 2000: Exploration for dimensional stone – implications and examples from the Precambrian of southern Finland. Engineering Geology 56: 275-29.

Shadmon, A., (1989), “Stone, An introduction”, Intermediate Techn. Publ.

Singewald, C., 1992: Naturwerkstein – Exploration und Gewinnung. 260 p., Steintechn. Inst. Mayen, Köln (Verlagsges. Müller).

Sonmez, H., Ulusay, R., and Gokceoglu, C.; “A practical procedure for the back analysis of slope failures in closely jointed rock”. International Journal of Rock Mechanics and Mining Sciences. Vol. 35-2 (1998). pp. 219-233.

STONE 2000 – by Carlo Montani - Gruppo Editoriale Faenza. 2001.

Swenson, J.M.,1991: Quality from the quarry. Dimensional Stone vol. 7, No.9: 56-59,79.

Taboada, J., Vaamonde, A., Saavedra, A. Alesano, I., 1997: Application of geostatistical techniques to exploitation planning in slate quarries. Engineering Geology, 47, 269-277.

Taboada, J., Vaamonde, A., Saavedra, A., Arguelles, A., 1998: Quality index for ornamental slate deposits. Engineering Geology 50: 203 – 210.

Taboada, J., Vaamonde, A., Saavedra, A., 1999: Evaluation of the quality of a granite quarry. Engineering Geology 53: 1-11.

Tavchandian, O., Rouleau, A., Marcotte, D., 1993: Indicator approach to characterise fracture spatial distribution in shear zones. In: Soares, A. (Ed.), Geostatistics Troia `92, Kluwer Academic Publishers.

Tercan, A.E., Özçelik, Y., 2000: Geostatistical evaluation of dimension-stone quarries. Engineering Geology 58: 25-33.

Tucker M.E.; “Sedimentary Petrology”. Blackwell science. (2001). ISBN: 0-632-057351.

United Nations-ECE, 1997: United Nations International Framework Classification for Reserves/Resources – Solid Fuels and Mineral Commodities. ENERGY/WP.1/R.70: 1 – 23, Economic Commission for Europe, Geneva.

United Nations-ECE, 2001 a: Key for the Classification of Reserves/Resources – United Nations International Framework Classification for Reserves/Resources (UNFC). ENERGY/2001/10: 1 – 29, Economic Commission for Europe, Geneva.

United Nations-ECE, 2001 b: Guidelines to the United Nations International Framework Classification for Reserves/Resources – Solid Fuels and Mineral Commodities. ENERGY/2001/11: 1 – 40, Economic Commission for Europe, Geneva

Walker, R. G. (Ed.), 1984: Facies Models. 2nd. Edition, Geoscience Canada, Reprint Ser. 1, 317 pp., Geol. Assoc. Canada.

Waltham, A.C.; “Foundations of engineering geology”. Blackie Academic & Professional. (1994). 87 p.

Weber, J., Dehnhart, J., Lepper, J., 2001: Trennflächenanalyse zur Vorratsermittlung von Naturwerkstein-Lagerstätten. Z. angew. Geol. 47/2: 74-78.

Webster, R. and Oliver, M.A., 1990: Statistical Methods in Soil and Land Resource Survey. 316 pp., Oxford University Press, New York.

Wellmer, F.W., 1998: Economic Evaluations in Exploration. 2nd. Edition, 163 S., Berlin etc., Springer.

Winkler, E. M., 1994: Stone in Architecture: Properties, Durability. 3rd ed., 313 pp., Springer-Verlag, Berlin (Germany).

Xiating, F.; “A neural network approach to comprehensive classification of rock stability, blastability and drillability”. International Journal of Surface Mining, Reclamation and Enviroment. Vol. 9 (1995). pp 57-62.

http://www.findstone.com

http://www.marbleandmore.com

http://www.piedrasb2b.com

http://www.techstone.it

ASM Handbook: Nondestructive Evaluation and Quality Control, vol. 17, Materials Park, OH: ASM, 1992, p. 231.-284 – 358.

ASNT Handbook: Nondestructive Testing Handbook, 2nd ed., vol. 3, Columbus, OH: ASNT, 1985.

ASTM C 597-83 "Standard Test Method for Pulse Velocity through Concrete", 1991

Binda, L. and Tiraboschi, C., Flat jack test as a slightly destructive technique for the diagnosis of brick and stone masonry structures, Proc. 8th Int. Conf. Struc. Faults and Repair, London, July, (CD), 1999.

Binda-Maier, L., Baldi, G., Carabelli, E., Rossi P.P. and Sacchi-Landriani, G., Evaluation of the statical decay of masonry structures: methodology and practice, report 166 of ISMES, Bergamo, 1982.

Binda-Maier, L., Rossi, P.P. and Sacchi-Landriani, G., Diagnostic analysis of masonry buildings, report 189 of ISMES, Bergamo, 1983.

Borsetto, M., Frassoni, A., Giuseppetti, G. and Zaninetti, A., Flat Jack measurements and interpretation, Recent advances, report 188 of ISMES, Bergamo, 1983.

Bossi, R.H. and Georgeson G.E., Materials Evaluation, 53, October 1995, pp. 1198-1203.

Bossi, R.H., Cross D.A. and Mickelsen R.A., Proceedings of the 22nd International Symposium for Testing and Failure Analysis (1996), pp. 77-82.

Bray, D.E. and Mcbride, D., Nondestructive Testing Techniques, New York: John Wiley & Sons, 1992.

BRE, BRE Digest 421 The screw helix pull out method ,BRE, 1997.

BRE, Digest 409, Masonry and Concrete structures: measuring in-situ stress and elasticity using flat jacks, BRE. Digest, 1995.

BS 1881: Part 203: 1986 "Testing Concrete - Recommendations for measurement of velocity of ultrasonic pulses in concrete".

Cartz, L., Nondestructive Testing, Materials Park, OH: ASM, 1995.

Chagneau, F. and Levasseur, M., Control des materiaux de construction par Dynamostratigraphie, ,Materiaux et Constructions, V22, 231.,1989.

Copley, P.C., Eberhand J.W., And Mohr G.A.*, JOM, 46 (1),* 1994*, pp. 14-26.*

Mix, P.E., Introduction to Nondestructive Testing, New York: John Wiley & Sons, 1987.

De Vekey, R.C., Thin stainless steel flat-jacks: calibration and trials for measurement of in-situ stress and elasticity of masonry, Proc 7th Canadian Masonry Symposium, Hamilton, V2, pp1174-1183, 1995.

De Vekey, R.C., Measurement of horizontal compressive stress in masonry using flat jacks, Acta Polytechnica, V36 No. 2, pp 117,125, Prague, 1996.

De Vekey, R.C., Measurement of stress in Sandstone blockwork using flat jacks, J. of Brit. Mas. Soc. V.11, No.2, pp56-59, UK, 11, 1997.

De Vekey, R.C. and Sassu, M., Comparison of non-destructive in-situ mechanical tests on masonry mortars: The PNT-G method and the Helix method, Proc. 11th IBMAC, Shanghai, V.1, p376 - 384, 1997.

DIN/ISO 8047 (Entwurf) "Hardened Concrete - Determination of Ultrasonic Pulse Velocity" in German.

Ekinci, S. and Bilge, A.N., British Journal of NDT, 33 (9), 1991, pp. 450-452.

EN 12371, Natural Stone test methods – Determination of frost resistance.

EN 12372, Natural Stone test methods – Determination of flexural strength under concentrated load.

EN 12407, Natural Stone test methods – Petrographic description.

EN 13161, Natural Stone test methods – Determination of flexural strength under constant moment.

EN 13364, Natural Stone test methods – Determination of breaking load at dowel hole.

EN 1341, Slabs of Natural Stone for external paving – Requirements and test methods.

EN 13755, Natural Stone test methods – Determination of water absorption at atmospheric pressure.

EN 13919, Natural Stone test methods – Determination of resistance to ageing by SO_2 action in the presence of humidity.

EN 1925, Natural Stone test methods – Determination of water absorption coefficient by capillarity.

EN 1926, Natural Stone test methods – Determination of compressive strength.

EN 1936, Natural Stone test methods – Determination of real density and apparent density and of total and open porosity.

Epperson, G.S. and Abrams, D.P., Nondestructive evaluation of masonry buildings, Chapter 5 - Flat jack test, Advanced Construction Technology Centre - University of Illinois at Urbana Champaign, Report 89-26-03, pp39-48, 1989.

Espion, B., Elinck, J.P., Halleux, P., Fox, R., Didier, G. and Stoll, Ch., In situ measurements with flat jacks in large masonry arch, Proc. 8th Int. Conf. Struc. Faults and Repair, London, July, (CD), 1999.

Exadaktylos, G., Tiano, P. and Filareto, C., Validation of a model of rotary drilling of rocks with the drilling force measurement system, International Journal for Restoration of Buildings and Monuments, vol 6, n° 3, 2000, 307-340, 2000.

Ferguson, W.A. and Skandamoorthy, J., The screw pull-out test for the in-situ measurement of the strength of masonry materials, Proc. 10th Intl. Brick and block Mas. Conf., Calgary, V3. pp1257, 1266, 1994.

Ferguson, W.A., Further data on the screw pull-out test for the in-situ measurement of the strength of masonry materials, Proc. Brit Mas. Soc. 2nd symp. on Testing. To be published, 1997.

Gucci, N. and Barsotti, R., Determination in-situ of mortar load capacity by a drilling technique, ,Proc. 10th Intl. Brick and block Mas. Conf., Calgary, V3. pp1315-1324, 1994.

Gucci, N. Sassu, M., Rossi, P.P. and Pulcini, A., A comparison of non-destructive in-situ techniques for vertical load strength assessment, Proc.STREMA 95, V2, pp349-356, Chania, 1995.

Holler, P. et al., eds., Nondestructive Characterisation of Materials, 1988.

Hughes, T.G. and Pritchard, R., An investigation of the significance of flatjack flexibility in the determination of in-situ stresses, Proc. 10th Intl. Brick-Block Mas. Conf., V2., pp569-578, 1994.

ISRM – Suggested methods for determining hardness and abrasiveness of rocks. Part 3- Suggested methods for determination of the Schmidt rebound hardness.

Jones, R. and Facaoaru I., Testing of concrete by the ultrasonic pulse method. Materials and Structures, Vol. 2, No. 10, July-August 1969, p. 253-661.

Leslie, J.R. and Cheeseman, W.J., An ultrasonic method for studying deterioration and cracking in concrete structures. Amer. Concrete Inst., Proceedings, Vol. 46, Sept. 1949, p. 17-36.

Lewis, W.J. et al., Nondestructive Testing and Evaluation, 11, 1994, pp. 155-164.

London, B., Yancey, R.N. and Smith, J.A., Materials Evaluation, 48, May 1990, pp. 604-608.

Newman, A.J., The measurement of moisture content in building materials, 'Building Materials', Jan/Feb, pp32-34,1975.

Noland, J.L., Atkinson, R.H. and Baur, J.C., An investigation into methods of nondestructive evaluation of masonry structures, ‚Report to the National Science Foundation, Atkinson – Noland Associates, Boulder, Colorado, USA., 1982.

Noland, J.L., Atkinson, R.H. And Schuller, M.P., A Review of the Flat-jack Method for Nondestructive Evaluation, Proceedings of Non-destructive Evaluation of Civil Structures and Materials. Colorado, October. F3, 1990

Popovics, S., And Popovics, J.S., "Potential ultrasonic Techniques Based on Surface Waves and Attenuation for Damage Evaluation in Concrete - A Review," Diagnosis of Concrete Structures, T. Javor, Editor, Proceeding of the International RILEM - IMEKO Conference, Experteentrum, Bratislava, 1991. pp. 101 - 104.

prEN 14066, Natural stone test methods – Determination of thermal shock resistance.

prEN 14147, Natural stone test methods – Determination of resistance to ageing by salt mist.

prEN 14158, Natural stone test methods – Determination of rupture energy.

prEN 14579, Natural stone test methods – Determination of sound-speed propagation.

RILEM, LUM D.2 In-situ stress tests on masonry based on the flat jack, RILEM Technical recommendations for the testing and use of construction materials, E&F Spon, London, pp 503-505, 1994.

RILEM, LUM D.3 Strength / elasticity tests on masonry based on the flat jack, RILEM Technical recommendations for the testing and use of construction materials, E&F Spon, London, pp 506-508, 1994.

RILEM, Rilem recommendation MS.D.7, Determination of pointing hardness by pendulum hammer,Materials and Structures, vol.30,July, pp323-324, 1997.

RILEM, RILEM recommendation MS-D.10: Measurement of moisture content by drilling, Materials and Structures, V30, pp 327-328, 1997.

RILEM, Rilem recommendations for strength and hardness tests of materials MS.D.2: Determination of masonry rebound hardness, Materials and Structures, V31, 210, pp363-377, 1998.

RILEM/NDT 1 "Testing of Concrete by the Ultrasonic Pulse Method", 1972.

Ronca, P., Tiraboschi, C. and Binda, L., ln-situ Flatjack Tests Matching New Mechanical Interpretations, Proc. 11th IBMAC, V1, pp357-366, 1997.

Sacchi Landriani, G. and Taliercio, A., Numerical Analysis of the Flat Jack Test on Masonry Walls., Journal of theoretical and applied mechanics". Vol.5, No.3,1986.

Schmiedmayer, R., Nondestructive In Situ Determination of Mortar -Load Capacity Using a Modified Schmidt Rebound Hammer, Proc. 11th IBMAC, V1, pp 367-376, 1996.

Standard guide for computed tomography imaging, *E1441-95, Philadelphia, PA: ASTM,* 1995.

Standard Terminology for Nondestructive Examinations, *E1316-96, Philadelphia, PA: ASTM,* 1996.

Tiano, P., Filareto, C., Ponticelli, S., Ferrari, M. and Valentini, E., Drilling force measurement system a new standardisable methodology to determine the stone cohesion: prototype design and validation, International Journal for Restoration of Buildings and Monuments, vol 6, n° 2, 2000, 133-150, 2000.

Tiano, P. and Viggiano, A., A new diagnostic tool for the evaluation of the hardness of natural and artificial stones" , International Journal for Restoration of Buildings and Monuments, vol 6, n° 5, 2000, 555-566, 2000.

Winkler, E.M., Stone in Architecture, Spriger Verlag, Berlin, 1994.

Websites of slate museums or associations in the U.S.A. and U.K:
www.easdale.co.uk
www.nmgw.ac.uk
www.pahs.org
www.slatebeltchamber.org
www.slatevalleymuseum.org

Websites of slate producers around the world:
www.bvslate.com
www.data-wales.co.uk/slate.htm
www.evergreenslate.com
www.exatech.fr/dourgne
www.greenslate.com
www.greenstoneslate.com
www.lozere.net/galta.htm
www.malet-materiaux.fr/ardoise-segus
www.members.aol.com/vaslates
www.neslate.com

Websites of slate traders in the U.S.A:
www.americanslate.com

www.echeguren.com
www.premiumslate.com
www.traditionaltimberframe.com

Bruno, R., Persi Paoli, S., Laurenge, P., Corsi, C., Coluccino, M., Muge, F., Pina, P., Ramos, V., Sottomayor, L., Chica-Olm, M., Serrano, E. & Qiereda, J., 1999: Characterization and classification of ornamental stones by image analysis. In: I. Paspaliaris, M. Taxiarchou, A. Adjemian & G. Katalagarianakis (eds.), Proceedings of the Second Annual Workshop (EUROTHEN '99), 337-351, Athens, NTUA

Germann, K., Koch-Moeck, M., Crassoulis, G., Kazatsanidis, L., Thoraval, A., Ferrero, M., Iabichino, G., Gardenato, M. & Dell'Antone, F., 2001: Development of an integrated computer aided design and planning methodology for underground marble quarries. In: I. Paspaliaris, M. Taxiarchou, A. Adjemian & G. Katalagarianakis (eds.), Proceedings of the Fourth Annual Workshop (EURUTHEN 2001), 207-236, Athens, NTUA

Harben, P. & Purdy, J., 1991: Dimension stone evaluation – From cradle to gravestone. Industrial Minerals, 281: 47-61

Institution of Mining and Metallurgy (IMM), European Federation of Geologists, Geological Society of London & Institute of Geologists of Ireland, 2001: Code for Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves (The Reporting Code), 34 pp. http://www.miro.co.uk/docs/thereportingcode.pdf

Lebrun, V., 2001: Quality control of ceramic tiles by machine vision. http://www.ulg.ac.be/mica/pdf%20files/Ceramic%20tiles.pdf

Mononen, S. Söderholm B., Tammenmaa, J. & Ärmänen, E., 1998: Multicolor dimension stone evaluation by integration of geomethods. Helsinki University of Technology, Department of Materials Science and Rock Engineering, Laboratory of Engineering Geology and Geophysics, Research Report TKK-IGE-A-22, 57 pp. + 10 appendices. ISBN 951-22-3977-9, ISSN 0785-9732.
www.hut.fi/Units/Rock/Abstracts/tkk-ige-a-22.html

Müller, F. 2001: Gesteinskunde. 6th Edition, 276 pp., Ebner Verlag, Ulm. ISBN 3-87188-122-8

Nelles, P., 1996: Die Granit-Natursteingewinnung weltweit. Erzmetall 49: 286-299

Power, W. R., 1994: Stone, Dimension. In: D. D. Carr (Sen. Ed.), Industrial Minerals and Rocks. 6th Edition, 987-1001.

Primavori, P., 2002: Surface treatment on ornamental stones. Marmomacchine (on the net), 9 pp. http://www.marmomacchine.it/ve/eframesart.htm

Accardo G., M. Laurenzi Tabasso, S. Massa, P. Rossi-Doria "*Measurements of porosity and of mechanical resistance in order to evaluate the state of deterioration of some stones*" In the Proceedings of the Intern. Symposium on Deterioration and Protection of Stone Monuments. Paris, June 5- 9 1978, 2-1/1-22.

Aberg G., S. D. E. (1997). Weathering and conservation in depth determined by carbon isotopes released by laser ablation. 4th International Symposium on the Conservation of Monuments in the Mediterranean , Rhodes.

Aires-Barros, L., et al. Dry and wet laboratory tests and thermal fatigue of rocks. Engineering Geology, 1975. 9 p. 249-265.

Alfes A, Breit W & Schiessl P., (1992) Hardness testing for the measurement of stone degradation. 7th International congress on deterioration and conservation of stone.

Alesiani, M. Et al. Evaluation of stone pore size distribution by means of NMR. 9th International Congress on deterioration and conservation of stone, Venice 19-24 June 2000.

Alnæs, L. Quality and durability of natural stone. Influencing factors and test methods. (In Norwegian, summary in English) Dr.ing-thesis No. 1995:5. Institute for geology and mineral resources engineering, University of Trondheim, NTH, Norway, 1995.

Alfes C., W. Breit and P. Schiessl " *Hardness testing for the measurement of stone degradation*" In the Proceedings of the 7th Intern. Congress on Deterioration and Conservation of Stone. Lisbon, 15-18 June 1992. J.Delgado Rodriguez, F. Henriques, F.T. Jeremias Eds., Vol II, 771-780

Alexandri, I., 1991: *The Greek marble index.* Print All Publications, Athens.

Amrhein, J.E., Et al. Designing successful stone slab veneer. Stone World, Nov., pp. 46-. 1993

Amoroso, G.,G., Fassina, V. "*Stone decay and conservation".* Material Science Monographs n° 11, Elsevier Ed. , Amsterdam, The Netherlands, 1983.

Arnold, A. and Zehnder, K.: Salt weathering on monuments . La conservatione dei monumenti nel bacino del Medetiriano. Atti del 1° Simposio internazionale, Bari 7-10 giugno (1989).

Ashall, GJ., Massey,S W., Yates TJS., and Butlin, RN. 1999 Evaluation of decay to stone tablets after exposure for 8 Years. Quantification of effects of Air pollutants on materials. *Proc. UN/ECE Workshop Berlin*, May 24-27, 1999. Federal Environmental Agency (Umweltbundesant), Berlin. Ed. S Fitz

ASM Handbook : Non destructive Evaluation and Quality Control, vol. 17 (Materials Park, OH: ASM, 1992). Composites" *JOM-e* Nov 1998 (vol. 50, no. 11).

Auras M "*Stone conservation by impregnation with polyurethane*" In the Proceedings of the International RILEM/UNESCO Congress on Conservation of Stone and Other Materials. Paris, June 29 - July 1, 1993, M.-J.Thiel Ed., E & FN Spon Publ., London, vol II, 717-724.

Azzoni A., F. Bailo, E. Rondena, A. Zaninetti " *Mechanical, chemical and petrographical evaluation of stone degradation induced by different laboratory techniques*" In the

Proceedings of the 7th Intern. Congress on Deterioration and Conservation of Stone. Lisbon, 15-18 June 1992. J.Delgado Rodriguez, F. Henriques, F.T. Jeremias Eds., Vol II, 827-836.

Bain, G.W. Spontaneous rock expansion. The Journal of Geology; The University of Chicago, Volume XXXIX, No. 8, November-December 1931. 1931.

Bekker P.C.F. 1995 Durability testing models and methods for masonry. *In Evaluation and strengthening of existing masonry structures*. Proceeding of the Joint Int. Workshop RILEM TC 127 MS and CIB W 23. L. Binda and C. Modena Eds. University of Padua Publisher, 127-142.

Bray D.E., and McBride D., *Nondestructive Testing Techniques* (New York: Wiley &Sons Eds, 1992).

Blasi P., Frisa Morandini A., Mancini R., Marini P., 1998 – An experimental investigation on marble testing for bending strength: reliability of the results and size effects. *II Congr. Int. de la Piedra, Madrid , May 1998.*

Bonnell, D.G.R., Et al. The thermal expansion of concrete. National Building Studies, Technical Paper No. 7.1951

Bortz, S.A. Review of Durability Testing in the United States and Europe ASTM "Symposium on …." New Orleans. 1999

Bortz, S.A., Et al. Review of durability testing in the United States ande Europe. STP 1394 Dimension Stone Cladding: Design, Construction, Evaluation and Repair, November, 94-109. 2000

Bouineau, A., Et al. La decohesion granulaire maladie des revetements de facades en marbre. Mines et Carrières - Industrie Minérale, pp. 69-77. 1995

Bouineau, A., Et al. La decohesion granulaire menace pour les facades en marbre. Le Mausolee, 9, pp. 52-59. 1995

Butlin, RN., Coote AT., Devenish M., Hughes SC., Hutchens CM., Irwin JG., Lloyd GO., Massey SW., Webb AH., and Yates TJS. 1993 Preliminary results from the analysis of stone tablets from the National Materials Exposure Programme (NMEP). Atmos. Env 26B, 189-198.

Butlin R.N., A.T. Coote, K.D. Ross and T.J.S. Yates "*Weathering and conservation studies at Well Cathedral, England*" In Proceedings of the Symposium on Science, Technology and European Cultural Heritage, Bologna 13-16 June 1989. Butterworth-Heinemann Ltd., Oxford, England, 1991, 306-309.

Böhm, C. B., Küng, A. and Zehnder, K.: Art and Chemical Sciences. Chimia 55 (2001) 996-1001. Salt Crystal Intergrowth in Efflorescence on Historic Buildings.

Calia, A., Et al. A research into intrinsic parameters material to the durability of highly porous building stones. 9th International Congress on deterioration and conservation of stone, Venice 19-24 June. 2000

Cantisani, E. Et al. Relationships between microstructures and physical properties of white Apuan marbles: inferences on weathering durability. Periodico di Mineralogia, 69, 3, pp. 257-268. 2000

Cassaro M.A., K.L. Gauri, M. Sharifinassab and A. Sharifian "*On the Strength and Deformation Properties of Indiana Limestone and Concrete in the Presence of Salts*" In the Proceedings of the 4th Intrn. Congress on the Deterioration and Preservation of Stone Objects. Luisville July 7-9 1982. 57-76.

Cattaneo, Sara; Labuz, J.F. Damage of Marble from Cyclic Loading. Journal of Materials in Civil Engineering, Nov./Dec. 2001, pp. 459-465.2001

Cavallucci, F., Et al.Mechanical decay process in lapideous materials (Carrara marbles): Preliminary study of creep phenomena. Proc. 4th Int. Symp. on the Conservation of Monuments in the Mediterranean, pp. 91-100. 1997

Cavallini T., M. S., Valentino A (1997). Environment and deterioration of the monuments of Bari. 4th International Symposium on the Conservation of Monuments in the Mediterranean, Rhodes.

Celestino, T. Et al. Fracture Mechanics of Marble using a splitting tension test. Journal of Materials in Civil Engineering, Nov./Dec. 2001, pp. 407-411. 2001

Cheng, R.J., Et al. Deterioration of marble structures. Analytical Chemistry, 59(2), pp. 104A-106°. 1987

Christaras B. "*Weathering of granites and mechanical behaviour changing, in northern Greece*" In Atti del 1° Simposio Internazionale La conservazione dei monumenti nel bacino mediterraneo. Bari 1989. F. Zezza Ed., 335-339.

Clifton H.E., Hunter K.E., Swanson F.I. and Phillips R.L., 1969"Sample size and meaningful gold analysis*", U.S.G.S. Professional Paper*, No 625-C,.

Colback, P.S.B., Et al. The influence of moisture content on the compressive strength of rocks Proceeding of the Rock Mechanics Symposium - 3RD Canadian Symposium, Toronto, pp 65-83. 1965

Cooper, H.W., Et al. The effect of cracks on the thermal expansion of rocks. Earth and Planetary Science Letters, 36, pp 404-412. 1977

Crampin, S. Geological and industrial implications of extensive-dilancy anisotropy. Nature, 328, pp. 491-496. 1987
Commission RILEM 25 - PEM "*Protection et èrosion des monuments*" Reccomandation provisoires, P834, 1980,

Crisci G.M, Leoni L., & Sbrana A. 1975. La formazione dei Marmi delle Alpi Apuane (Toscana). Studio petrografico, mineralogico e chimico. Atti della Soc. Tosc. Sc. Nat. Ser. A 82, 199-236.

David M., Dagbert M. and Beauchemin Y., 1977 “Statistical Analysis in Geology: Correspondence analysis method”, *Qly. Col. School of Mines*, Vol. 72, No 1, Golden, Colorado,.

Delgado Rodrigues J. "*Mechanisms and measurement of damage in stone monuments*" In Proceedings of the Symposium on Science, Technology and European Cultural Heritage, Bologna 13-16 June 1989. Butterworth-Heinemann Ltd., Oxford, England, 1991, 124-137

Delgado Rodrigues, J. and Costa, D. "*Assessment of the efficay of consolidants in granites".* Proc. Workshop on Degradation and Conservation of granitic rocks in Monuments, Santiago de Compostela (E), Nov. 1994.

Delgado Rodriguez J., 1987 Proposed geotechnical classification of carbonate rocks based on Portuguese and Algerian examples *Engineering Geology* 25, 33-43.

Delgado Rodriguez J., & Telmo Jeremias F. 1990 Assessment of rock durability through index properties. In proceedings of Sixth Int. Congress IAEG, 6-10/8/1990, Amsterdam (NL). D.G. Price Ed., A.A. Balkema, Publ. Rotterdam, 3055-3060.

De Witte E. "*The evaluation of conservation materials*" In Proceedings of the Symposium on Science, Technology and European Cultural Heritage, Bologna 13-16 June 1989. Butterworth-Heinemann Ltd., Oxford, England, 1991,246-254

De Witte E. Oostvogels A. 2000 In situ application of the DFMS apparatus *Proceedings of the Drillmore EC - Workshop* Munich 16-17/3/2000. P. Tiano Ed. Centro Stampa Toscana Nuova, Firenze , Marzo 2000, 58- 63.

Dombrowski, K; Aselmeyer, G. Vergleichende Untersuchungen zur Übertragbarkeit von Ergebnissen des Kristallisationsversuches auf den Frostwiderstand von Gesteinen Thesis, Wissenschaftliche Zeitschrift der Bauhaus-Universität Weimar, Heft 5/6, pp. 180-194
2001

Dunakin, R. Mechanical aspects of weathering in marble crack growth. M.Sc. Thesis, dept. materials science, royal institute of technology, stockholm, p. 60. 1999

Dunakin, R. Mechanical and Environmental Studies of Marble Deterioration. Licentiate Thesis, Kungl. Tekniska Högskolan, Stockholm, ISBN 91-7283-099-9. 2001

Dürrast, H, Et al. Schadensanalyse von Natursteinen mittels Ultraschalldiagnostik: Möglichkeiten und Grenzen. Z. Deutsch. Geol. Ges. 150 (2) pp. 359-374. 1999

Dürrast, H, Et al. Correlation between rock fabrics and physical properties of carbonate reservoir rocks. Int. Journ Earth Sciences, 88, pp. 392-408. 1999

Exadaktylos G., Tiano P., Filareto C. "*Validation of a Model of Rotary Drilling of Rocks with the DFMS*" International Journal for Restoration of Buildings and Monuments vol 6, n 3, (2000), 307-340.

Exadaktylos G. and Tiano P., 2000 Determination of the compressive strength and angle of internal friction on rocks by microdrilling. *Proceedings of the Drillmore EC - Workshop* Munich 16-17/3/2000. P. Tiano Ed. Centro Stampa Toscana Nuova, Firenze , Marzo 2000, 22-29

Exadaktylos, G., 1998. Gradient elasticity with surface energy: Mode-I crack problem. *Int. J. Solids Structures* Vol. 35, Nos 5-6, pp. 421-456.

Exadaktylos, G. 1997. Characterization of Mechanical Properties and Damage of Natural Building Stones in Historical Monuments. *First Annual Workshop on Environmentally Friendly Construction Technologies* (Targeted Research Action), Organized by ECCREDI, Toulouse, France, October 30th-31st, 1997.

Esbert R.M, C. Grossi, L.M. Suarez del Rio, L. Calleja, J. Ordaz, M. Montoto "*Acoustic emission generated in treated stones during loading*" In the Procceding of the VIth Intern. Congress on Deterioration and Conservation of Stone, Torun 12-14.09.1988, 403-410.

Facaoaru I. and C. Lugnani " *Contributions to the diagnosis of stone and concrete historical structure using non destructive techniques*". In the Proceedings of the International RILEM/UNESCO Congress on Conservation of Stone and Other Materials. Paris, June 29 - July 1, 1993, M.-J.Thiel Ed., E & FN Spon Publ., London, vol 1, 238-251.

Francois-Bongarcon D., 1993 "The practice of the sampling theory of broken ores", *C.I.M. Bulletin*, Vol. 86, No 970, p. 75-83, Montreal.

Fratini, F., Et al. Metodi di campionamento ed analisi per lo studio di processi di dedicamento fisico-meccanico di lastre di marmo. Convegno su le cave di pietre ornamentali, Torino, 28-29 Nov. 2000

Garzionio, C.A., Et al. Analyses of the physical parameters correlated to bending phenomena in marble slabs. 9th International Congress on deterioration and conservation of stone, Venice 19-24 June 2000

Garzonio, C.A., Et al. Analyses of geomechanical decay phenomena of marbles employed in historical monuments in Tuscany. Mechanics of jointed and faulted rock, ed. Rossmanith, pp. 259-63. 1995

Guillitte, O. (1995) Bioreceptivity: a new concept for building ecology studies. The Science of the Total Environment, vol 167, 215-220

Guillitte, O., Dreesen, R. (1995) Laboratory chamber studies and petrographical analysis as bioreceptivity assessement tool of building materials. The Science of the Total Environment, vol 167, 365-374.

Giornetti, M. Stone industry technical glossary. Internazionale Marmi e Macchine Carrara. 1991

Grieken, R.V., Et al. Modern micro-analytical techniques to elucidate the causes and mechanisms of damage to cultural property. ???, pp. 101-110

Griffith, J.H. Thermal expansion of typical American rocks. Bulletin 128, Iowa Eng. Experiment Station, Vol. XXXV, No. 19, Oct. 7. 1936

Grimm, W-D.Marmor als werkstein und denkmalgestein. Naturstein, (12)1996

Grimm, W-D.Zum Steinerweichen. Naturstein, 55. 1994

Grimm, Wolf-Dieter. Observations and reflections on the deformation of marble objects caused by structural breaking-up
Zeitschrift der Deutschen Geologischen Gesellschaft, Band 150, teil 2, Themenheft: Marmor-Konservierung, pp195-235. 1999

Grolier, J., Fernandez A., Hucher M., Riss J. 1991 *Le propriétés physiques des roches-théories and modèls*. Masson Ed. Paris. 118- 134.

Gueguen, Y., and Palciauskas, V.. 1994 Introduction to the physics of rocks, Princeton University Press, NJ.

Hagerman, T. Om svenska bergarter och deras provning för konstruktionsändamål". Statens Provningsanstalt, meddelande 85, 5p. 1943

Harris D., Pan G. 1994 Intrinsic sample methods for mineral exploration and resources assessments. Non renewable resources Vol 2 , n° 2, 113-121.

Hatzor, Y.H., Et al. Microstructure effects on microcracking and brittle failure of dolomites. Tectonophysics 281, p. 141-161. 1997

Hawes, F. Designing stone buildings to prevent weathering. Stone World, Nov., pp. 27-. 1993

Heilbronner R., Herweg M. 1997 Time slicing, an image processing technique to visualize the temporal development of fabrics. *Journal of Structural Geology* vol 19, 861-874.

Holler P., et al., eds. 1988, *Nondestructive Characterization of Materials*

Hockman, A., Et al. Thermal and moisture expansion studies of some domestic granites. US Dep. Of Commerce, Nat. Bur. Of Stand. Res. Paper RP 2087, Vol. 44, April, pp. 395-410. 1950

Hoffmann, D., Et al. Moisture movement in brick.. Proceeding 5th International Congress on Deterioration and Conservation of stone, 1, Lausanne 1985

Hoffmann D, N. K., Plagge R, (1996). Relationship between pore structure and other physico-chemical characteristics of stone. 8th International congress on deterioration and conservation of stone.

Hoffmann D, N.-N. M., Niesel K, (1996). Evaporation as a feature of physico-technical characteristics of stone. 8th International congress on deterioration and conservation of stone.

Hogarth, C.A., Blitz, J. Techniques of Non-Destructive Testing. Butterworth & Co., London, 213 p. 1960

Howart, D. F. The effect of pre-existing microcavities on mechanical rock performance in sedimentary and crystalline rocks
International journal of Rock Mechanics, Mining sciences & Geomechanics, Vol. 24, pp. 223-233. 1987

Howarth, D.F. Experimental study on the relationship between rock texture and mechanical performance. Trans. Instn Min. Metall., Vol 95, A41- A45. 1986

Ihalainen, P. Methods applied in determining the variations of strength and structure of plutonic rock material exposed to artificial weathering treatment. Bull. Of the Geol. Soc. Of Finland, No. 65, Part 2, pp. 67-76. 1993

Ihalainen P. 1994 - Changes in porosity of some plutonic building stone depending on the type of artificial weathering treatment. *Proc III Int. Symp. on the Conservation of Monuments in the Mediterranean Basin,* Venice 22-25 June 1994, 109-113.

I.S.R.M., 1981.*"Rock Characterization Testing and Monitoring",* E.T. Brown Ed., Pergamon Press,

Jedrzejewska, H. "*Physical-chemical factors in the conservation of stone.* In The Conservation of Stone II, Part A, R.Rossi-Manaresi Ed., Bologna, 1981, 195-204.

Johnson, W.M., 1991 "Sample preparation and assaying", *Proc. Symposium on Sampling and Ore Reserves, Prospectors and Developers Association of Canada*, Toronto, Ontario,.

Jones, R. and I. Facaoaru. 1969 Testing of concrete by the ultrasonic pulse method. *Materials and Structures*, Vol. 2, No. 10, July-August 1969, p. 253-661.

Journel A.G., Huijbregts Ch. J., 1978 "Case studies of structural analysis", in *Mining Geostatistics, Academic Press*, London, p. 236-293,.

Kim J.and Liaw P.K. 1998 "The Nondestructive Evaluation of Advanced Ceramics and Ceramic-Matrix

Kryszton D., 1988"Pre and post-failure behaviour of rock samples", *Modelling of Mine Structures*, Kibybinski and Kwasniewski Eds., A.A. Balkema, Rotterdam.
Leslie, J.R. and W.J. Cheeseman. 1949 An ultrasonic method for studying deterioration and cracking in concrete structures. *Amer. Concrete Inst., Proceedings*, Vol. 46, Sept. 1949, p. 17-36.

Logan J.M., Hastedt M., Lehnert D. & Denton M. 1993 "A Case Study of the Properties of Marble as Building Veneer", *Int. J. Rock Mech., Min. Sci. & Geomech. Abstr.*, Vol.30, No.7, pp.1531-1537.

Malaga-Starzec K., Sahlin, T & Lindqvist, O., 2000: *Laboratory Investigations of Weathering Behaviour of Fresh and impregnated Limestone and sandstone from Central*

Sweden. Proceedings of the 9th International Congress on Deterioration and Conservation of Stone. Venice, Italy. Elsevier.

Mancini R., Morandini Frisa A., Marini P. 1994 - On the importance of a careful characterisation of decoration stones aimed to durability assessment: an example of faked aesthetic equivalence in stones used in public buildings lining in Turin. *Atti 7° Int. Congr IAEG, Lisbon 5 - 9 september 1994. (in press)*

Mamillan, M. Recent knowledge of the physical properties of building stones. Industrie Minérale - Les Techniques, pp. 287-299. 1982

Mancini R., Marini P. 1994 - Confronto fra due metodi di prova di resistenza a trazione indiretta per le rocce. *Renc. Jeunes Cherch. Geol. Appl., Lausanne 21 April 1994*, 135-139.

Massey, SW. Chapter on "Modelling - Fractal analysis of particulate deposition". *Particulate Pollution and Stone damage.* Eds. Watt, J. and Kendall,M.. EC contract EV5V-CT94-0519.

Michalopoulos, A.P., Et al. Influence of water on hardness, strength and compressibility of rock. Bull. Of the Ass. Of Eng. Geologists, Vol. XIII, No. 1, pp. 1-22. 1976

Mirwald, P.W. Evaluating damage and accelerated exposure and field studies: Modelling techniques. pp. 111-123

Mobbs, S.F., Et al. Low temperature thermoluminescence of marble and its possible correlation with stress history. Modern Geology, 8, pp. 149-154. 1984

Mix P.E., 1987 *Introduction to Nondestructive Testing* (New York:J. Wiley &Sons Eds.,

Merks J.W., "Sampling in exploration: theory and practice", in Sampling practices in the minerals industry, *Australasian Institute of Mining and Metallurgy,* Publication series No 10/92 p. 59-63, Parkville, Vic. 1992.

Molli G. & Heilbronner R. 1999 Microstructures associated with static and dynamic recrystallization of Carrara marble (Alpi Apuane Toscana NW, Italy). Geologie en Mijnbouw 78, 119-126.

Mamillan M. " *Methodes d'evaluation des degradations des monuments en pierre*". In the Procceding of the VIth Intern. Congress on Deterioration and Conservation of Stone, Torun 12-14.09.1988, 456-465.

Martin J., M. M. J. (1997). A new protocol for quantifying capillary water absorption by porous building materials. 4th International Symposium on the Conservation of Monuments in the Mediterranean , Rhodes.

Marini P. 1994 - Degrado artificiale in rocce ornamentali: una prova di invecchiamento accelerato in camera climatica. *Giornata di Studio in Memoria del Prof. S. Zucchetti, Torino 12 maggio 1994, Politecnico. (in press)*

Massey, S W.. The effects of ozone and NO_x on the deterioration of calcareous stone, *The science of the Total Environment*, 227, 1999, pg 109 – 121.

Meng, B., 1993: *Characterization of pore structure for structure for the interpretation of moisture transport. Conservation of Stone and Other Materials*: Proceedings of the International RILEM/UNESCO Congress, New York, E &FN Spon, 155-162.

Mirwald P.W., and Bruggerhoff S. 1997 Requirements for and Interpretation of Accelerated and Field Testing. Saving Our Cultural Heritage. The conservation of Historic Stone Structure. Ns. Baer and R. Snethlage Eds., J. Wiley & Sons Ltd. 254-267.

Nielsen K. et P. Schimmelwitz "*Deux méthodes pour caractériser des processus lors de l'altération de pierres de construction*" In the Proceedings of the 2nd Intern. Symposium on the Deterioration of Building Stones. Athens, Sept 27- Oct. 1 1976, 127-131.

Nielsen, T.P.H. Bjergarters fysisk/mekaniske egenskaber. Betonforskningslaboratoriet, Karlstrup, BFL intern rapport nr. 242, oktober 1970

Nimis, P.L., Pinna, D., Salvadori O. (1992) Licheni e conservazione dei monumenti C.L.U.E. Ed., Bologna.

Nolen-Hoeksema R., Et al. Optical Detection of Crack Patterns in the Openin-Mode Fracture of Marble. Int. J. Rock Mech. Sci. & Geomech., 24, pp. 135-144. 1987

NORMAL AA.VV. "Protectives Experimentation Subgroup" "*Methodology for the evaluation of protective products for stone materials, part II: experimental tests on treated samples*". In the Proceedings of the International Colloquium on "Methods of Evaluating Products for the Conservation of Porous Buildings Materials in Monuments", Roma 19-21-June 1995, 301-316.

Nwaubani,S. O., Mulheron, M., Tilly, G.P. and Schwamborn, B., 2000: Pore-structure and water transport properties of surface-treated building stones. *Materials and Structures*, Vol.33, 198-206.

Marmorbeklædning . (Marble cladding, in Danish). RAMBØLL internal report, (in Danish) 1998

Anchoring thin-stone veneers .Architecture, Dec. 1993, pp. 105-107. 1993

EOS of carbonates. Dep. Of Geological Sciences, Cornell University (Mineral Physics Lab), homepage, 2pp. (2000)

Wintry discontent. Architecture, October 1998

Final appeal No. 21 of 1998 (civil). www.info.gov.hk 1998

Curling of concrete slabs, 3p. www.lafargecorp.com/ttt_ccs.htm. 1999

Denomination of natural stone.CEN prEN12440:1996 (WI 00246029). 1996

Natural Stones - marble granite stone directory. Studio marmo, Firenze. 1998

Oliveira, R, Et al. Comparison of weathering resistance of some building stones based on treatments simulating different external conditions. Proc. 7th Int. Con. Int. Ass. Of Eng. Geology, pp. 3613-3618. 1994

Ordaz, J., Esbert, R.M. Porosity and capillarity in some sandstone and dolomite monumental stones. Proceeding 5th International Congress on Deterioration and Conservation of stone, 1, Lausanne. 1985

Papadopoulos, Z., Et al. On the anisotropy of the athenian schist and its relation to weathering. Bull. Of the Ass. Of Eng. Geologists, No. 45, pp. 111-116. 1992

Perrier, R., Et al. Thermal decohesion in marble and marmoreal limestone. www.informstone.es/t4.html, 21 p. 1999

Perrier, R. La descohesión térmica en mármoles y calizas marmóreas, pp. 59-71. Investigacion y Desarrollo

Quessier A., F. Girardet, V. Furlan "*Mesure de cohesion et tenur en soufre des couches superficielles de la pierre alteree par la pollution atmospherique*" In the Procceding of the VIth Intern. Congress on Deterioration and Conservation of Stone, Torun 12-14.09.1988, 475-483.

Panozzo Heilbronner R. 1992 The autocorrelation function : an image processing tool for fabric analysis. *Tectonophysics.* 212, 351-370.

Pantani L., Ballerini G., Cecchi G., Edner H., Lagnoli D., Johansson T., Raimondi V., Svanberg S., Tiano P., Tomaselli L., Weibring P. "*Experiments on stony monument monitoring by lased-induced fluorescence*". Journal of Cultural Heritage, vol 1, n 1, 2000, 345-348.

Prim P., F.H. Wittmann "*Methode de mesure de l'effet consolidant de produits de traiment de la pierre*". In Proceedings of Vth International Congress on Deterioration and Conservation of Stone. Lausanne 25-27.9.1985, Press Polythniques Romandes, vol 2, 787-794

Reeder, J., Et al. Carbonates: mineralogy and chemistry. Reviewes in mineralogy Vol. 11, Mineralogical society of America, pp. 400. 1983

Renard, F. Pressure dissolution: A mechanism of viscous deformation in rocks. Web (2000)

Ridout, G. Thin stone cladding defects. Technical Forum Building Technical File No. 26 July. 1989

Rink, M. Et al. Pore structure and physical properties of porous sedimentary rocks. Pageoph, Vol. 114 , Basel. 1976

Rodrigues, J.D. Causes, Mechanisms and measurement of damage in stone monuments, pp. 125-137

Rosenholz, J.L., Et al. Linear thermal expansion of calcite, Var. Iceland Spar, and Yule marble. The American Mineralogist, 34, P. 46-854. 1949

Rossi-Doria, P. Pore structural analysis in the field of conservation: state of the art and future developments. C.N.R. Centro "Conservazione Opere d'Arte, Roma, Italia, 32pp.

Rosso-Doria, P, Et al. Viellissement naturel et artificiel des pierres: Eventuelles relations decelables a l'aide de mesures porosimetriques. The conservation of stone I, International symposium, Bologna, ed. Rossi-Manaresi, pp.749-61. 1976

Royen, N. Naturstenens tekniska egenskaber och dess användning till husbyggnader och skyddsrumsäläggningar (in Swedish)
Transactions of Chalmers University of Technology, Gothenburg, no. 8, p. 16. 1942

Royen, N. Undersökningar Rörande sprickbildninger i kalkstensplattor (Investigation of crack-formation in limestone plates, in Swedish) Byggmästaren, nr. 16, Allmänna Uppl. 11, pp. 81-84. 1933

Royer-Carfagni, G., Et al. The characterization of marble by cyclic compression loading: experimental results. Mechanics of cohesive-frictional materials, 6th March, pp. 29. 2000

Royer-Carfagni, G. A model for the characterization of damage in cyclically loaded stones. XIV congresso nazionale dell'associazione italiana di meccanica teorica ed applicata, Como. 6-9 Ottobre. 1999

Royer-Carfagni, G. Some considerations on the warping of marble facades: the example of Alvar Aalto's Finland Hall in Helsinki
Construction and Building Materials, 13, pp. 449-57. 1999

Royer-Carfagni, G.F. On the thermal degradation of marble. International journal of Rock Mechanics and Mining sciences, 36, pp. 119-126. 1999

Sage, J.D. Thermal microfracturing of marble. Engineering Geology of Ancient Works, Monuments and Historical Sites, pp. 1013-1018. 1988

Sahlman, L. Et al. Varför böjer sig marmorplattor på fasader? Sten 2/97. 1997

Sarsàno, R. L'applicazione del marmo nei rivestimenti di facciata: analisi di laboratorio e studio del costruito per la prevenzione del degrado legato alle deformazioni permanenti Tesi di Laurea, Politecnico di Torino, Facoltà di Ingegneria. 1998

Scavuzzo, R. Et al. In-place load testing of a stone cladding anchorage system. STP 1394 Dimension Stone Cladding: Design, Construction, Evaluation and Repair , November, pp 177-184. 2000

Schaffer, R.J.The Weathering of Natural Building Stones. Building Research, special report No. 18. 1932

Scheffler, M.J. Et al. Natural weathering of granite: A case study. STP 1394 Dimension Stone Cladding: Design, Construction, Evaluation and Repair, November, pp 79-94. 2000

Schouenborg, B. Et al. Testing of nordic natural stone. Nordtest - projekt 1019-91, technical report 236 or SP report 1994:19. 1994

Shadmon, A. Environmental implications of surface treatment of building stones and ornamental rocks. 7th International IAEG Congress, Balkema, Rotterdam pp. 3677-3682. 1994

Sheremeti-Kabashi, F. Et al.. Determination of structural anisotropy of Carrara marble with ultrasonic measurements
9th International Congress on deterioration and conservation of stone, Venice 19-24 June. 2000

Siegesmund, S, Et al. Marble as a natural building stone: rock fabrics, physical and mechanical properties
Z. Deutsch. Geol. Ges. 150 (2) pp. 237-258. 1999

Siegesmund, S., Et al. Deterioration characteristics of columns from the Marmorpalais Potsdam (Germany) by US-tomography

Proceedings 19. Int. Congress Deterioration of Stones, Venice, Elsevier (in press). 2000

Siegesmund, S., Et al. Marmor als Werk- und Denkmalsgestein. Z. Deutsch. Geol. Ges. 150 (2) pp. 193-406. 1999

Siegesmund, S., Et al. Physical wheathering of marbles caused by anisotropic thermal expansion. Int. J. Earth Sciences, 89, pp. 170-182. 2000

Siegesmund, S., Et al. Die Anwendung der geologischen Gefügekunde für die Charakterisierung natürlicher Werksteine - Fallbeispiel Kauffunger Marmor Int. J. f. Restoration of Buildings and Monuments, 3, pp. 269-292. 1997

Siegesmund, S., Et al. Control of marble weathering by thermal expansion and rock fabrics. Proceedings 19. Int. Congress Deterioration of Stones, Venice, Elsevier (in press). 2000

Slaton, D., Scheffler, M.J. Failures. Why things bow. www.csinet.org 2001

Smith, M.R. Stone: Building stone, rock fill and armourstone in construction. The Geological Society, pp. 475. 1999

Solinski, Joseph P. Thin stone veneer/Study and remediation. STP 1394 Dimension Stone Cladding: Design, Construction, Evaluation and Repair , November, pp 161-177. 2000

Sorace, S. Long-term tensile and bending strength of natural building stones. Materials and Structures, Vol 29, August/September, pp 426-435. 1996

Stambolov, T., Et al. The deterioration and Conservation of Porous Building materials in Monuments. A Preliminary Review.
Central Research Laboratory for Objects of Art and Science, Amsterdam.. 1967

Stocksiefen, W. . Marmorschäden:Analyse und therapie. Naturstein, (12) 1996

Suenson, E Byggematerialer, Natursten, 3rd volume. (Building materials, Natural stones, in Danish). Jul. Gjellerups Forlag, København. 1942

Schaffer, R., J. "*Causes of deterioration of building materials. I Chemical and physical causes"*. Chemistry and Industry, **23**, 1967, 1584-1586.

Schmid J., et al. 1999 A quantitative fabric analysis approach to the discrimination of white marble. *Archeometry,* 239-252.

Shaw W.J., Khosrowshahi S., Horton J., Waltho A., 1998 "Predicting and monitoring variability of sampling, sample preparation and assaying", *Bull. Aust. Inst. Geosci*., No 22, p. 11-19.

Simon, S., Snethlage, R.: 1996 Marble Weathering in Europe - Results of EUROCARE EUROMARBLE Exposure Programme 1992 - 1994. In: J. Riederer (ed.), *Proceedings 8th Intern. Congress on Deterioration and Conservation of Stone*, p. 159-166, Berlin, 1996.

Sizov B. (1996). Evaluation of moisture content measurement in stone. 8th International congress on deterioration and conservation of stone.
Snethlage, R. (1999): Marble Conservation in Germany - A Brief Account on the State of the Art. Bauwerkserhaltung, Festschrift 65. Geburtstag Prof. H.-R. Sasse, S. 87-108, RWTH Aachen 1999.

Snethlage, R., Ettl, H., Sattler, L.: Ultraschallmessungen an PMMA-getränkten Marmorskulpturen. *Z. dt. Geol. Ges*. 150/2, s. 387-396, Stuttgart 1999.
Snethlage, R., He Ling, Ma Tao, Wendler, E., Sattler, L., Simon, S.: Der Sandstein von Dafosi - Untersuchungen zu den Ursachen der Schäden und zur Konservierung. In: *Der Große Buddha von Dafosi*, Arbeitshefte des Bayerischen Landesamtes für Denkmalpflege, Band 82, S. 220-239. München, 1996.

Snethlage R., E. Wendler, L. Sattler "*The application of laboratory processes and studies to real structures*" In Proceedings of the Symposium on Science, Technology and European Cultural Heritage, Bologna 13-16 June 1989. Butterworth-Heinemann Ltd., Oxford, England, 1991, 255-268

Stoeppler M. ed.,1997 "Sampling and sample preparation", Springer-Verlag, ISBN 3-540-61975-5, 202pp, Berlin.

Theoulakis P, M. A. (1997). Porous stone decay by ssalt crystalization. The case of the building material of the Medieval City of Rhodes. 4th International Symposium on the Conservation of Monuments in the Mediterranean , Rhodes.

Thomasen, S.E., Et al. Durability of thin-set marble. Proc. 3rd int. conf. on durability of building materials and components, ASTM, pp. 313-323. 1984
Thomasen, S.E., Et al. Assessment of building facades in masonry and stone. ASTM STP 1098, eds. Kelley and Marshall, pp. 108-116. 1990

Tiano P., C. Manganelli Del Fà, U. Matteoli, E. Pecchioni, F. Piacenti "*Nuove tecniche di valutazione del grado di coesione di superfici lapidee*". In Atti del Convegno di Studi Scienza e Beni Culturali, Bressanone 24-27 Giugno 1986, Libreria Progetto Ed., 1986, 527-541.

Tiano P. "*Biodeterioration of Stone Monuments. A Critical review*" in Biodeterioration of Cultural Heritage vol I, K.L. Garg, N. Garg & K.G. Mukerji Eds., Naya Prokash Publ. Calcutta, 1994, 301-321.

P. Tiano, C. Manganelli Del Fà "*Valutazione della consistenza superficiale dei materiali lapidei*" in Atti del Convegno di Studi n° 10 Bilancio e Prospettive, Bressanone 5-8 Luglio 1994, Libreria Progetto ed., Padova, 1994, 41-53

Tiano, P., Accolla, P. and Tomaselli. L., (1995) Phototrophic Biodeteriogens on lithoid surfaces: an ecological study. Microbial Ecology, vol 29 n° 3, 299-309.

standardisable methodology to determine the stone cohesion: Prototype design and validation" International Zeitschrift für Bauinstandsetzen und Baudenkmalpflege 6, Jahrgang, Aedificatio Publisher, Heft 2, (2000), 115-132.

Tiano P., Filareto C., Ponticelli S., Ferrari M., Valentini E., "*Drilling force measurement system, a new*

Tiano P., Viggiano A., *"A new diagnostic tool for the evaluation of the hardness of natural and artificial stones*" International Journal for Restoration of Buildings and Monuments, vol 6, n° 5 (2000), 555-566

Tiano P. "Una nuova metodologia per la valutazione "in situ" dei trattamenti consolidanti delle pietre monumentali – DFMS" ARKOS Scienza e Restauro, 2/2001, UTET Periodici, 2001, 42,49

Tiano P., "The use of microdrilling techniques for the characterization of stone materials" RILEM TC177 MDT International Workshop on "Site control and non destructive evaluation of masonry structures and materials", Mantova (I), 12-13 Nov. 2001 (in press).

Tiano P., Delgado Rodriguez J., De Witte E., Verges-Belmin V., Massey S., Snethlage R., Cadot-Leroux L., Garrod E., Singer B. *"The conservation of monuments: a new method to evaluate consolidating treatments*" International Journal for Restoration of Buildings and Monuments vol 6, n 2, (2000), 133-150.

Till R., 1974 "Sampling and Test of Significance", in *Statistical Methods for the Earth Scientist*, Mc Millan, London, p. 47-81.

Yates, T.J.S. and Butlin, R.N. 1996. Predicting the weathering of Portland limestone buildings. In *Processes of Urban Stone Decay* (Eds) Smith, B.J. and Warke, P.A., 194-204, Donhead, UK

Urzì, C., Realini, M., (1996) Bioreceptivity of Rock Surfaces and Its implication in Colour Changes and Alteration of Monuments, Study Case of Noto's Calcareous Sandstones. Dechema Monographs vol 133, VCH Ed.,151-159.

Valdeon, L., King, de Freitas, M., (1992) Ultrasonic methods for quantifying the degradation of building stones. 7th International congress on deterioration and conservation of stone.

Vardoulakis I., E. G., Kurkoulis S, Papadopoulus C (1997). Characterization of mechanical and damage of natural building stones in historical monuments. 4th International Symposium on the Conservation of Monuments in the Mediterranean , Rhodes.

Vellet J.M., V.Verges- Belmin, V. Romanosky. " *Efficacitè des produits employes pour la conservation de la pierre en France: premiers resultats d'une enquete menee aupres des professionnels de la conservation*". In the Proceedings of the International Colloquium on "Methods of Evaluating Products for the Conservation of Porous Buildings Materials in Monuments", Roma 19-21-June 1995, 275, 282.

Warscheid, T., Petersen, K. & Krumbein, W.e:, (1988) Effect of cleaning on the distribution of microorganisms on rock surfaces. In Biodeterioration 7, D.R.Houghton, R.N. Smith and H.O.W.Eggings Eds., Elsevier Applied Science Publ. 455-460.

Weiß, T., Et al. Microfabric of fresh and weathered marbles: Implications and consequences for the reconstruction of the Marmorpalais Potsdam. Z. Deutsch. Geol. Ges. 150 (2) pp. 313-332. 1999

Weiss, T., Et al. Microfabric of fresh and weathered marbles and its implication on the weathering phenomena observed at the Marmorpalais in Potsdam (Germany). Proceedings of the 9th Workshop EUROCARE-EUROMARBLE (EU 496), Forschungsbericht, Bayerisches Landesamt für Denkmalpflege, 17, pp. 15-30. 1998

Weiss, T., Et al. The relationship between deterioration, fabric, velocity and porosity constraint. Proceedings 19. Int. Congress Deterioration of Stones, Venice, Elsevier (in press). 2000

Wenk, H.R., Et al. Comparison of neutron and x-ray diffraction in texture analysis of deformed carbonate rocks. Journal of structural geology, 6(6), pp. 687-92. 1984

West, David G., Et al. Anchorage pullout strength in granite: Design and fabrication influences. STP 1394 Dimension Stone Cladding: Design, Construction, Evaluation and Repair, November, pp 121-137. 2000

Wheeler, N.E. On the thermal expansion of rock at high temperatures. Transactions of the Royal Society of Canada, Ser. III, iv. 1910

Widhalm, C., Et al. Acoustic emission and anisotropic expansion when heating marble. Journal of the performance of constructed facilities, 11(1), pp. 1-6. 1997

Widhalm, C., Et al. Anisotropic thermal expansion causes deformation of marble claddings. Journal of the performance of constructed facilities, 10(1), pp. 5-10. 1996

Willis, T.F., Et al. Thermal volume change and elasticity of aggregates and their effect on concrete.

Wiman, Sten. A preliminary study of experimental frost weathering. Geografiska Annaler, Svenska Sällskabet för Antropologi och Geografi, XLV, pp. 113-121. 1963

Winkler, E.M. A durability index for stone. Proceeding 5th International Congress on Deterioration and Conservation of stone, 1, Lausanne, p 151-156. 1985

Winkler, E.M. Buttressed expansion in granitic rocks in the field and on buildings. 4. Int. Kolloquium Werkstoffwissenschaften und Bauinstandsetzen, pp. 537-542. 1996

Winkler, E.M. Properties of marble as a building material. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 33(2), pp. 215-18. 1996

Winkler, E.M. Weathering of crystalline marble. Engineering geology of ancient works, monumnets and historical sites, ed. Marinos, P.G., and Koukis, G.C., Balkema, Rotterdam, pp. 717-721. 1988

Winkler, E.M. Weathering of crystalline marble at the field museum of Natural History, Chicago. APT Bulletin (The Assoc. Preservation Technoco, Vol. XXIII, No.4). 1991

Winkler, H.G.F. Metamorphic reactions in carbonate rocks, chapter 9, Petrogenesis of metamorphic rocks, 5th ed.

Wonneberger, B., Et al. Comparing Laboratory and Field Durability Testing of Stone. 8th Int. Conf. On Durability of Building Materials and Components, Vancouver, Canada. 1999

Yates, T.J.S., Et al. Lightweight veneer stone cladding panels. BRE Information paper; IP 17/98. 1998

Yates, T.J.S., Et al. Stone cladding panels: in-situ weathering. BRE Information paper; IP 18/98. 1998

Zezza, U., Et al. Effect of temperature on intergranular decohesion of the marbles. Proc. 5th int congr. on deterioration and conservation of stone vol. 1, ed. G. Felix, Lausanne, France?, pp. 131-140 . 1985.

Zezza, U. Decay evolution depending on the textural anisotropy of marbles in monuments. Proc. 2nd International Symposium, The conservation of monuments in the Mediterranean Basin, pp. 289-302. 1991

Zehnder, K.: Gypsum Efflorescence in the Zone of Rising Damp. Monitoring of Slow Decay processes Caused by Crystallizing Salt on Wall Paintings. 8th International Congress on Deterioration and Conservation of Stone, Berlin, (1996) 1669-1678.

Zezza, U. Influence of mechanical anisotropic behaviour to tensile strength on decay evolutions of marbles in monuments. Conservations of Stones and Other Materials, RILEM, pp. 220-226. 1993

Zezza, U. L'anisotropia fisico-meccanica delle pietre da costruzione e il rilevamento in situ sul patrimonio architettonico a mezzo prove non distruttive Atti Conv. Int. "Il recupero degli edifici antichi. Manualistica e nuove tecnologie" (Napoli), pp. 425-432. 1993

Van Hemelrijck Danny, A. Athanassopoulos,1996 "Non Destructive Testing*", Proc. First Joint Belgian-Hellenic Conference*, Patra 1995, A.A. Balkema, Rotterdam.

Van der Klugt L., Koek J., and Van Hess R. 1995 Some test methods for stone-like materials to be considered for Rilem reccommendation. . *In Evaluation and strengthening of existing masonry structures*. Proceeding of the Joint Int. Workshop RILEM TC 127 MS and CIB W 23. L. Binda and C. Modena Eds. University of Padua Publisher, 143- 161.

Vutukuri V.S., R.D. Lama and S.S. Saluga, 1974 "*Handbook on Mechanical Properties of Rocks*", Vol. I, Trans Tech Publications.

Zezza F., F. Racaniello, P. de Bellis, T. Carofiglio "*L'indice di resistenza quale parametro di diagnosi nella classificazione di calcareniti alterate*" In Atti del 1° Simposio Internazionale La conservazione dei monumenti nel bacino mediterraneo. Bari 1989. F. Zezza Ed., 329-333.

Bearman, R. A., (1999): "The use of the point load test for the rapid estimation of Mode I fracture touvhness". Int. J. Rock Mech. Min. Sci. 36 (1999) 257-263.

Bodare, A. (1998). Non destructive test methods of stone and rock. Geo Texts & Publications en http://www.geoforum.com.

Bradley, F., 1998 – Natural Stone - A guide to selection. Studio Marmo, pg. 286, W.W.Norton & Co, New York/ London.
Broch, E. and Franklin, J.A. (1972). The point load strength test. Int J Rock Mech Min Sci vol 9, pp. 669-697.

Brook, N. (1985). The equivalent core diameter method of size and shape correction in point load testing. Int J Rock Mech Min Sci and Geomech Abstr., vol. 22 (2), pp. 61-70.

Brook, N. (1982). Small scale brittle model studies of mine roadway deformation. In: Farmer IW, editor. Proc Sym Strat Mechanics Developments in Geotechnical Engineering, 32. Elsevier, pp. 184-189.

Cargill J. S. and Shakoor A., Evaluation of empirical methods for measuring the uniaxial compressive strength of rock. Int. J. Rock Mech. Min. Sci. & Geomech. Abst., 1990, 27, 495-503.

Carvalho, C. & Moura, A. C., 1999 – Rochas naturais: Estudo comparativo dos desgastes Amsler e Capon. Boletim de Minas, vol. 36, nº 3, pp. 301-307, IGM, Lisboa.

Castaing, Ch. & Rabu, D., 1993- Méthodologie pour la recherche des roches exploitables: exemples des granits armoricains. Mines & Carrières. Les Techniques, May/1993.

CEN Standards for stone products- EN 1341, EN 1342, EN1343, prEN 1467, prEN 1468, prEN 1469, prEN 12057, prEN 12058, prEN 12059, EN 12326-1, EN 771-6

CEN Standards for stone testing - EN 1925, EN 1926, EN 1936, EN 12370, EN 12371, EN 12372, EN 12407, EN 12670, EN 13161, EN 13364, EN 13755, prEN 13373, EN 14157, EN 14158, WI 00246011, WI 00246012, WI 00246016.

CEN TC 125-WG 6, 1990 – Doc N 142 - Classes d'exposition en fonction des conditions d'environement. Exigeances de durabilité en fonction des conditions d'environement. Extrait de document de travail du G.F. des Bétons, pg. 2, 1990.

Day M. J. and Goudie A. S., Field assessment of rock hardness using the Schmidt Test Hammer. British Geomorph. Res. Gp. Tech. Bull., 1997, 18, 19-29.

Departament d'Enginyeria del Terreny, Cartogràfica i Geofísica, Universitat Politècnica de CatalunyaEnsayo de carga puntual.
http://www.etcg.upc.es/asg/engeol/pdf_files/4.4ensayo_txt.pdf

Garcia, E. O., 1995 – Investigación de yacimientos, in Manual de Rocas Ornamentales, C. L. Jimeno (Ed.), pp 139-174, Madrid.

Goktan R. M. and Ayday C. A., Suggested improvement to the Schmidt rebound hardness ISRM suggested methods with particular reference to rock machineability. Int. J. Rock Mech. Min. Sci. & Geomech. Abst., 1993, 30, 321-322.

Greminger, M. (1982). Experimental studies of the influence of rock anisotropy on size and shape e€ects in point-load testing. Int J Rock Mech Min Sci and Geomech Abstr., vol. 19, pp. 241-246.
Hucka V. A rapid method of determining the strength of rocks in situ. Int. J. Rock Mech. Min. Sci. & Geomech. Abst., 1965, 2, 127-134.

Hudson, J.A. (1993). Rock properties, testing methods and site characterisation. In: Hudson JA, Brown ET, Fairhurst C, Hoek senior E, editors.

Comprehensive rock engineering principles, practice and projects, 3. Pergamon Press, Pp. 46-51.

IICE - Instituto lnternazionale di Commercio Estero (l982) - Marmi Italiani, F.lli Vallardi (Éd.), Milano.

ISRM. Suggested methods for determining hardness and abrasiveness of rocks. Int. J. Rock Mech. Min. Sci. & Geomech. Abst., 1987, 15, 89-97.

ISRM. (1972). Suggested method for determining the point load index. Committee on Field Tests, Document No. 1, pp 8-12.

ISRM. (1985). Suggested method for determining point load strength. J.A. Franklin (working group co-ordinator). Int J Rock Mech Min Sci and Geomech Abstr, vol. 22 (2), pp 51-60.

ISRM. (1985). Suggested Method for Determining Point Load Strength. International Society for Rock Mechanics,

Commission on Testing Methods, International Journal of Rock Mechanics and Mining Sciences and Geotechnical Abstracts, Vol 22, No. 2, pp 51- 60.

Kahraman, S. (2001a). A correlation between P-wave velocity, number of joints and Schmidt hammer rebound number. Int. J. Rock Mech. Min. Sci. 38, 729-733.

Kahraman, S. (2001b). Evaluation of simple methods for assesing the uniaxial compressive strenght of rock. Int. J. Rock Mech. Min. Sci. 38, 981-994.

Kahraman, S. Et al, (2002): "Predicting the Schmidt hammer values of in-situ intact rock from core sample values". Int. J. Rock Mech. Min. Sci. 39, 395-399.

Katz, O., Reches, Z., Lyakhovsky, V. and Baer G., Rock Damage at the Proximity of Small Faults: Field Measurements of Elastic Wave Velocity and Elastic Rebound. In AGU 1999 Spring Meeting, EOS, Transaction, American Geophysical Union, 1999, 80, 17 Supplement, 335-336.

Katz, O., Reches, Z., Roegiers, J-C. (2000). Evaluation of mechanical rock properties using a Schmidt Hammer. International Journal of Rock Mechanics and Mining Science, vol 37, pp 723-728.

Kolaiti E. and Papadopoulos Z. Evaluation of Schmidt rebound hammer testing: a critical approach. Bulletin of the Inter. Ass. of Engineering Geology., 1993, 48, 69-76.

Montani, Carlo, 2001 - STONE 2000-World Marketing Handbook. Faenza Editrice, pg 175, 2000.

Moura, A. Casal, et alia, 2000 – Granitos e rochas similares de Portugal. I.G.M. Ed.), pg 180, Jul/2000.

Muñoz, P., 1989 – La investigación minera de la piedra natural. Roc-Máquina, 3º Trim / 1989.

Poole R. W. and Farmer I. W., Consistency and repeatability of Schmidt Hammer rebound data during field testing. Int. J. Rock Mech. Min. Sci. & Geomech. Abst., 1980, 17, 167-171.

Quick, G., 2000 – The CSIRO "BEST" methods for evaluating stone tiles. Roc-Máquina nº 37, pp 44-53, Jun 2000.

Reichmuth, D. R. (1968). Point load testing of brittle materials to determine tensile strength and relative brittleness. In: Proc of the Ninth Sym on Rock Mech. University of Colorado, pp. 134-59.

Shadmon, Asher, 1996 – Stone. An introduction. Ed. ITP, London,1996.

Schmidt E., A non-destructive concrete tester. Concrete,1951, 59, 8, 34-35.

Smith, H. J. (1997). The Point Load Test for Weak Rock in Dredging Applications. Int. J. Rock Mech. Min. Sci. 34, 702.

Sousa, L. M., 2000 – Estudo da fracturação e das características físico-mecânicas de granitos da região de Trás-os-Montes com vista à sua utilização como rocha ornamental. Dissertação de Doutoramento, UTAD, Vila Real.

Tugrul A. & Zarif, I. H. (1999). Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey". Engineering Geology 51, 303-317.

University of Alberta: "Index testing for rock properties".
http://www.civil.ualberta.ca/SMPE/Facilities/Index%20Tests.doc
US Army Engineer Waterways Experiment Station. (1982).

Proposed Standard for Determination of the Point Load Index for Rock. in Rock Testing Handbook, RTH-325-82.

Vicksburg, M.S. (1989). Suggested Method for Determining Point Load Strength. Rock Testing Handbook, RTH-325-89.

Winkler, E. M., 1997 - Stone in Architecture. Properties, Durability. Springer-Verlag (Ed.), 3d Ed., pg. 314, Berlin.

Yaalon D. H. and Singer S., Vertical variation in strength and porosity of calcrete (nari) on chalk, Shefela, Israel and interpretation of its origin. Journal of sedimentary Petrology, 1974, 44, 4, 1016-1023.