ORNAMENTAL STONES network

EUROPEAN COMMISSION
Competitive and Sustainable Growth Programme

Stone for Construction and Architecture
from Extraction to the Final Product

OSNET Editions
Volume 10

Edited by: M. Founti
EUR 20637/10

Published and printed by the
Laboratory of Metallurgy,
National Technical University of Athens
GR-157 80 Zografos, Athens, Greece
Athens 2004

Forward

This edition of the "Technology Transfer Sector" of the OSNET Network covers a significant need of stone professionals and consumers concerning the right selection and use of the stone products in construction applications. It includes all the necessary information and material to understand the stone aesthetic and technical characteristics, the stone selection and application criteria and stone conservation and maintenance issues. I believe that this edition is a remarkable contribution in the application of stone products and significantly narrows the gap between stone producers, end-users and applicants.

Prof. I. Paspaliaris

OSNET Coordinator

Preface

The last thirty years have undoubtedly been a golden age for natural stone with its long string of successes and rediscovery by architects and the design world. As is generally believed, one of the principal reasons for its success is that it is no longer tied to its superstructures heritage dating back to the 40's. Technological progress in the production and processing cycles has been a decisive factor and natural stone has in fact evolved, albeit later than its rivals, into a real industry.

From the beginning of the century, designers had preferred concrete, steel, glass and ceramics to natural stone because of the advantageous prices, ready availability and easy installation of these materials. Natural stone was obviously at a disadvantage since it was unable to cope with the large quantities required by the architectural world during that period which had to come to grips with the new mass societies and the need for large buildings as fast as possible. This discrimination was perhaps founded when quantity was the important factor yet this did not stop it being used in great works of artistic value. Thus, the belief that the ideals of the International Modern movement and after were contrary to the use of stone is only partly true. In fact, when natural stone completed its technological evolution between the mid 60s and the mid 70s, it became a widely used material in world architecture. Moreover, it was chosen as now for its unique qualities.

Today, more than 60 million tons of stone materials are quarried all over the world, compared to approximately 20 million tons in the early Eighties. More and more new countries are being involved in this industry, in addition to the traditional producer countries. New products with versatile aesthetic, mechanical and physical properties are continuously being developed and enter the market. It gradually becomes clear that only stone can guarantee the production of large units and thickness required for long-term architectural projects that follow through to the final details of the building. Floors and facings always start off on the designer's drawing board where they are created with specific shapes, joints and colour combinations for a specific place and a specific use. However, a large group of architects, constructors and stone applicators still conceive the use of stone, based essentially on its ornamental qualities (colour, vein patterns, various decorations), yet not forgetting its material solidity.

"STONE FOR CONSTRUCTION & ARCHITECTURE" aims to serve as a guide-book for professionals in the building – construction sectors, wishing to learn more about the origin, extraction techniques, recognition, characteristics, classification, potentials and new products emerging in the ornamental stone sector. For this purpose, the edition is organised in nine chapters, dealing with issues relating to terminology and classification of dimensional stones, their commercial characteristics, transformation of stones from rock to final products, non-destructive testing methods, product types and selection criteria and, last but not least, new types of products and related innovative uses.

Maria Founti

Technology Transfer Sector Leader

Marcantonio Ragone

Internazionale Marmi e Macchine Carrara S.p.A.

Contributors

Blasi Paola – Ch 1 – 3 - 5
(Internazionale Marmi e Macchine Carrara)
Viale Galilei 133
54036
Marina di Carrara
Italy
p.blasi@immcarrara.com

Bradley Frederick - Ch 2
(Internazionale Marmi e Macchine Carrara)
Viale Galilei 133,
54036
Marina di Carrara
Italy
f.bradley@immcarrara.com

Dominguez Luis e. Opes – Ch 4
(Asociacion de Investigation de Industias de la Construccion - AIDICO.IDI, Investigacion Y Desarrollo Industrial)
Parque Tecnologico de Valencia,
46980Paterna
Valencia
Spain

Fusco Mariano
(Consorzio E.R.IC.A)
Via Dorsale 13
54100, Masssa
Italy
erica@bicnet.it

Founti Maria – Preface - Ch 1 - 2
(National Technical University of Athens School of Mechanical Engineering)
Heroon Polytechneiou 9
15780, Athens
Greece
mfou@central.ntua.gr

Fuente J.V. – Ch 4
(Asociacion de Investigation de Industias de la Construccion - AIDICO.IDI, Investigacion Y Desarrollo Industrial)
Parque Tecnologico de Valencia, Paterna
46980, Valencia
Spain
angel.lopez@aidico.es

Kontodimos Kostas – Ch 1 - 2
(National Technical University of Athens School of Mechanical Engineering)
Heroon Polytechneiou 9
15780 Athens
Greece
kkontod@central.ntua.gr

Laskaridis Kostas – Ch 5
(Institute of Geology and Mineral Exploration, LITHOS Laboratory, Dept. of Economic Geology)
1st Km Markopoulou Av.
19002 PAIANIA
Greece
lithosgr@otenet.gr

Lopez - Buendia Angel M. – Ch 4
(Asociacion de Investigation de Industias de la Construccion - AIDICO.IDI, Investigacion Y Desarrollo Industrial)
Parque Tecnologico de Valencia
46980 Paterna
Valencia
Spain
angel.lopez@aidico.es

Lopez Monteaguto Roberto – Ch 4
(Asociacion de Investigation de Industias de la Construccion - AIDICO.IDI, Investigacion Y Desarrollo Industrial)
Parque Tecnologico de Valencia
46980, Paterna
Valencia
Spain
robertolm@aidico.es

Manni Orazio - Ch 5
(Centro di Progettazione, Design & Tecnologie dei Materiali - CETMA.ENG)
Cittadella della Ricerca
S.S. 7 per Mesagne, km 7 +
72100, Brindisi 300
Italy
omanni@cetma.brindisi.enea.it

Modarelli Rosa - Ch 5
(Centro di Progettazione, Design & Tecnologie dei Materiali - CETMA.ENG)
Cittadella della Ricerca
S.S. 7 per Mesagne, km 7 +
72100, Brindisi 300
Italy

Ragone Marcantonio – Preface - Ch 5
(Internazionale Marmi e Macchine Carrara)
Viale Galilei 133
54036, Marina di Carrara
Italy
m.ragoane@immcarrara.com

Symons Raymond
(British Stone)
77 Compton Road
WV3 9QH - Wolverhampton
UK
raysymons@britishstone.demon.co.uk

Table of contents

1

Terminology and Classification of Dimensional Stones

MARIA FOUNTI, KOSTAS KONTODIMOS

The term “dimensional stone” commonly refers to "a natural building stone" that has been selected, trimmed or cut to specified shapes or sizes with or without one or more dressed surfaces [1][12]. This definition applies to rough blocks, slabs and polished stones used mainly in building, construction, monuments and funeral art.

1.1. GEOLOGICAL CLASSIFICATION OF ORNAMENTAL STONES

In Earth Sciences, rocks are classed according to their common origin, regardless of their macroscopic appearance, physical properties, fabric, mineralogical and chemical composition, which are considered as less important for the geological classification of rocks. To the geologists, any mass of mineral matter, whether consolidated or not, produced by natural processes either on earth or anywhere else in the universe, is a rock. Rocks usually consist of aggregates of one or more mineral species, and divided into three main groups according to their origin: Igneous, Metamorphic and Sedimentary.

1.1.1. Igneous rocks

These are produced by the cooling and crystallisation of silicate melt, (magma), on the surface of the earth or inside the earth. Generally speaking, igneous rocks have a crystalline appearance, although non-crystalline igneous rocks do occur. They include: basalt, gabbros, granite, syenite, diorite, anorthosite, etc.

Why we are so detailed about the origin of igneous rocks? The origin of the rock –any kind of rock- is correlating with the rocks' physico-mechanical characteristics. Therefore we must have an idea of the "petrogenesis" (the rock-forming process) in order to evaluate the quality of the rock.

1.1.2. Sedimentary rocks

These are rocks formed from materials derived from pre-existing rocks by processes of denudation, together with material of organic origin.

The term includes both consolidated and unconsolidated material; the process of conversion of unconsolidated to coherent sedimentary rocks is called diagenesis.

Rivers, oceans, winds, and rain runoff all have the ability to carry the particles washed off of eroding rocks [7]. Such material, called detritus consists of fragments of rocks and minerals. When the energy of the transporting current is not strong enough to carry these particles, the particles drop out in the process of sedimentation. This type of sedimentary deposition is referred to as clastic sedimentation. Another type of sedimentary deposition occurs when material is dissolved in water, and chemically precipitates from the water. This type of sedimentation is referred to as chemical sedimentation. A third process can occur, wherein living organisms extract ions dissolved in water to make such things as shells and bones. This type of sedimentation is called biogenic sedimentation. Thus, there are three major types of sedimentary rocks:

- Clastic sedimentary rocks
- Chemical sedimentary rocks
- Biogenetic sedimentary rocks

Table 1. Classification - Clastic sedimentary particles are classified in terms of size

Name of Particle	Size Range	Loose Sediment	Consolidated Rock
Boulder	>256 mm	Gravel	Conglomerate or Breccia (depends on rounding)
Cobble	64 - 256 mm	Gravel	
Pebble	2 - 64 mm	Gravel	
Sand	1/16 – 2 mm	Sand	Sandstone
Silt	1/256 - 1/16 mm	Silt	Siltstone
Clay	<1/256 mm	Clay	Claystone, mudstone, and shale

1.1.3. Metamorphic rocks

These resulted from the transformation of pre-existing rocks by heat, pressure and fluids within the earth's crust.

Metamorphic processes are considered as taking place in the solid state and involve re-crystallisation, changes in the fabric and mineralogical and chemical composition of the parent rock.

Some of the most common metamorphic rocks are: gneiss, mica schist, amphibolite, migmatite, phillite, marble.

The word "Metamorphism" comes from the Greek: Meta = change, Morph = form, so metamorphism means to change form. In geology this refers to the changes in mineral assemblage and texture that result from subjecting a rock to pressures and temperatures different from those under which the rock originally formed.

Metamorphic rocks result from mineralogical and structural adjustments of solid rocks to physical and chemical conditions differing from those under which the rocks originally formed. Changes produced by surface conditions such as compaction are usually excluded. The most important agents of metamorphism are temperature, and pressure. Equally as significant are changes in chemical environment that result in chemical recrystallization where a mineral assemblage becomes out of equilibrium due to temperature and pressure changes and a new mineral assemblage forms [8].

Table 2. Foliated (banded) rock classification

Metamorphic Environment	50-300 ^{o}C	300-450 ^{o}C	Above 450 ^{o}C
Metamorphic Grade	Low	Intermediate	High
Rock Name	SLATE	SCHIST	GNEISS
Rock Description	Minerals not visible with the naked eye or with a hand lens, rock shows slaty cleavage, is usually dark-coloured. A product of low-grade metamorphism of shale or mudstone.	Rock is medium to coarse grained with visible grains of mica or other metamorphic minerals. Often, shiny due to reflection of mica on foliation planes. Product of intermediate grade metamorphism of shale, slate, phyllite, basalt or granite.	Rock is coarse grained and usually banded with alternating layers of light and dark minerals. Foliation bands may be folded. Product of high-grade metamorphism of shale, schist, granite or many other rock types.

The mineral constituents of foliated metamorphic rocks are oriented in a parallel or sub parallel arrangement. Foliated metamorphic rocks are generally associated with regional metamorphism. Four kinds of foliated textures are recognized. In order of increasing metamorphic grade, these are slaty, phyllitic, schistose and gneissic.

Table 3. Non -foliated rock classification

	Marble	Quartzite	Anthracite Coal
Mineral(s)	Calcite	Quartz	Crystalline carbon
Description	Coarse-grained recrystallized limestone or dolomite. Typically harder than the protolith. May have dark bands due to organic impurities.	Rock has intergrown quartz grains, thus is massive and hard. Protolith is sandstone. Intermediate to high-grade metamorphism.	Hard, black shiny coal; product of low-grade metamorphism of bituminous coal.

- Slaty Texture - This texture is caused by the parallel orientation of microscopic grains. The name for the rock with this texture is slate, and the rock is characterized by a tendency to separate along parallel planes. This feature is a property known as slaty cleavage. (Slaty cleavage or rock cleavage is not to be confused with cleavage in a mineral, which is related to the internal atomic structure of the mineral.)
- Phyllitic Texture. This texture is formed by the parallel arrangement of platy minerals, usually micas, that are, barely macroscopic (visible to the naked eye). The parallelism is often silky, or crenulated. The predominance of micaceous minerals imparts sheen to the hand specimens. A rock with a phyllitic texture is called a phyllite

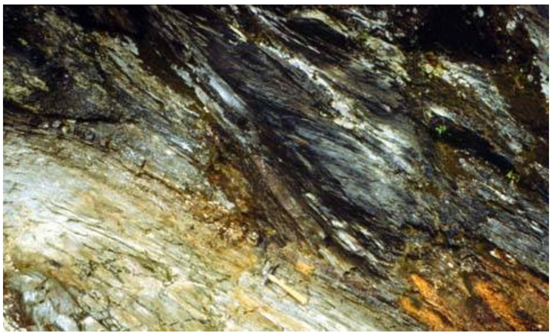


Figure 1. Phyllitic texture, Source:wrgis.wr.usgs.gov/

Figure 2. Slaty texture, Source:www.usd.edu/esci

- Schistose Texture. This is a foliated texture resulting from the sub parallel to parallel orientation of platy minerals such as chlorite or micas. Other common minerals present are quartz and amphiholes. A schistose texture lies between the parallel platy appearance of phyllite and the distinct banding of gneissic texture. The average grain size of the minerals is generally smaller than in gneiss. A rock with schistose texture is called a schist
- Gneissic Texture. This is a coarsely foliated texture in which the minerals have been segregated into discontinuous hands, each of which is dominated by one or two minerals. These bands range in thickness from 1 mm to several centimetres. The individual mineral grains are macroscopic and impart a striped appearance to a hand

specimen. Light-coloured bands commonly contain quartz and feldspar and the dark hands are commonly composed of hornblende and biotite. Accessory minerals are common and are useful in applying specific names to these rocks. A rock with a gneissic texture is called gneiss.

➲ Nonfoliated Texture. Metamorphic rocks with no visible preferred orientation of mineral grains have a nonfoliated texture. Nonfoliated rocks commonly contain equal dimensional grains of a single mineral such as quartz, calcite, or dolomite. Examples of such rocks are quartzite, formed from quartz sandstone, and marble, formed from a limestone or dolomite. Conglomerate that has been metamorphosed may retain the original textural characteristics of the parent rock, including the outlines and colours of the larger grain sizes such as granules and pebbles. However, because metamorphism has caused recrystallization of the matrix, the metamorphosed conglomerate is called metaconglomerate. In some cases, the metamorphism has deformed the shape of the granules or pebbles; in this case the rock is called a stretched pebble conglomerate.

Figure 3. Schistose texture, www.geo.umn.edu

Figure 4. Gneissic texture, wrgis.wr.usgs.gov/

1.2. COMMERCIAL CLASSIFICATION OF ORNAMENTAL STONES

Unlike most fields of the mining industry, in the ornamental stone sector terminology and materials classification are still an open problem and, instead of providing universally recognized reference points, they are too often open to interpretations that are subjective and partial and hence lacking in validity. The reasons for this inevitably creating communication problems on the technical and commercial levels can be traced to four factors that have always characterized the stone industry [10]:

- The absence of standardized, universally recognized terminology
- The absence of a controlled denomination of origin for rocks
- The commercial need to offer stone products under "fanciful" names that strike the imagination more than giving information about the material
- The limited scientific knowledge operators have about stone

One could also add that the world of science, often inattentive to this particular mining sector; has never in the past felt the need to set it in order; much less to deal with the problem giving its commercial aspect the right weight. The result, as we have said, has been the creation of sui- generis classification, often of only local validity, having little or nothing to do with scientific rock classification. On the practical side this has had three consequences:

- Difficulties in comprehension between operators using different terminology (in different countries, for example).
- Difficulties in transmitting correct, univocal information to third parties not experts in the field but working in the sector (such as architects and interior designers).
- Difficulties in finding a correspondence between a certain material and the lithotype it refers to, when there is a need (as is often the case) to know the material's lithographic or petrographical nature in order to solve use problems.

The addition of quartzites, as a group apart, is a recent fact for the market and not yet universally recognized. However, these materials have special commercial features that suggest their separate classification from other ones. On the normative level, marbles are identified in different ways in different countries. In Italy UNI norm 8458 defines marble as "any compact, polish able rock mainly constituted of minerals with Mohs hardness of 3 to 4 (such as calcite, dolomite and serpentine). Belonging to this category are marbles proper (recrystallized metamorphic limestones), line-bearing stones, cipolins, dolomites, calcareous breccias, serpentinites and ophicalcites."

In commercial practice, marbles taken in the widest sense of the term include four sub-groups of material:

1. Marble by the strict commercial sense (hereafter known as marbles s.s.), including all marbles in the scientific sense of the term (carbonate rocks recrystallized due to metamorphic events) and several ophiolite rocks such as serpentinites and ophicalcites, whether or not they underwent metamorphic events.
2. Limestones, including all sedimentary rocks of a carbonate nature, formed through clastic accumulation or chemical precipitation and, to á limited degree, of organic genesis (reef limestones).
3. Travertine, including non-compact rocks of a carbonate nature and sedimentary origin formed through chemical precipitation in a sub-aerial environment.
4. Onyx, including compact rocks of a carbonate nature and a sedimentary origin formed through chemical precipitation generally in underground cavities. If the crystals are particularly large (some centimeters) and visible to the naked eye these rocks are locally known as alabasters (i.e., alabastrites or calcareous alabasters, not to be confused with gypsum-formed alabasters).

Commercial definitions of rock types derive from their quality (durability, strength, etc.) and the techniques required for their processing [12,14,15].

In a very broad sense, "marble" includes any rock, which can be polished, whereas a "stone" cannot be polished.

More accurate definitions, grouping together the terms most commonly used in the stone market, are as follows:

1. MARBLE - a rock mainly composed of minerals with a hardness of 3-4 on the Mohs scale, for example calcite, dolomite and serpentine. All carbonate rocks, such as true marble (metamorphic carbonate rock), limestone, dolostone, calcareous breccia, etc., belong to this category. Alabaster, onyx, serpentine, and ophicalcite belong to this category too.

Table 4. Commercial stone types and their geological equivalents [11]

Commercial name	Equivalent geological names
Granite	Granite Granodiorite Adamellite Porphyry Gabro Dolerite Diorite Quartz diorite Monzonite Gneiss Syenite Tonalite Rhyolite Dacite
Sandstone	Sandstone Greywacke Arkosic sandstone Feldspathic sandstone Calcereous sandstone Quartz arenite Litharenite
Flagstone	Sandstone Siltstone Slate Limestone
Slate	Slate Fine-grained siltstone or sandstone Quartz schist Fine-grained mica schist
Quartzitic sandstone	Quartzitic sandstone Quartzite

Commercial name	Equivalent geological names
Black granite	Gabbro Norite Diorite Peridotite
Trachyte	Trachyte
Bluestone	Basalt Andesite Feldspathic snadstone Bluish siltstone
Limestone	Limestone Calcarenite Coquina Oolitic limestone Dolomite Travertine Biomicrite Biosparite
Marble	Marble Limestone (able to take a polish) Travertine Dolomite Serpentinite Calcschist
Green marble	Serpentinite Diopsidic marble Peridotite
Greenstone	Greenstone Meta-dolerite Meta-basalt

It is clear from these definitions that the commercial terms 'granite' and 'marble' can encompass many different rock types, which therefore can exhibit a great variation in physical properties. For these reasons, it is imperative that all stones be tested. The physical properties of an average granite or marble may not suffice.

2. GRANITE - a rock mainly composed of an aggregate of visible crystals, the hardness of which is 7 or 8 on the Mohs'scale, for example quartz, k-feldspar and plagioclase. In commercial jargon, granite includes: granite, syenite, granodiorite, diorite, monzonite, gneiss, migmatites, porphyry ignimbrites and porphyry subvulcanic rocks. Gabbro, dolerite, charnockite and anorthosite also fall into this category.
3. STONE - Any rock, which cannot be polished, is regarded as being a "stone" in the commercial usage. Therefore, the term stone may include: calcarenites and sandstone with low or medium diagenesis level; volcanic and pyroclastic rocks, such as basalt and tuff; metamorphic rocks, such as micaschists, gneiss, shale and slate.

In current commercial jargon, rock varieties are identified by fanciful names (mainly in Italian) derived from certain aesthetic features or, alternatively, by well-established names after specific places.

For instance, names such as Botticino and Perlato refer to places in Italy; whereas Nuvolato (cloudy), Fior di Pesco (peach flower), Bardiglio, Multicolour are taken from the peculiar aesthetic attributes of the rocks. Sometimes, the name of a stone variety includes terms related to the geological classification of the rocks, which may or may not coincide with the accurate scientific name of the rock. Some other times, the same name is referred to different stones, or similar varieties are referred to with different names. This is often misleading for a proper qualitative determination of rocks.

The correct identification of dimensional stone should include the commercial name or names, the geological definition of the rock, the quarry location, the technical features and photographs on a 1:1 scale of a standard polished sample showing the range of variation, if any.

According to the new European Norm EN 12440 Natural Stones – Denomination Criteria dimensional stones will be described by the following: traditional commercial name, scientific name, range of colour and place of origin. Process conditions, natural features, petrographic name and geological age can also be added.

Table 5. EuroStat terminology for Ornamental Stones. [9]

2514 00 00	Slate, whether or not roughly trimmed or merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape
2515 00 00	Marble, travertine, ecaussine and other calcareous monumental or building stone of an apparent specific gravity of 2,5 or more, and alabaster, whether or not roughly trimmed or merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape
Marble and travertine	
2515 11 00	Crude or roughly trimmed
2515 12 00	Merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape
2515 12 20	Of a thickness not exceeding 4 cm
2515 12 50	Of a thickness exceeding 4 cm but not exceeding 25 cm
2515 12 90	Other
2515 20 00	Ecaussine and other calcareous monumental or building stone; alabaster

2516 00 00	Granite, porphyry, basalt, sandstone and other monumental or building stone, whether or not roughly trimmed or merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape
Granite	
2516 11 00	Crude or roughly trimmed
2516 12 00	Merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape
2516 12 10	Of a thickness not exceeding 25 cm
2516 12 90	Other
Sandstone	
2516 21 00	Crude or roughly trimmed
2516 22 00	Merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape
2516 90 00	Other monumental or building stone
6801 00 00	Setts, curbstones and flagstones, of natural stone (except slate)
6802 00 00	Worked monumental or building stone (except slate) and articles thereof, other than goods of heading 6801; mosaic cubes and the like, of natural stone (including slate), whether or not on a backing; artificially coloured granules, chippings and powder, of natural stone (including slate)
6802 10 00	Tiles, cubes and similar articles, whether or not rectangular (including square), the largest surface area of which is capable of being enclosed in a square the side of which is less than 7 cm; artificially coloured granules, chippings and powder
6802 10 00	Tiles, cubes and similar articles, whether or not rectangular (including square), the largest surface area of which is capable of being enclosed in a square the side of which is less than 7 cm; artificially coloured granules, chippings and powder
Other monumental or building stone and articles thereof, simply cut or sawn, with a flat or even surface	
6802 21 00	Marble, travertine and alabaster
6802 22 00	Other calcareous stone
6802 23 00	Granite
6802 29 00	Other stone
6802 91 00	Marble, travertine and alabaster
6802 91 10	Polished alabaster, decorated or otherwise worked, but not carved
6802 91 90	Other
6802 92 00	Other calcareous stone
6802 92 10	Polished, decorated or otherwise worked, but not carved
6802 92 90	Other
6802 93 00	Granite
6802 93 10	Polished, decorated or otherwise worked, but not carved, of a net weight of 10 kg or more
6802 93 90	Other
6802 99 00	Other stone
6802 99 10	Polished, decorated or otherwise worked, but not carved, of a net weight of 10 kg or more

6802 99 90	Other
6803 00 00	Worked slate and articles of slate or of agglomerated slate
6803 00 10	Roofing and wall slates
6803 00 90	Other

1.3. INTERNATIONAL STANDARDS ON DIMENSIONAL STONE

The national bodies having jurisdiction in each country issue standards on the trade, processing and application of dimensional stone [13]. The best-known international standards are those by ASTM (American Society for Testing and Material). They are recognised and enforced not only in North America, but also in many other countries, especially Asian countries, which do not have their own national rules.

Up to a few months ago, in Europe, the main rules concerning natural stone were German (DIN), British (BSI) and French (AFNOR). In addition, there were Italian (UNI), Spanish, Portuguese and Belgian rules. Today, the scenario is completely different, since the first ten European standards are already available on the market. These are the first few documents developed by the European Committee for Standardization CEN TC 246 – Natural Stones, which has been working for about ten years now, drawing up standard rules for the entire European Single Market. The TC 246 Committee is one of the approximately forty CEN's Technical Committees, which have been established within the framework of the European Community Council's Directive of December 21st, 1988, "Construction Products" (CPD-89/106/EEC).

Other Technical Committees partly dealing with natural stone are the TC 125 on Masonry, the TC 128 on Discontinuous Roofing and Cladding Products and the TC 178 on Paving Units and Kerbs which has completed its work.

The TC 246 consists of three Working Groups:

- WG 1, which has already completed its work by issuing two rules, which have already been published ("Denomination Criteria" – EN 12440 and "Terminology" – EN 12670)
- WG 2, which prepares rules on standard test methods, eight of which have already been published
- WG 3, which is in charge of product specifications; this Group too, has completed its work: the first three product rules should be issued in the next months of 2002.

As the new rules are gradually enforced, all CEN countries shall lend them the status of national legislation and repeal any contrasting national rule. This is, therefore, a dramatic change for the European stone sector, resulting in the suppression of any technical barrier to free trade and to the exchange of stone material. For instance: a Spanish producer who wanted to sell his product to Germany or to the UK may supply such material – after obtaining the European certification – everywhere in the Single Market, without having to take upon himself to have it tested to different rules.

Another important innovation, doomed to change the current commercial customs of the stone industry, adds to this situation. It is the enforcement of the CE mark for cladding slabs, modular tiles and flooring and stair slabs.

As is already happening for other building materials, no cladding or flooring slab or tile may any longer be put on the market unless it is provided with the specific CE mark. This will occur as soon as the above product rules are published, i.e., as we mentioned, presumably in the second half of 2002. From then on, the companies will have a twenty-one months' provisional period to comply with the requirements set forth by the new legislation, after which the provisions will become mandatory and binding.

It is understood that all of those companies wishing to place their products within the European Single Market, i.e. both those European who supply the local market and non-EU companies wishing to export their products to the EU market, will have to comply with such provisions.

What does the CE mark mean? The CE mark certifies that the product complies with the following requirements laid down by the above Directive on Construction Products: mechanical resistance and stability, safety in case of a fire, hygiene, health, and environment, safety in use, protection against noise, energy economy and heat retention.

What will the enforcement of the CE mark involve for the business? The companies will have to submit the product to a whole series of inspections, consisting both of a set of initial tests and controls on production in their plants. Every stone company shall, therefore, set up a production control system within its plant, to ensure that the quality of its finished products keeps up with the levels found during the initial product tests. In particular, these rules will include a whole set of inspections, both on the geometrical and aesthetic features and on the physical and mechanical properties of the products. Companies already inspect the former, and this is nothing new, therefore, for the stone companies. The determination of physical and mechanical properties is, instead, less frequent and the companies shall, therefore, especially at the beginning, set up proper facilities to do so.

Theoretically, such tests could be conducted by the company's in-house test laboratory. Since, however, only the larger companies could have their in-house laboratories, a different scenario is certainly to be expected: very simple tests, such as the determination of water absorption, will be conducted in the plant by way of a control system to test any change in the basic properties of the material, while more complex tests will be conducted by a laboratory specialising in the testing of stone materials according to the European standards.

Once completed, the most complex and demanding tests shall be valid for ten years (this figure could be changed before the standards are published) and will have to be repeated earlier only if the properties of the material are assumed to have substantially altered. Other tests to be conducted less frequently will also be included.

At the end of the process, the company shall affix the CE mark on the package and/or on the accompanying commercial documents as well as prepare the special labels containing the data required by the legislation.

To illustrate to stone operators the innovations brought about by the enforcement of the CE mark, Internazionale Marmi e Macchine Carrara, which, in its capacity as a national delegate, has been supervising the CEN TC 246's Normative Works since the very beginning, will issue a specific technical handbook in the next few months.

Table 6. American Standards for Dimension Stones – prepared by the ASTM C-18

CODE	TITLE
C 615 - 99	Specifications for Granite Dimension Stone
C 568 - 99	Specifications for Limestone Dimension Stone
C 503 - 99	Specifications for Marble Dimension Stone (Exterior)
C 616 - 99	Specifications for Quartz-based Dimension Stone
C 406 - 00	Specifications for Roofing Slate
C 629 - 99	Specifications for Slate Dimension Stone
C 241 - 90*	Test Method for Abrasion Resistance of Stone Subjected to Foot Traffic
C 97 - 96	Test Method for Absorption and Bulk Specific Gravity of Dimension Stone
C 170 - 90 (99)	Test Method for Compressive Strength of Dimension Stone
C 880 - 98	Test Method for Flexural Strength of Dimension Stone
C 120 - 00	Test Method for Flexure Testing of Slate (Modulus of Rupture, Modulus of Elasticity)
C 99 - 87 (00)	Test Method for Modulus of Rupture of Dimension Stone
C 1201 - 91 (96)	Test Method for Structural Performance of Exterior Dimension Stone Cladding Systems by Uniform Static Air Pressure Difference
C 121 - 90 (94)	Test Method for Water Absorption of Slate
C 217 - 94	Test Method for Weather Resistance of Natural Slate
C 1352 - 96	Test Method for Flexural Modulus of Elasticity of Dimension Stone
C 1353 - 98	Test Method for Abrasion Resistance of Dimension Stone by the Taber Abraser
C 1354 - 96	Test Method for Strength of Individual Stone Anchorages in Dimension Stone
C 119 - 00	Terminology relating to Dimension Stone
C 1242 - 00	Guide for Design, Selection and Installation of Exterior Dimension Stone Anchors and Anchoring Systems

Note: the first part of the code, such as C - 615, represents its fixed designation; the number immediately following the designation indicates the year of original adoption or, in case of revision, the year of last revision.

A number in parentheses indicates the year of last re-approval.

An * indicates an editorial change since the last revision or re-approval.

Table 7. European Standards for Natural Stones prepared by the CEN TCs 178 – 128 – 154 – 125

CODE	TITLE	
EN 1341	Slabs of Natural Stone for External Paving - Requirements and Test Methods	CEN TC 178 WG2
EN 1342	Setts of Natural Stones for External Paving - Requirements and Test Methods	
EN 1343	Kerbs of Natural Stones for External Paving - Requirements and Test Methods	
prEN 12326-1	Slate and Stone Products for Discontinous Roofing and Cladding - Part 1: Product Specification	CEN TC 128 SC8
prEN 12326-2	Slate and Stone Products for Discontinous Roofing and Cladding - Part 2: Methods of Test	
prEN 13242	Aggregates for Unbound and Hydraulically bound Materials for Use in Civil Engineering Work and Road Construction	CEN TC 154 SC4
prEN 13383-1	Armourstone - Part 1: Specification	
prEN 13450	Aggregates for Railway Ballast	
prEN 13383-2	Armourstone - Part 2: Test Methods	
prEN 771-5	Specification for Masonry Units - Part 5: Manufactured Stone Masonry Units	CEN TC 125 WG 1 TG6
prEN 771-6	Specification for Masonry Units - Part 6: Natural Stone Masonry Units	

EN = European Norm

prEN = Project of European Norm

Table 8. European Standards for Natural Stones prepared by the CEN TC 246

CODE	TITLE	Availability
prEN 12371	Determination of Frost Resistance	2001-12
prEN WI 246011	Determination of Thermal Dilatation Coefficient	2003-09
prEN WI 246012	Determination of the Sound Speed Propagation	2003-09
prEN 14157	Determination of Abrasion Resistance	2002-09
prEN 14205	Determination of Knoop Hardness	2003-09

CODE	TITLE	Availability
prEN 14066	Determination of Thermal Shock Resistance	2002-06
prEN 14231	Determination of Slip Coefficient	2002-02
prEN WI 246018	Determination of Static Elastic Modulus	2003-09
prEN 14158	Determination of Rupture Energy	2003-09
prEN WI 246030	Determination of Surface Finishes (Rugosity)	deleted
prEN 13373	Determination of Geometric Characteristics on Units	2001-12
prEN 14147	Determination of Ageing by Salt Mist	2003-09
prEN13919	Determination of Resistance to Ageing Actions by SO2 in presence of Humidity	2002-03
prEN 14146	Determination of Dynamic Elastic Modulus (by Fundamental Resonance Frequency)	2003-01
prEN 13161	Determination of Flexural Resistance (under Constant Moment)	2001-12
prEN 1467	Rough Blocks - Specifications	2001-12
prEN 1468	Semi-Finished Products (Rough Slabs) - Specifications	2001-12
prEN 12057	Finished Products, Modular Tiles - Specifications	2001-12
prEN 1469	Finished Products, Slabs for Cladding - Specifications	2001-12
prEN 12059	Finished Products, Dimensional Stone Work - Specifications	2001-12
prEN 12058	Finished Products, Slabs for Floors and Stairs - Specifications	2001-12
EN 1925	Determination of Water Absorption Coefficient by Capillarity	published
EN 1936	Determination of Real Density and Apparent Density and of Total and Open Porosity	published
EN 1926	Determination of Compressive Strength	published
EN 12370	Determination of Resistance to Salt Crystallization	published
EN 12372	Determination of Flexural Strength under Concentrated Load	published
EN 12407	Petrographic Examination	published
EN 12440	Denomination Criteria	published
EN 13364	Determination of the Breaking Load at the Dowel Hole	published
EN 12670	Terminology	published
EN13755	Determination of Water Absorption at Atmospheric Pressure	published

EN = European Norm
prEN = Project of European Norm

References

1. ASTM C119 (1988). Standard Definition of Terms Relating to Natural Building Stone – American Society for Testing and Materials
2. Bradley F. (1989). Cenni sull'analisi geologica delle rocce ornamentali, *Technostone S.p.A.*
3. Bradley F. (1991). Guide to the quarries in Carrara, *Internazionale Marmi e Macchine Carrara S.p.A.*
4. Combined Nomenclature, 2002. http://europa.eu.int/comm/eurostat
5. Blasi P. International standards on dimensional stone. *Internazionale Marmi Macchine Carrara S.p.A.*
6. EN 12440 (2000). Natural Stones, Denomination Criteria, European Committee for Standardisation
7. Frederick Bradley, (1999). Marble Quarrying/Technical And Commercial Manual
8. Geoff Quick, CSIRO Building/Construction and Engineering, http://www.dbce.csiro.au/innovation/2002-04/stone.htm
9. Giornetti M. Stone Industry Technical Glossary, *Internazionale Marmi Macchine Carrara S.p.A.*
10. http://geology.csupomona.edu/alert/igneous/igclass.htm
11. http://geology.csupomona.edu/alert/metamorphic/metaclass.htm
12. http://www.tulane.edu/~sanelson/geol111/igneous.htm
13. http://www.tulane.edu/~sanelson/geol111/sedrx.htm
14. Milazzo G., Blasi P. An introduction to dimensional stone quarrying in ACP countries, *Internazionale Marmi Macchine Carrara S.p.A. – in press*
15. TEAM, European research project within EU's 5th Framework Program - Competitive and Sustainable Growth (GROWTH). Testing and Assessment of Marble and Limestone (TEAM). http://www.sp.se/building

2

Commercial Characteristics

FREDERICK BRADLEY, MARIA FOUNTI, KONSTANTINOS KONTODIMOS

2.1. INTRODUCTION

To have a commercial value, each litho-type included in the commercial groups defined above must have certain characteristics that allow for its use as an ornamental stone material. These characteristics correspond to three fundamental prerequisites that form the basis, in the stone industry, of the concept of raw material and also the basis for the whole production process, from excavation to installation.

In essence these prerequisites refer to the following factors:

- Aesthetic features
- Technica1 features
- Availability

In addition to directly meeting with specific demands, this set of three factors also indirectly determines how a material will be used, influencing its economic value and hence, the market price. Before dealing with these prerequisites in detail - and to better understand their significance - it is a good idea to have a look at marble's main use destinations on the worldwide scale (Table 9)

Table 9. End uses of marble products in 1997, source Frederick Bradley, Marble Quarrying/Technical and Commercial Manual, 1999

Type of Installation	'000 eq m^2	'000 tons	%
External Paving	12280	660	6.0
Internal Paving	61380	3320	30.0
External Floorings	15345	830	7.5
Internal Facings	32735	1770	16.0
Stairs and similar	11250	610	5.5
Structural works	16370	885	8.0
Funerary trade	24550	13330	12.0
Special works	13910	750	6.8
Other uses	16780	905	8.2
Total	204600	11060	100.0

2.2. AESTHETIC CHARACTERISTICS

Appearance is the first factor given attention in assessing a material's commercial possibilities. In fact, the stone industry gives priority to aesthetics, relegating other characteristics (often wrongly) to second place. On the other hand, appearance is often what characterizes a certain kind of material, required first and foremost to serve a decorative purpose and only rarely used as a true structural element. Like other ornamental stones, a marble's look is the result of the sum and interaction of its three basic components: colour, pattern and grain size.

2.2.1. Colour

Colour is generally the most important aesthetic aspect, to the point that it can decide a rock's commercial chances apart from other aesthetic features. The result is that in many cases the market characteristics of marbles differ mainly due to colour.

Table 10. Marble classification according to market characteristics and colours

Market	Colour	Categories
High quality, medium/high cost marbles characterised by colours which are easy to use; often supply does not satisfy demand; availability is generally constant.	White, Pink, Black, Red, Green	Classic
High quality, medium/high cost Marbles with limited uses compared with the classics; demand may vary considerably; in many cases availability is not constant.	Violet Yellow Brown	Special
Average quality, relatively low cost marbles availability is generally very good and fairly constant	Beige Grey	Common

In detail, there are no less than three market ranges to which differently coloured materials may belong (Table 9). One range covers commonly used marbles, often demanded and supplied in large amounts, with relatively low cost and a fairly constant market. These are mostly beige limestones and beige travertines. To a lesser extent this group also includes gray limestones. The range also includes medium and low quality white marbles and gray ones but in this case market demands varies greatly from variety to variety and in any case much lower than for the preceding materials. Another range includes marbles of greater commercial worth than the previous, classic materials easy to use and utilized above all for fine furnishings. Market demand is often greater than supply and cost is rather high. Materials of this type are good quality white marbles, and pinks along with red limestones and black. Finally, a third range covers premium materials with an inconstant market that can heavily oscillate even in relatively short times due mainly to changing tastes but also to unsatisfactory supply. These are marbles whose colours do not lend them to large-scale use and which are generally combined with marbles in other colours; cost is generally high. Belonging to this group are yellow marbles and blue ones, red travertines and yellow ones, pink limestones, brown, and yellow and to a small extent those with a grey background and differently coloured veining. On the whole, therefore, marbles in the widest sense offer a rather broad range of colours - practically all the main shades. And given the important role that colour plays in the trade, it is an excellent idea to learn about its origins. Not only to satisfy mere scientific curiosity but also to understand possible colour variations on the deposit level which may account for as many variations in the material's value. Furthermore, knowing why a certain commercial variety has a certain colour makes it possible to understand (and hence prevent) chromatic deterioration phenomena, thus furnishing important information on possible uses.

The colour of marble has different origins. In most cases it derives from impurities in the rock's structure in the form oxides. This is true of all red marbles in the widest sense, which owe their colour to high concentrations of microcrystalline hematite (Fe_2O). Lower concentrations of the same oxide generate a pink colour: Similarly, yellow marbles in the wide sense get their colour from limonite (Fe_2O_3) a ferrous hydroxide that in heavy concentrations can generate a brown colour: Violet is caused by manganese oxide. Sulphur content, especially of microcrystalline pyrite (FeS) is responsible for the grey colour of marbles s.s. and their veining in the same colour; the dark gray and black of limestones is instead due mainly to bituminous substances. But the colour of a marble can also derive from its main mineralogical component. This is the case with green marbles s.s. (sensus stricto), coloured by chlorite or serpentine. Moreover, colour may depend solely on the refraction light undergoes in crossing the crystalline structure of the minerals making up the rock. This phenomenon is quite rare in commercial varieties and mostly concerns blue marbles s.s. Rather more frequently, marbles without impurities are white like the natural colour of their main mineralogical components (calcite and dolomite). To conclude this brief summary of the causes of marble colouring it is important to mention that, while this is an intrinsic feature of the rock, in many cases the chromatic features of a material can change according to slab cutting direction. This happens when the colour or coloured elements of the rock are not homogeneously distributed but take a direction that generally follows the pattern of the rock itself:

2.2.2. Pattern

The pattern of a marble is given by its weave, i.e., by the spatial distribution of the elements comprising the rock, whether they be mineral crystals, as in the case of metamorphic marbles s.s., or clasts, as in the major part of limestones. In the latter and in travertine and onyx, the pattern also derives from overlapping layers of different colours. From the commercial viewpoint, marbles have the following patterns.

Homogeneous, veined, nuvolato (cloud-like), oriented brecciated, arabescato (arabesque-like).

Pattern is homogeneous when, on the scale of a tile or slab, comprising elements have no preferential arrangement and so the rock is visually isotropic.

Homogeneous design does not change with cutting direction. In marbles in the widest sense this kind of pattern is rare and in practice limited to monochromatic materials with no veining. This is why they are also called solid. Typical example of homogeneous patterns is absolute black limestones (Nero Belgio) and some varieties of marbles s.s. coloured white (Taxos White) and pink (Rosa Portugal).

As its name implies, the veined pattern is caused by veins crossing the ground of the rocky mass either giving the material a well defined direction (if the veins run the same way) or forming a more less uneven weave if the veins are randomly arranged. In commercial jargon, reorientation is called grain (verso). When a material has a grain, cutting direction influences its appearance since this can vary with variations in the spatial relation between the cutting surface and the rock's direction. Apropos of this there are three different conditions regarding three limited cases. That is:

a) The cutting surface is at a right angle to the grain's direction, the veins tend to lose (even if not entirely) a definite direction, forming an essentially uneven pattern with clear, straight stretches. Sometimes the veins are reduced almost to dots. In commercial jargon this cutting direction is called the hard way.

b) The cutting direction is at a right angle both to the grain and to the hard way surface. This direction highlights the longitudinal development of the veining, giving the cutting surface a marked direction. In commercial jargon this is called the easy way.

c) The cutting surface is parallel to the grain and at right angles both to the hard way and to the easy way. In this case the cut is parallel to the veining. In the even more theoretical than probable -that the veins are perfectly one-directional, the cutting surface might never cross or coincide with them. In practice they are always sub-parallel to the cut and so on the slab's surface they form blandly undulating lines, sometimes also semicircles, often featuring a certain thickness and shaded edges. In commercial jargon this cutting direction is called grain.

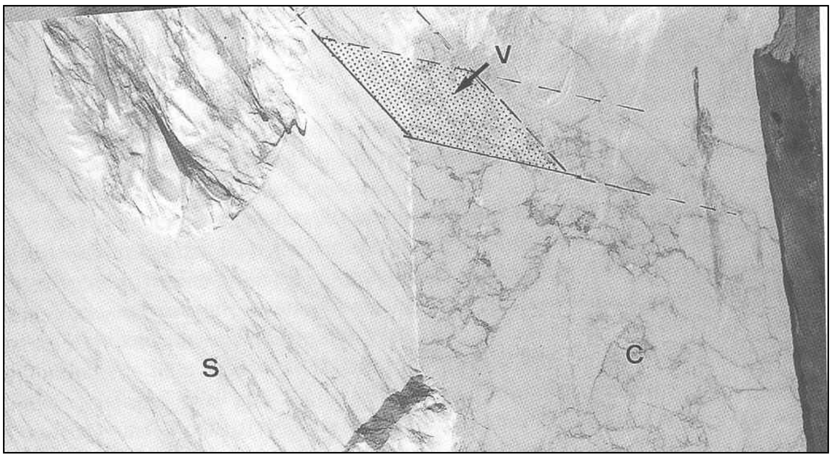


Figure 5. Block showing surfaces along the hard way (c), easy way (s), and grain (v), source: Frederick Bradley, Marble Quarrying/Technical And Commercial Manual, 1999

In addition to these three cutting directions there can also be intermediate ones gotten by changing the cutting surface's angle of incidence with respect to the rock orientation. These directions are called fa1se hard way, fa1se easy way and false grain depending on whether the cutting direction is similar to a), b) or c). Usually, to achieve a commercially worthy appearance, veined marble is cut along the hard way or the easy way. The grain cut often gives the material an unattractive look featuring a sequence of rounded shapes; in jargon this is known as spadellato (off-target).

As far as uses are concerned, veined marbles lend themselves to installation using the libro aperto (open-book) or macchia aperta (mirror-image) technique, which the slabs taken from a single block are arranged in reciprocally mirroring groups of two or four at a time. The veined pattern is characteristic of marbles s.s.

They frequently have directed veining (Bianco Venato Carrara) or uneven veining, (Verde Rameggiato). However, this kind of pattern can also be not infrequent found in limestones (Alpenina, Negro Marquifia). The combination of colours of the veining and the ground is interesting and quite varied. The most frequent combinations in marbles s.s. are gray veining on a white ground (Bianco Venato Carrara) or a pink one (Rosa Portugal) and white veining on a green ground (Verde Alpi). More rare are green veins on a white ground (Cremo Tirrenico) or a dark green one (Verde Rameggiato), white on a gray ground (Blu Venato d'Italia), on red (Rosso Lepanto) or on black (Abu Black) and azure on a white ground (Azul Cielo). Among the limestones there are varieties with pinkish or yellowish veins on a grey ground (Salome and Supren, respectively), with yellow veins on a black ground (Portoro), with red veins on a beige ground (Alpenina) and with white veins on a black ground (Negro Marquina).

The nuvolato pattern a variation on the veined and follows it's veining in combination with a particular chromatic pattern. On a ground homogeneous in colour (generally gray) ovoid shapes (generally white) appeal; coalescing with the veins and looking something like cloud formations. The clouded pattern may stem from rock's intrinsic structure (as with other kinds of design) or be artificially created by cutting certain veined materials along the false grain. This makes the veins look quite uneven and shaded on the slabs, running in curves which, if not actual circle-like (as in the spadellato pattern) take the form of a cloud. A typical example of the nuvolato pattern can be found in a marble s.s. that even repeats the name Nuvolato Apuano. The varieties that can give a pattern of this type when cut as described above are found mainly among the marbles s.s. and in the onyx group.

The oriented pattern appears when the rock's components take a preferential direction appreciable on the scale of a slab or tile. The oriented pattern differs from the veined because all the rock components visible to the naked eye run in the same direction on a defined surface and are not limited to isolated elements (as in the case of veining) but themselves form the entire rocky mass. This design is typical of many layered limestones (Serpeggiante, Sivabella Classico) and almost all travertines where, in practice, it is due to the dense and continual overlapping of the layers that form the rock. In this case, too, the material, being directional, has a defined grain, with the consequences we have seen on the sawing level. Nonetheless, the generally flat run of the layers often make hard way and the easy way directions coincide and cuts made parallel to them lead to the same aesthetic result.

The brecciated pattern derives from a specific genetic characteristic of some kinds of rock. It is typical of rocks formed by the accumulation of lithoid elements of various sizes and shapes that are wholly or partially incorporated into a matrix that may consist of tinier bits of the same lithoid elements or have its own composition. Usually, in the rocks utilized like marble the lithoid elements have sharp edges. If the accumulation has no direction or particular grain size, varying cutting direction makes no great difference to appearance. Sometimes, however veining or polar piece arrangement makes it necessary to select a certain cutting direction, as with the veined and oriented patterns. The brecciated pattern is mainly found in commercial varieties belonging to the limestone group (Breccia Pernice, Breccia Aurora) and to a lesser extent to marbles (Rajasthan Green, Rosso Antico d'ltalia).

Undergoing more or less intense high-pressure metamorphosis, rocks with a brecciated design tend to become arabescato,. These are characterized by a veining pattern which, from the brecciated (where lines intersect and enclose defined elements) shades, in different materials, into the more properly veined, where wavy lines break off after brief stretches and fade into the background mass. More frequently arabescato materials have a pattern somewhere between the two extremes of brecciated and veined, featuring a series of elements with a semi-ovoid shape, more or less elongated, delimited by a thick weave of directional, interconnected veining. Taking a direction, and thus having a grain, the arabescato pattern follows what was previously said about cutting directions for veined materials, including the open-book and mirror-image solutions.

Given its origin, it is characteristic of varieties belonging to the group of marbles s.s., to which often gives a commercial denomination (Arabescato Piana, for instance).

2.2.3. Grain size

Grain size (or granulometry, the scientific term) defines the sizes and in some cases the shape of the crystals or lithoid elements that constitute a rock. In marble from the commercial standpoint, there are three grain-classes:

- Fine grain size, when the crystals or other constituent elements are impossible to distinguish with the naked eye and the rock appears to be formed by a homogeneous, although often vari-coloured, ground.
- Medium grain size, when the crystals or other elements are just visible to the naked eye and are sized about a millimeter.
- Large grain size when the crystals or other elements are quite visible to the naked eye and are two millimetres in size or larger. If, due to the size of its crystals the rock looks like a mosaic of tiny reflecting surfaces, in commercial jargon it is known as crystalline. This is essentially found in marbles s.s.

Where a material's general aesthetic worth is concerned, grain size is much less influential than colour and pattern. Nonetheless, the size of a marble's components can influence the brightness of its colour and the elegance of its pattern. In large-grain marbles s.s. for instance, the veining has more shadowy edges than materials in the fine grain group; they lose their incisiveness and definition, in extreme cases turning from a decorative element into a shapeless blob. Grain size is also significant in physical-mechanical terms, and thus influences use possibilities. Fine grain materials often have compression resistance and micro-hardness much higher than a large grain material, which means they are harder to work but also have greater use potential both in the gamut of uses and as type of final product. On the other hand, many large grain materials, especially marbles s.s., are too fragile and subject to wear to be used for flooring and in sharp-cornered pieces.

2.3. TECHNICAL CHARACTERISTICS

From the technical standpoint, the potential uses of a variety of stone are determined by petrography, mineralogica1 composition, chemica1 composition and the physica1-

mechanica1 properties of the lithotype it corresponds to. Together these factors constitute the technical characteristics of the commercial variety that should be referred to both in selecting the material and in defining its possible uses. Although there is a reciprocal relationship between these factors they work in different ways and to different extents in defining possible uses for a material since their importance depends on numerous variables such as the installation environment and method, the type of finished product, the performance required of it, etc. It is therefore best to have a complete picture of a material's technical characteristics in order to assess its true commercial potential. We will describe each of these factors's significance and the role it plays in a material's technical behaviour.

2.3.1. Petrography

Petrography defines the characteristics and the genesis of the minerals comprising a rock as well as the reciprocal relations they have in its structure. Knowing a rock's petrography takes on practical importance especially when trying to understand and prevent problems of alteration in the material (colour variations, a decrease in mechanical resistance, etc.) when it is subjected to particular use conditions (strong sunlight, pollution, etc.). Normally, petrographical data should be interpreted along with mineralogical and chemical information. An analytical definition of the factor is given through petrographical ana1ysis, which consists of examining a section (thin section) of the material under a microscope.

2.3.2. Mineralogical composition

Mineralogy describes the types and characteristics of the minerals comprising a rock. The mineralogical composition of a commercial variety gives important information about its workability and about certain physical-mechanical properties. It is also indispensable in understanding and preventing many types of esthetic alterations (colour variations, staining, etc.), in assessing different use possibilities and in checking the material's natural degree of alteration. The laboratory text that determines this factor is mineralogical ana1ysis, done through X-ray diffractometry.

2.3.3. Chemical composition

This parameter defines the type and percentage of the chemical elements comprising a rock. The chemical composition of a material supplies important data on its possible use in specific environmental conditions (air pollution, for instance) and on its eventual predisposition to show alterations or chromatic defects over time. The laboratory test to determine this factor is chemical ana1ysis, done through mass spectrometry.

2.3.4. Physical-mechanical properties

To be used as an ornamental stone material a rock must have a set of physical-mechanical properties that as a whole give it specific characteristics of workability and durability and thus the ability to be used. The main physical-mechanical properties for a rock used as a decorative material are:

Apparent volumetric mass, defined by the ratio between the material's weight and apparent volume (that is, including vacuums inside the material, or its porosity) and stands for its real weight. It is of fundamental importance in assessing the loads that the material exerts on anchorage and support structures and also gives information about how compact it is.

Compression break load, which defines the material's ability to take loads. Assessing this is therefore indispensable on materials given a structural function (solid columns, arches, etc.) but it is also important where cladding or facing and flooring are concerned, where the material undergoes compression stress for different reasons.

Compression break load after frost, which defines the material's ability to take loads in environments subject to big temperature jumps above and below 0 °C. A frost-sensitive material is one whose compression resistance after cycles of frosting/melting (from -10 °C to +35 °C) drops over 25 %. This factor therefore plays an important role in external uses (cladding and paving) in climates that have big temperature changes in a 24-hour period.

Porosity defines the volume of vacuums in a material in relationship to the rock's volume and gives information about its compactness (and thus, indirectly, about its mechanical resistance). It also supplies important data about the rock's ability to contain liquids.

Imbibitions, defines the material's ability to absorb liquids and gives indirect information about its porosity. This is important in uses in which the material is in frequent contact with liquids (bathrooms, kitchens, outdoor uses, etc.).

Bend resistance, which defines the material's resistance to loads that could warp it. This is an extremely important aspect for an ornamental stone material since conditions of mechanical stress that could directly or indirectly induce warping are common in many applications (cladding, especially in high-wind areas, stairways, roofs, ledges, tombstones, ventilated floors or pavements, architraves, etc.).

Thermal dilatability, which defines the material's ability to dilate at hi temperatures. This property is important only when the material is used in particularly hot rooms or climates and above all when used externally in direct sunlight. Apropos of this, it is interesting to note that, when dark and light materials are combined they can react differently when the temperature climbs, creating discrepancies in the structural set up.

Elasticity, defines the materials tendency to bend under mechanical stress. It has a direct relation to the material's bend resistance and is important in assessing the effect of static loads on the material, especially when used as cladding.

Wear resistance, which defines the material's resistance to abrasion and rubbing. Its role is fundamental in assessing a material's suitability for use as flooring and paving (even for streets and roads), for ledges, etc.

Shock resistance, which gives information about the breakage resistance of the material subjected to concentrated loads. It has a certain importance in flooring, paving and shelving.

Hardness gives information about a material's resistance to scratching (Mohs hardness) and about its crystalline components' resistance to concentrate, (Knoop microhardness). It is a property that is quite important especially for flooring, shelving, coverings close to heavily trafficked areas, etc.

All these physical-mechanical properties can be analyzed through specific laboratory tests that follow standard procedures defined by official standardization boards. Since there is no one international standardization board recognized world wide, in practice it is necessary to refer to the analytic standards set by various countries, although these may differ at times.

The materials available on the international market are usually analyzed according to the methods set by the various countries in which the materials are used. The methods most frequently followed are the ASTM (American Standard Testing Method) in North America and the Far East. In daily practice, however; there is often a need to know how a material will behave from aspects not dealt with in standard physical-mechanical analysis, for specific purpose of preventing possible deterioration. In general these are cases, which an installed stone material will be exposed to particular environmental conditions such as air that is heavily polluted or especially damp and salty. It is possible to run ad hoc tests in such cases, although only certain laboratories specialized in them, and in any case they still have interpretative limitations because they attempt to recreate in a brief time what would normally be revealed after a number of years. The most common tests of this kind are:

- Attack by chemica1 agents, which shows how the material will behave to pollutants, generally found in city air
- Exposure to ultraviolet rays, which gives data on how the material will behave when exposed to strong sunlight
- Exposure to heavi1y saline air, which shows how the material will react to salty air

2.4. AVAILABILITY

Like all mining products, to have a stable role on the market ornamental stones must meet with availability prerequisites that respond to well defined needs. There are four factors determining the availability of stone materials:

- Constancy in aesthetic features
- Available volumes
- Raw production characteristics and
- Supply times.

Constancy in esthetic features is a factor that may vary in significance and hence in value from material to material. In the case of materials with a homogeneous colour and pattern (for example, solid monochromatic marbles s.s.), the market's tolerance for esthetic variations is very low and even tiny differences can compromise the quality of the material. There is greater tolerance, instead, on material whose esthetic value stems precisely from non-homogeneous colour and pattern, especially when appreciable on slab scale. In this case, quite infrequent in marbles, esthetic range is defined for the quality of the material in order to assess esthetic variations. This range may include features normally considered defects but which for some materials are typical characteristics. On the other hand, defining a defect in an ornamental stone material is anything but precise and sometimes may be quite subjective. In any case, attempting to provide a definition we can state that defect are all those physica1 or chemica1 e1ements in the material that can compromise in use, either by altering the esthetic characteristics recognized by the market or by lowering its physica1-mechanica1 resistance parameters well below the va1ues typical of similar materials. It is important to stress the occasional character of the element considered a defect. If it is found in a great part of the quarry's output it becomes a characteristic, albeit a negative one, of the material and must be presented as such to the market.

Available volumes mean the amount of material with the defined esthetic and technical characteristics that can be extracted from the quarry clear of waste, or already as blocks. In this case, too, conditions vary from one commercial variety to another. Normally a material has to be available in quantities sufficient to guarantee the manufacture of the finished product it was destined for.

For example, a marble which, for its esthetic and technical features, is mainly used for large-scale cladding has to be available in large amounts to maintain its place on the market, otherwise it risks losing its dependable supply and hence its ability to compete. Here it's the market that influences the usable limits of a material's available volumes. On the other hand, for varieties with high commercial value and features suited to premium detailing, the quality of the material is more important than its lessened availability, which does not affect its image on the market. In this case the market adapts to the material's availability, finding ways in which it can be used.

Raw production characteristics consist of the size and shape of the blocks produced in the quarry. These are viewed both in absolute terms and in relation to the material's possible esthetic orientation, on which the quarry product’s economic value and physical-mechanical properties may depend.

Supply time is the only availability factor that directly concerns work external to extraction. In fact, it depends not only on the quarry's production capacity, but also on the time required to haul blocks to the sawmill and process them into finished products.

References

1. Frederick Bradley, (1999). Marble Quarrying/Technical and Commercial Manual

3

Transformation of Stone from Rock to Final Product

INTERNAZIONALE MARMI E MACCHINE CARRARA

3.1. QUARRY PRODUCTS

The basic goal of all dimensional stone quarrying operations is to optimise the production of stone pieces or units properly dimensioned for direct sale or further processing.

Form and dimensions of stone units vary according to the stone end use and are regulated by selling prerequisites.

For architectural uses of stone, which is the most important use in the stone market, sizeable blocks suitable for industrial processing are required.

In addition to stone quality consistency (i.e. lack of defects such as colour variation, textural changes, inclusions, fractures, etc.), the industrial standard for processing stones used in architecture requires that stone blocks possess characteristics which allow stone finishing to be performed on them and still have acceptable processing yields [21].

Blocks should be of regular rectangular prism shape [3,6,19]. The maximum length and height of the blocks are constrained by the dimensions of the gang-saw frame, where blocks are placed and cut to produce slabs.

Block dimensions range between 2.8 to 3.2 meters in length, and between 1.5 to 1.8 meters in height. The block maximum width is constrained by weight limits that are given by safety factors in handling and transportation of the blocks.

Quarrying and processing practices demonstrate that the larger block dimensions are, the lower their production costs and the higher the processing yields.

In addition, the larger the surfaces of finished products (slabs), the higher the price of end products. The dimensions of specific end products, such as architectural panels for cladding surfaces of buildings, dictate the block dimensions. For instance, panels of 60 x 60 x 2 cm are obtained with a good processing yield if block dimensions are multiple of 60 cm, net of off-cuts.

In order to maintain the processing yield within acceptable tolerance limits, the form of blocks should be as regular as possible, roughness of block sides the lowest, and parallelism between opposite block sides consistent.

The commercial volume of blocks is computed according to the dimensions of the maximum rectangular prism inscribed into the actual block volume, minus an allowance of 5 cm per side, which corresponds to the processing off-cut portions of the block.

Figure 6. Open Pit Quarry, source: Frederick Bradley, Marble Quarrying/Technical and Commercial

Total off-cut volume decreases as form regularity of blocks increases.

Aesthetic characteristics that appear in finished stone surfaces change in relation to the orientation of block-cut-direction. This depends on the texture of the stone, if stone has an oriented texture at all.

Mechanical properties of finished stone products are also influenced by orientation of block-cut-direction if stone has strong directional properties.

If the stone is used for the production of tiles, block sizes may be smaller than those of standard blocks used for the production of large slabs. Form regularity of blocks is not a special requisite for production of tiles.

3.2. Quarrying Methods and Types of Quarries

The arrangement and the geometrical configuration of dimensional stone quarries depend on the type of exploited dimensional stone, quarrying methods, morphologic characteristics, size, as well as the geometry and structural features of the exploitable body [2, 8, 12].

The type of dimensional stone alone does not determine the quarry configuration. In fact, similar quarrying methods may be applied to different types of dimensional stone quarrying.

Morphological conditions and structural and geometrical features of the deposit dictate quarrying methods, planning and geometrical configuration of the quarry.

Many dimensional stone deposits are suitable for boulder quarrying method. Boulder quarry may represent the initial stage of a quarry development, wherever exploitable boulders represent the overburden of the deposit. If boulders represent the total reserves of the dimensional stone deposit, boulder quarrying may persist for the whole duration of the quarry life.

Boulder quarries, ordinarily developed in dominant flat topographies or along gently dipping slopes, lack a regular geometry.

Many granite and carbonate deposits are affected by intense weathering, which is a typical feature of many tropical regions. This makes them suitable for developing into boulder quarries.

Bench quarries are generally considered to be preferable for dimensional stone exploitation, since they allow a regular and checkable quarry development.

Boulder and bench quarries represent two extremes instances of a large number of quarrying methods.

As in most dimensional stone quarries, quarrying blocks is carried out taking advantage of the presence of regular fracturing patterns or pronounced directional properties of the stone, which dictate the quarry development and geometry.

Bench quarries may assume different shapes and configurations, depending on the morphologic and structural characteristics of the deposit.

Quarrying always follows the geometry of the exploitable rock mass that may occur in the form of beds, layers, or other complex geometrical configurations.

Bench quarries of dimensional stones are developed as open-pit operations, whereas underground dimensional stone quarries are still a minority.

Underground quarries are developed wherever it is the only way to exploit the deposit.

Landscape preservation can also represent an important constraint for the underground development of dimensional stone deposits.

The underground quarrying of a dimensional stone can be executed safely and in a technically viable manner only when there is a high grade of rock integrity.

Room-and-pillar quarries represent underground dimensional stone quarries.

Quarrying methods used in open pit and underground dimensional stone quarries are similar to each other, both involving progressive downward lowering of the quarry floor by removal and levelling of benches.

Open pit quarries (Figure 6) of dimensional stones are on average characterised by steeply dipping or near to the vertical pit slopes, as the comparatively high rock soundness of most dimensional stone deposits does not generate problems of slope stability.

In regions where the topographic surface is flat and gentle, open pit quarries may assume a typical configuration similar to that of an amphitheatre, with several quarry fronts and beds, where the various phases of the operation may be done simultaneously.

If the pit bottom is below the water table, pumping plants and channelling systems need to be set up in order to keep dry the working areas.

When open pit quarries are developed along hills or mountainsides, the shape is similar to that of a portion of an amphitheatre. In such cases, water is easily removed from the excavation area by simple drainage systems or captured and re-cycled to feed the quarrying equipment.

When quarries are located on hill or mountaintops, the development proceeds by progressively removing the top and then gradually lowering and levelling the rocky surface.

Construction and maintenance of quarry roads is a major concern of hill or mountainside quarries. For such types of quarry, areas that are abandoned and dump areas can be re-used for the construction of quarry roads.

3.3. QUARRYING SEQUENCE

Dimensional stone quarrying operations basically involve isolating blocks from the parent ledge by cutting it free on all sides perpendicular to each other.

The isolated stone block has dimensions suitable for sale and processing or it may be much larger so that further subdivision into smaller blocks may be made.

Quarrying operations vary from a quarry to another, depending on all factors previously mentioned.

The basic quarrying sequence includes the following working steps:

- pre-production operations
- primary cuts
- secondary cuts and finishing of blocks
- removal and haulage of blocks

The production efficiency of the operation increases if these four working phases may be done simultaneously. This sequence represents the guideline for a correct work organisation in the quarry [16].

3.4. QUARRYING TECHNOLOGIES

Separation of benches, slices and blocks from their parent ledges may be done by using natural joint surfaces. Failing these, cutting requires the use of mechanical tools [5,8,14,16,19,20].

The most frequently used stone cutting technologies may be grouped into three main categories:

- cutting by drilling
- cutting by abrasion
- cutting by disaggregation

3.4.1. Cutting by drilling

This technique is normally used wherever exploited stone is characterised by a comparatively high hardness and abrasion coefficient, such as most granite, quartzite and other siliceous rocks.

In addition, cutting by drilling is done in all those deposits where water supplying, which is essential to cutting by abrasion methods, is not viable.

In quarries where the preferred cutting method is by abrasion, drilling methods still represent a valid support.

Drill holes may vary in length, depending on the depth of the cutting surface. Drill depth may be from 3 to 9 meters in primary cuttings, i.e. in bench or slice separation, or from 1.5 to 3 meters when block cutting is performed.

The hole diameter corresponds to the diameter of the drill rod series which normally varies from 32 to 36 mm; drill bars series of 40 or 42 mm are also used.

Cutting by drilling may be performed following two major procedures:

- Channelling by line drilling: drill holes are on the same plane, parallel to each other, closely spaced and intersected one to another, so as to make a channel cut
- Line drilling and pre-splitting: drill holes are on the same plane, parallel to each other, and drilled at a regular distance, which may vary from a cut to another from few centimetres up to 25 cm, with an average of 15 cm. Then, rock separation is done by pre-splitting or soft blasting

Figure 7. Drilling method

Channeling is comparatively common in granite quarries, but only along some particular cutting planes, such as the opening of channels, where the use of pre-splitting method would affect the rock integrity.

Generally speaking, an extensive channel cutting in granite is not economically viable because, due to the relative hardness of this material and the large amount of drill holes to be made, it would involve a high consumption and frequent sharpening of drill rods.

The combination of drilling and pre-splitting is the most popular cutting method used in granite quarries, but it is also commonly done in marble or limestone quarries, where cutting by abrasion methods are not applicable.

Pre-splitting consists in firing light linear charges inserted into the holes. The most common explosive charge, which is normally used, is the detonating penta-erythrite fuse (8 to 12 g PNT/m).

Alternative explosive types are also used, such as the mixture of ANFO explosive with ammonium nitrate and fuel oil in fixed proportions, and black powder. All strands of detonating fuse are inserted into the holes and connected to a master cord, so that firing occurs almost simultaneously.

The charge-hole wall gap may be filled with water if more powerful explosive effect is desired in rock pre-splitting. This is normally done in granite quarries. There are some major differences and prerequisites in the pre-splitting methods of dimensional stone quarrying with respect to those used in ordinary mining operations:

- the linear charge is much lower than in conventional pre-splitting;
- the rock integrity of the separated masses has to be maintained after pre-splitting: radial cracks that develop around the holes must be avoided or reduced;
- a controlled amount of displacement of the detached rock mass from the parent ledge is desired.
- Theories that have been developed to explain the pre-splitting mechanism converge into two main categories:
- Superposition of shock waves from adjacent holes;
- Generation of tensile stress conditions, which produce a master crack connecting the holes.

Pre-splitting may be done along the base and sides of benches (slices or blocks) simultaneously. Normally, base detachment or lifting by pre-splitting requires a relative larger amount of charge per cut unit area, with respect to that used in lateral pre-splitting.

In fact, in addition to the energy required for the detachment, more energy is required for lifting, because of the weight of the detached rock portion.

Stone cutting by pre-splitting should be done parallel to the easiest directions of rock breaking and taking advantage of natural joint planes, if any.

Indeed, if the main directions of tensile stress induced by charge firing in pre-splitting coincide with those of rock residual stress, pre-splitting may be performed with maximum efficiency.

On the contrary, where parallelism between cutting planes and easiest rock breaking directions is not observed, the rock integrity may be affected by the formation of visible or even invisible cracks, which develop near the cut surface and increase off-cut volumes.

For this reason, one of the most important prerequisites of pre-splitting by soft blasting is the understanding of the rock mechanical behaviour. Fracturing analysis and exploratory excavation may help.

Black powder is another explosive charge type being successfully used in pre-splitting. The use of black powder is particularly suitable in all those cases where rock easiest parting directions are well defined, such as in many granite boulder quarries, i.e. in all those types of deposits where residual stress conditions are comparatively homogeneous and residual stress magnitude is near to exceed the elastic limit of the rock.

In such cases, spectacular and high-efficiency vertical cuttings of stone may be obtained by simply blasting from a single and short vertical drill hole, which has been partially filled with black powder. Sometimes, this is called the “block-hole” method.

Black powder is also used when the rock portion to be cut is already detached from its ledge by natural joints and when further separation or lateral displacement of the exploiting rock mass is desired.

3.4.2. Drilling equipment

Cutting by drilling in dimensional stone deposits is normally done by means of pneumatic or, in fewer cases, hydraulic drilling tools.

This drilling equipment is:

- Jack-hammers
- Drill rigs
- Wagon drills

Jack hammers operated by compressed air are of different sizes and accordingly used for different cut types. Manually held jack-hammers are from 10 to 15 kg in weight and are normally used in secondary cuts, whereas heavy duty jack-hammers are mounted on a quarry bar, such as in block-cutters, or built in a rigid frame (wagon drill).

There are also some hydraulically operated types. Hydraulic jack-hammers are renowned for their longer life and lower maintenance costs than normal pneumatic jack-hammers, but their cost is much higher.

All types of jack-hammers are operated by means of a percussion and rotation mechanical device, so that simultaneous percussion and rotation movements are conveyed to the drill bars which are inserted into the terminal inlet of the jack-hammer.

Drilling progresses by simultaneous chiselling and chopping actions exerted by the drill bars against the rock.

Figure 8. Drill rig

Drill rigs are one of the most common drilling tools. The wagon-drill is a drilling tool composed by a quarry bar where two or more (maximum four) heavy-duty jack-hammers are mounted, as in the block-cutter. The quarry bar is, in turn, mounted on a wheel or chain tractor. The quarry bar and the jack-hammers may be hydraulically positioned, and drilling may be done accordingly. The wagon-drill is used in large-scale operations, as average-sized companies cannot easily afford the high cost of this tool.

3.4.3. Wedging

Wedging conveniently does rock splitting in secondary or minor cuts. This technique requires the use of mechanical tools instead of explosive charges, which may cause damages to the rock when the latter is particularly fragile.

The wedging tools are manual, such as plugs and feathers, or powered, for instance hydraulic feathers.

The depth of inserting feathers and plugs into the drill holes as well their reciprocal distance varies depending on the rock type, block size and extension of the cut surface.

Rock separation may be also being carried out using expansible fluids, which are poured into the drill holes. Expansion occurs when the fluid dries up and causes the rock to part along the surface between the holes.

3.4.4. Cutting by abrasion

Cutting stone by abrasion is a particularly suitable technique for all rock types of comparatively low hardness, such as carbonate and serpentine, but its application to dimensional granite is now spreading.

One advantage of cutting stone by abrasion, instead of drilling, is that it produces lower amounts of waste and preserves rock integrity.

Blocks with smooth and regular sides are produced with cutting by abrasion methods, so that the volumes of off-cuts are minimised during finishing.

Cutting by abrasion techniques include:

- Wire saw
- Diamond wire saw
- Chain saw
- Diamond belt saw
- Disk cutter

3.4.5. Wire saw

The helical wire was the most popular technique for cutting marble in the past. Nowadays, it has been replaced by more simple and efficient cutting methods. The helical wire consists of a double or triple strand of wire that runs over sheaves and is fed under tension into the stone. The wire feeds a constant flow of silica sand (alternatively, aluminium oxide or some other kind of abrasive) and water and wears a groove or channel in the stone. The sheaves are mounted on a tower or track, so that they can be moved into the cut.

The cutting speed by using helical wire saws in true marble is 0.5 to 1.0 m^2 / hour if silica sand is used, and may reach more than 2 m^2/hour when aluminium oxide is used as an abrasive.

Helical wire sawing is still preferred to other more modern quarry cutting methods in some stone quarries, where particular conditions for performing very large primary cuts make this method viable.

Figure 9. Diamond-wire saw, source: Frederick Bradley,
Marble Quarrying/Technical and Commercial Manual, 1999

3.4.6. Diamond wire saw

Since the seventies, diamond wire saw has progressively replaced the use of wire saw and is now the most common method for cutting marble. Diamond wire saws consist of a multi-strand steel wire of 4 - 5 mm in diameter, along which numerous diamonds coated or impregnated beads are positioned at close and regular distance between each other.

The diameter of the diamond beads is few millimetres wider than the wire diameter, so that the diamond beads exert abrasion only during stone cutting. The space between the diamond beads is occupied by spring or plastic cylinders, which protect the wire without changing its flexibility. Diamond coated or electroplated beads are used to cut comparatively soft stone types, such as chalky limestone and marble of low cohesiveness, whereas impregnated or sintered diamond beads are mostly used to cut a wide range of stone types, which vary in abrasiveness from low (marble, limestone) to high (granite, sandstone). The cutting speed of sintered diamond beads is lower than that of electroplated ones, but their life is generally much longer.

In order to maximise the performance of diamond wire cutting, different specific types of sintered diamond beads may be used which should be selected depending on hardness, grain size and interlocking of the main minerals forming the stone to be cut. A flywheel operated by an electrical engine directly or through a mechanical driving device drives the diamond wire.
Stone cutting by diamond wire saws is made possible by setting up the wire as a loop around the rock portion to be cut. Drilling two converging holes that define the limits of the cut surface initially sets up the loop. The maximum length of these converging holes, which correspond to 8 - 12 meters each, limits the maximum extension of the cut surface. The loop initial length is up to 50 meters or more than that and is progressively reduced during step-by-step backward movements of the machine.

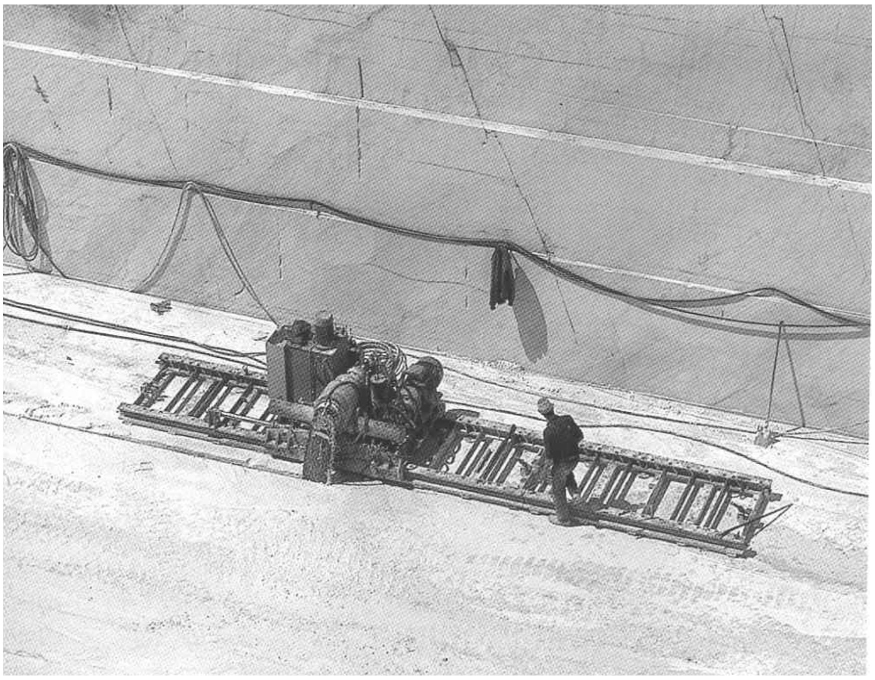


Figure 10. Chain saw for bench cutting, source: Frederick Bradley, Marble Quarrying/Technical and Commercial Manual, 1999

The backward movement of the machine as the cut progresses occurs along rails, which are anchored, to the ground. The wire needs constant feeding of water for cooling and keeping the wire clean from rock slime during cutting. The advantage of using diamond wire saws for stone cutting rather than helical wire is demonstrated by:

- Reduced manpower (2 – 3 workers only)
- Increase of cutting speed (up to 10 - 12 m^2/hour in true marble)
- Easy installation

Positioning the loop and the engine-stretching-flywheel tool accordingly may do cuts horizontally or vertically.

Diamond wire saws may be used in sizing blocks into regular shape before processing. In such a case, a special diamond wire tool has been designed to this particular purpose.

3.4.7. Chain saw

The use of chain saws is limited to cutting marble, non-metamorphic carbonate, serpentine and ophicalcite. The chain is provided with tungsten carbide teeth. Generally, the chain saw arm is designed to achieve a useful cutting depth of 3 meters.

Cutting is performed by pushing the whole arm of the chain saw though the rock in a perpendicular position with respect to the moving direction of the machine.

During cutting, the chain saw moves hydraulically along fixed and rigid metallic rails or along a cylindrical bar. The latter is used in underground operations. Water is injected into the cut surface during cutting, for cooling purposes. Chain sawing can be also performed in dry conditions, but in this case a reduction in the chain speed and an increase in the torque of the drive gear of the chain are both needed.

Cutting speed of the chain saw is about 5-6 square meters per hour in marble. Chain saws are designed for performing both horizontal and vertical cuts.

This tool is frequently employed in underground and open-pit quarries, where large and flat surfaces of solid marble may be prepared to let the chain cutter move smoothly along the rails.

Chain cutters and diamond wire saws may be used jointly: the former for horizontal cuts and the latter for primary vertical cuts. This is possible whenever quarrying methods contemplate the exploitation of high and narrow benches and in pit quarries.

3.4.8. Diamond belt saw

This is a new technology for stone cutting that can be applied to any stone type, including all hard and abrasive sandstone varieties, with the exception of granite.

Although the diamond belt saw is structurally comparable to the chain saw, the cutting mechanics are totally different. The diamond belt saw has a plastic belt with impregnated diamond segments placed at regular intervals, while the chain cutter has a chain with the tungsten carbide teeth inserted.

The diamond belt does not require oil or grease lubrication, but water consumption is higher than in chain saws (2-3 litres per second), since the belt speed is higher than the chain speed in the chain saw. A large amount of water is needed in diamond belt sawing to keep the diamond tools clean and cool and to allow the belt to glide on its guide bar through a water cushion (“aquaplaning”).

The cutting speed of the diamond belt saw is 4-5 m^2 per hour in marble. The use of the diamond belt saw is widespread, including carbonate rocks, marble, limestone, serpentine, slate and sandstone. Moreover, inclusions of abrasive materials, such as quartz veins or nodules found in many marble types ever so often, are cut more easily with a diamond belt saw than with a chain saw, as the tungsten carbide teeth of the chain would be seriously damaged by the abrasive material encountered during the cutting.

It is worth mentioning that both the chain saw and the diamond belt saw are safer cutting technologies than diamond wire, especially for horizontal cutting, because of the difficulties in installing a proper protection device in case of diamond wire breakage during cutting.

3.4.9. Disk cutter

A disk cutter consists of a steel disk edged with diamond abrasive. The disk is electrically propelled and has a diameter up to 300 cm. Maximum cut width is 120 cm, both horizontally and vertically. The disk cutter moves along metallic rails by means of a hydraulic device. Cutting speed is from 5 to 8 square meters per hour. The required amount of cooling water is from 1 to 2 litres per second.

This machine is only used in flat areas, where long horizontal surfaces of massive marble may be prepared, because of the comparatively difficult installation procedure required before performing a cut.

In addition, due to the limited cutting penetration, the disk cutter is used only for the production of small blocks and of not too abrasive rock types.

3.4.10. Cutting by disaggregation

Cutting by disaggregation technology includes:

- Flame jet

- Water jet

3.4.11. Flame jet

Channelling by the use of flame jet is a very common method in granite cutting. This method consists in disintegrating the rock with intense heat from the combustion of fuel oil and oxygen.

The thermal shock causes the rock to spall due to the differential thermal expansion or allotropic changes in the crystalline components. For this reason, the grain size of the rock should be large enough to enhance the differential thermal expansion of the crystals under heating, and the crystalline composition should be well diversified. The channel produced by flame-jet is from 6 to 8 cm wide. The flame temperature is about 2.500 °C. The torch, which is passed back and forth over the rock, is manually operated. Oxygen is pumped into the torch through compressed air. The intense noise produced by the flame (to 120 dB) requires ear protection. In granite quarries lacking natural discontinuities, primary cuts are made using this method. It does not work in carbonate rocks, because the intense heat causes the formation of refractory CaO.

3.4.12. Water jet

One of the most innovating technology for cutting granite and other rock types is the water jet. A pulsating jet of water at a pressure ranging from 95 to 275 MPa (to 3800 atm) causes the grains to disintegrate. It is less noisy, produces less dust, and promises to be more economical than the flame jet in long-term operations.

Water consumption is 20 lit./min and the average cut speed is 1 m^2/hour.

To enhance the cutting power of the water jet, abrasive powder may be added to the water. This method is also called abrasive jet.

3.5. AESTHETIC EFFECT AND SURFACE

The parameter designers are most interested in, when using stone materials, is the aesthetic appearance. It basically depends on three characteristics: colour, grain size and structure/texture.

The colour of dimensional stones depends on the colour of the minerals they are composed of and grain size. Sedimentary, igneous and metamorphic rocks have quite different characteristics, both in terms of colour and texture variation, and colour stability [4,7,9,13,19,21].

In particular, the pigments contained in the minerals of igneous rocks are rather stable: these minerals take on polishing well, and are resistant to aggressive atmospheric conditions, with the exception of biotite and pyrite.

Sedimentary rocks (sandstone, limestone, other calcareous stones) come in a practically endless variety of colours and hues. These are generally very warm, but also more variable and unstable due to the special nature of the pigments contained therein.

Finally, metamorphic rocks (slate, marble and serpentine) have colder and quite variable colours. The pigments they contain derive, especially in the case of marble, from the re-crystallisation of the pigments contained in the original rocks. These sometimes tend to concentrate, thus forming veins, sometimes very intense.

There are, therefore, some materials which can be considered as monochromatic due to the homogeneousness of their hue and grain size, such as Bianco P or Belgium Black, to the presence of a number of minerals with chromatically close colours, and, finally, to the prevalence of one hue over the others, as is the case for some kinds of Bardiglio and green marble from Val d'Aosta [15].

Polychromatic materials are, instead, those, which show a veined or brecciated or even "ghiandonato" (literally: acorn-shaped) pattern.

Veined materials generally consist in marble, though some kinds of granite, such as the multicoloured ones, also have veins of different colours, sizes and orientations. Larger and nicer veins can be used to create special decorative patterns, for instance "open spots".

Brecciated patterns generally belong to many kinds of marble, such as Arabescato, Rosso Levanto, and are due to the presence of fragments of rocks of the same or different materials, cemented to each other by some other material.

The "ghiandonato" or acorn-shaped pattern is generally produced by more or less large crystals or inclusions, soaked in a basic compound made of smaller minerals.

Other chromatic and textural peculiarities, such as the presence of inclusions or slight colour variations, are due to specific geological processes and cannot normally be regarded as material faults.

Sometimes it happens that the designer just considers the aesthetic features of a material, based only on the sampling shown by the supplier. This may cause some misunderstanding, since even the most homogeneous materials may naturally undergo some chromatic and textural variations, which can hardly be documented even by a very accurate sampling. The designer is advised to visit a project, which has already been made with the material to be used. Alternatively, if this is not possible, the designer should consult a specific data bank on stone materials, which may supply information also on recommended applications and projects already made [17, 18].

The dimensional rocks available on the international market can certainly fulfil any kind of designers' aesthetic requirement, even if their actual availability must always be checked beforehand: some materials, such as, for instance, white marble from the Apuan Alps, can be found in large quantities, while white granite is much less common.

Finally, the processing methodologies used both for cutting and surface finishing also provide designers with an opportunity to work on the aesthetic features of the material.

For instance, polishing a dimensional stone will highlight its chromatic characteristics, while sand blasting or flame texturing (processes used to obtain a rough surface) will tend to mitigate them. The colour will not change; it is just a different way to reflect light. Nice chromatic variations can, therefore, be obtained using, for instance, one single material with different surface treatments.

Often, the pattern of a material is closely related to the planes along which it is cut. A block of stone may be cut with the bed, across the bed or vein cut. In the "with-the-bed" cut, the cutting plane is parallel to the schistose and/or laying plane of the rock, while in the across-the-bed or vein cut, the cutting plane is perpendicular to the schistose and/or laying plane of the rock.

Each material generally shows an optimum cutting direction, in terms of pattern and physical-mechanical properties; this does not mean, however, that it cannot be cut in different ways, to obtain special aesthetic effects [15].

Surface treatments are operations performed on raw cutting slabs to change the surface layer [7,9,15,19,20]. The main surface treatments are Honing, Polishing, Bush-hammering, Flame-texturing, Sand-blasting, Water-jet streamed finish, Filling and Reinforcement.

1. Honing is a slab shaving process used to obtain flat surfaces with different honing degrees, depending on the granulometry of the abrasive used. Polishing is a shaving process used to obtain a light-reflecting surface, through the application of polishing substances, such as oxalic acid or alumina, etc. Polishers perform honing and polishing; they can be bridge polishers, belt polishers or arm polishers.

2. Polishing: Bridge polishers consist of a steel beam running transversally along some slides. The motor unit with the polishing head is installed on the beam. These machines can be used both for mass productions and special productions, such as, for instance, very thick slabs. The different finishing degrees are obtained by using abrasive sectors with different grain size values. In the belt polisher, it is the slab which moves. It is drawn by a belt, at right angles with which traverses a steel bridge, holding the mandrels with the relevant abrasive sectors of different grain size values. The machines used in marble conversion lines may be provided, at the in-feed of the polishing unit, with one or four diamond-plate gauging heads, which flatten the surface, bringing the slab to the required thickness. The same gauging operation may be performed using diamond plates with abrasive sectors having a large grain size. The arm polisher is the most traditional machine used for the honing and polishing of stones. It still is the best option for small-size jobs, honing and polishing specially shaped products or for the treatment of very thick parts. In these machines, the required finishing level is obtained by changing the kind of abrasive tool each time. The articulated arm, which is hinged to a pillar, holds at the end a mandrel with the abrasive plate.

3. Bush hammering is an operation to be performed on marble and granite slabs to turn their raw cutting surfaces into knurled finished surfaces at different levels. The machines used are bush-hammering machines, which are equipped with jackhammers. The slab is drawn by a motor-driven set of rolls. Each slab surface finishing level is obtained using a different tool.

4. Flame texturing is a surface treatment, which is only performed on granite and similar slabs, in order to lend the cut surface a rough appearance. The machines used are flaming machines, which use as a tool a blowpipe, emitting a high-temperature and high-speed oxypropane or oxyacetylene flame. The thermal shock causes the surface to crater, shedding tiny scabbles and becoming rough and textured.

5. Sandblasting is a finishing treatment obtained by blasting sand or other abrasive grains at high pressure against the stone surface in an even way.

6. Water-jet: A recent variation of this technique consists in exposing the stone surface to a constant, pressurised water jet. Both techniques produce finely rough surfaces, their colours differently enhanced or toned-down, depending on the characteristics of the material.

7. Filling is an operation, which is generally applied to travertine or to those materials, which have a vacuolated appearance, in order to fill these small cavities and/or holes: the porous surface thus becomes smooth and uninterrupted. This operation may be performed either manually or using the so-called filling machines, which are structurally similar to the belt polishers. Once the material has been filled, it is left to

dry and then is fed back to the conversion cycle, to be later polished, then cut and finished.

8. Reinforcement is an operation which is traditionally performed on coloured and loose calcareous materials: a pigmented resin is put in the joints and spread on the back of the slab; if required, a plastic net can also be glued as a reinforcement, to improve the mechanical properties of the material and the cohesion of its components.

References

1. ASTM C119 Standard Definition of Terms Relating to Natural Building Stone - American Society for Testing and Materials, 1988
2. Bradley F., (1989). Cenni sull'analisi geologica delle rocce ornamentali, *Technostone S.p.A*.
3. Bradley F., (1991). Guide to the quarries in Carrara, *Internazionale Marmi e Macchine Carrara S.p.A.*
4. Bradley F., (2000). Infomarble, Promorama
5. Bradley F., (1998). Marble Quarries of Carrara, Studio Marmo
6. Bradley F., (1999). Marble Quarrying – Technical and Commercial Manual - Promorama
7. Canavesio G., (1994-95). Marbles, Granites, Travertines and Stones: their selection and use in building, *Marmomacchine Directory* Ed. Promorama
8. Conti, Mannoni, Montani, Pinzari, Pucci, Ricci (1990). Marble in the world, *S.E.A.*, (2nd ed.)
9. Corbella E., Zini R., (1988). Manuale dei marmi pietre e graniti, F.lli Vallardi Ed.
10. EN 12440 Natural Stones. (2000). Denomination Criteria, European Committee for Standardisation
11. Giornetti M., Stone Industry Technical Glossary, *Internazionale Marmi Macchine Carrara S.p.A.*
12. Harben P., Purdy J., (1991). Dimension stone evaluation: from cradle to gravestone, *Industrial Minerals*, pp. 47-61
13. M.I.A. (1987). Dimension Stone - Vol. III, Marble Institute of America, Farmington (Michigan)
14. Manual de Rocas Ornamentales – Entorno Grafico s.l., 1999
15. Mignani A., Quadrelli S., (1993). Pavimenti e Rivestimenti Interni – SEI seconda parte, *Internazionale Marmi Macchine Carrara S.p.A.*

16. Milazzo G., Blasi P. An introduction to dimensional stone quarrying in ACP countries, *Internazionale Marmi Macchine Carrara S.p.A. – in press*

17. Morandini Frisa A., Sanvito M., (1996). La caratterizzazione tecnica delle rocce ornamentali: normativa e prove tecniche, *Rivista GEAM*

18. Morandini Frisa A., (1990). Studi e ricerche per la classificazione dei materiali lapidei, *Marmomacchine*, 92, pp. 142-156

19. Primavori P. (1999). Planet Stone, *Giogio Zusi Editore*

20. Shadmon A., (1996). Stone - An Introduction, Intermediate Technology Publications, London

21. Winkler E.M., (1994). Stone in Architecture, Spriger Verlag

4

Non Destructive Testing on Dimensional Rock Blocks

Angel M Lopez-Buendia, J.V. Fuente, Roberto Lopez, Luis Dominguez, E. Opes

Breakage in dimensional stone of block size is an usual problem that takes place during their processing operation, specially when the block is being cut in the gang-saws. This is quite important from the point of view of the work safety, breaking of the cutting machinery, waste of material, or idle time to repair damage. The document describes several existing non-destructive techniques of general defectology diagnosis on natural stone and the current state of art on this research area, taking into account industrial needs. For this reason, we focused on:

a) Classifying blocks according to their general status

b) Crack location inside the whole volume.

Both of these objectives can be satisfy using ultrasonic wavelength methods.

The industrial benefits derived:

a) Quality control on dimensional rock blocks at quarries and factories.

b) Information about the best orientation to set the block in the cutting process

4.1. INTRODUCTION

Breakage of the blocks comes from their unhomogeneities. These unhomogeneities can be: large fractures, family of microfractures, karstification, micro-karstification, breccified bands, differential cementation or stylolites. The behaviour of each defect, from ultrasonic detection point of view, is different. There are two main research lines on NDT in which actions in this field are focused. These are as follows:

- General estimation of the material damage in order to determine the block quality to evaluate the risk of breakage during the cutting process.
- Inspection methods as pulse/echo in order to detect the types and location of defects within the whole block. These method need tomography integrate methods for 2D & 3D pattern reconstruction of blocks by means data integration.

4.2. NDT-UT GENERAL DIAGNOSIS

Ultrasonic methods are well established in flaw and crack detection in the mechanical industry.

Acoustic propagation has been developed for composites materials. They are also applied in control of concrete (Wiberg, 1994) and have been used in the research of natural stone.

Ultrasonic inspection is a common tool in the steel industry, mainly in material characterization and welding checking. More recently some investigation has been carried out on marble, applied for small samples cores and small and medium sized rock block. In whole blocks some advances have been achieved using a few through-transmission measurements.

Acoustic and ultrasonic wavelength propagation in dimensional rock depends on porosity (size and distribution), mineral composition, cementation, and presence of unhomogeneities.

Impact Echo methods measure the impulse response spectrum, which is a transfer function between the output energy and input energy. From the impulse response spectrum it is possible to calculate the dynamic stiffness and the distance to a reflector.

Ultrasound based techniques can be used considering: a) the marble as media for ultrasonic wavelength propagation, and b) the block as a system, which filters the wavelength as a function of the internal state of the block.

4.3. INSPECTION METHODS APPLIED ON NATURAL STONES

There are a large number of applications on non-destructive testing area based on ultrasonic inspection where ultrasonic waves are propagated through highly attenuated material. There are many dimensional rock types in a variety of ultrasonic propagation features. In fact, the optimal ultrasonic wavelength and the power input signal has to be chosen for quality inspections. Ultrasonic wavelength and ultrasonic impedance differences between materials and discontinuities gives accuracy to the developed inspection methods.

According to the factory needs, research actions are aimed to get a method able to detect weak zones by means of A-scans grids. A level power input had to be chosen to improve large inspections without a drastically accuracy decrease. It is used through-transmission modes for lower resolution measurements and pulse/echo modes to determine the location and orientation inner defects.

Among antecedents related with the proposed ornamental stone industrial application there are several techniques developed:

- Rudimentary technique applied to dimensional rocks is based on hitting a mechanical impact along the surface of block faces. The quarry worker hears and performances the sound that it comes from impact and he tries to detect the presence of fissures or weak zones. Bass and very sharp sounds belongs unsound zones and expected sounds belongs sound zones.
- The pile driving techniques for predicting resistance and homogeneities of natural stones and constructive items which develop the concept of applying one dimensional wave propagation into a measurement direction (Pile Dynamics Inc, American company).
- Automatic system for inspection slate slabs is based on acoustic signal processing from impact echo technique for classification purposes. (Douet et al. Proccedings Eurothen 2000)
- Also there are some applications for dimensional rocks as SQS (Lenzi, G. Et al, Stone Quality Sound) where use a spatial scans by through-transmission techniques but it is impossible to obtain a good relation between fast and accurate method.

To overcome this point, a significant contribution was done in RESISTONE project (CRAFT), where a faster and accurate technique of general state of the block was developed. It is based on impact techniques using a multi-parameter algorithm to classify the block state on dimensional stone blocks.

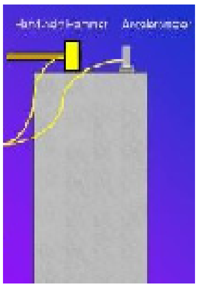
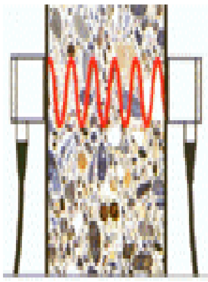
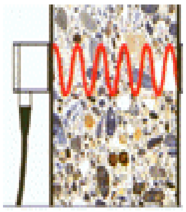
It is considered the methodology for Non-destructive testing on dimensional rocks developed, for the moment, needs an improvement and integration to obtain an technical tool to be used satisfactorily on:

- Quality control for blocks on quarries.
- To take advantage of material on cutting process.

In this sense, below it is detailed non-destructive techniques developed and applied on dimensional rock that they are able to satisfy the goals according to the needs of stone industries.

Ultrasonic wavelength based techniques have been found as the most effective methods to do both diagnosis and fissures location on a block scale. Other geophysical techniques have been rejected due to their lower resolution.

Different types of rock with known physical properties were selected to study the ultrasonic wavelength propagation. Three modes were used for satisfying industrial requirements: through-transmission, pulse/echo and impact-echo using a hammer as transmitter.

Scheme	Technique	Application on natural stone	Features
	Impact Echo	Rudymentary Technique: Dimensional Rock Pile Driving: natural stone Automatic system slates on slabs HM- Resistone: Dimensional Rock Resistone sofware: Dimensional Rocks	Low resolution and accuracy. Used only for classification purposes.
	Through-Transmission	✓ SQS: dimensional rock. ✓ LRM-Resistone: dimensional rock.	General method for scans and tomographies. Suitable on highly attenuated solids.
	Pulse/Echo	HRM- Resistone: dimensional-rock SAFT Technique is a PDS based on Pulse/Echo: composite materials at lab scale and tissues.	General Method for high resolution scans (materials and biomedicine). Suitable to locate fissures.

4.4. DIAGNOSIS OF THE ROCK BLOCK

In a factory scale (real scale) rock blocks have been studied using ultrasonic wavelength. Measurements have to be collected as digitised signals. Ultrasonic analysis must be correlated and evaluated with the real state of the block by visual inspection of the slabs when were cut.

Figure 11. Collecting data stage

The "Impact or hammer method" has been developed to discriminate the general block state.

The energy input comes from a hammer impact made in the centre of one of the block faces. The response is collected with broadband transducers located in opposite faces.

At the first stage, it must be captured the ultrasonic wave with a accelerometer piezoelectric when a mechanical excitation hits a block face, an ultrasonic wave propagates through the block and it could be considered as a filter system. The generated wave is composed of a wide spectrum range from 500 Hz up to 40 kHz and excites an extensive zone.

The analysis stage consists in extracting some parameters by signal processing on time and frequency domain. This stage needs a digital signal processing applying several algorithms.

After extraction stage the parameters are put in order being set at the same columns as array.

A single array is composed of parameters from measurements belongs the same block. Also others combined ratio parameters extracted from different measurements are calculated and considered.

On the other hand, it is built a reference database with valid block measurements, that is those measurements whose state is known after the cutting process. At this point, how to short the general state block must be decided:

- Sound blocks, no one slab was broken during the cutting process.
- Regular status, when an isolated defect (open fractures or cracks) produces a break on a slabs group.
- Unsound block, when some defects produce breaks in most of the slabs.

A large number of collecting data campaigns have been made to build a complete reference database.

The last diagnosis stage is the classifier implementation. Philosophy is to get a versatile classifier for those materials types exhibiting marked changes on its ultrasonic parameters depending on their states (sound, regular and unsound). Therefore, it has been found several parameters for each block with a high percentage of classification success.

The most important problem was to decide which blocks were in regular or unsound state. As not clear limits between these states were achieved, it has been implemented a classifier with two classification modes:

- Mode 1: sorting blocks on three statuses, sound, regular or unsound.
- Mode 2: sorting blocks on two statuses, sound or unsound.

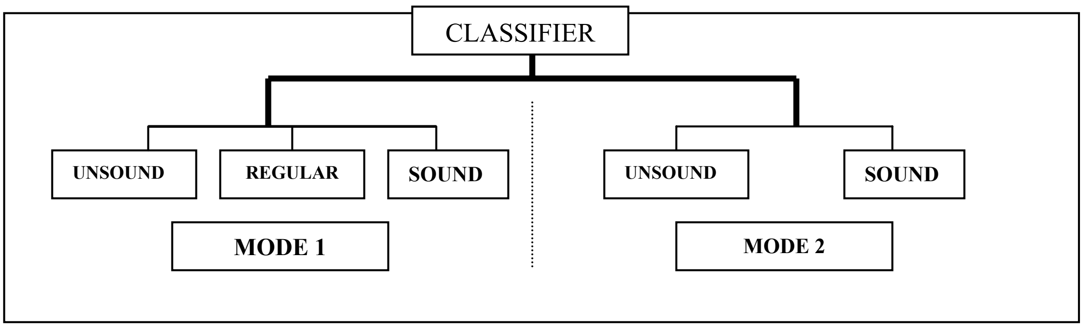


Figure 12. Scheme of classification modes.

For the tested blocks, high percentage of success was obtained using two classification modes.

The classifier shows a high percentage sorting unsound and sound blocks. The most important goal is related to high percentage of success (up to 90 %) on detecting unsound blocks. In this sense, none unsound block is processing on factory. Also, it is showed a good percentage on sound block classification (in all cases up to 75 %). The classifier shows a decrease on regular state percentage when there are one or two isolated defects.

4.5. TOMOGRAPHY METHODS.

More intuitive analysis is performed in order to locate inner defects on the blocks. According to this, a grid is made on a face block. Distances between grid points depend on the nominal frequency of the transducers.

The “Low Resolution Method” has been developed to detect weak or anomalous zones with A-scans by through-transmission mode, setting emitter and receiver aligned. A high pulse voltage has been employed to increase power scans. We obtained different kinds of 2D tomographies. These are a Map of velocities and attenuation.

Moreover, a “High Resolution Method” has been developed to detect the exact location of fissures. In this case, only a transducer acts as emitter and receiver driver. This method provides a good resolution for frequencies employed up to 250 kHz and high pulse voltage.

4.6. LOCATION OF DISCONTINUITIES.

The “Low Resolution Method” allows locating and discriminating defective zones.

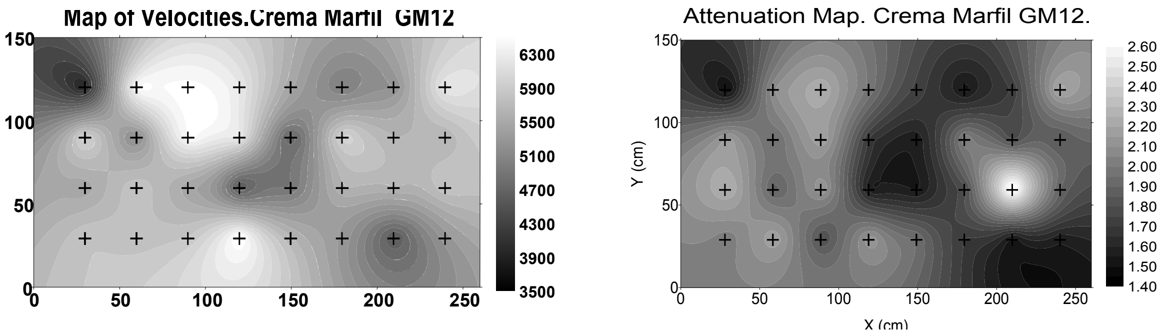


Figure 13. Map of longitudinal wave velocity, and attenuation longitudinal wave map

Both attenuation and velocities maps show defective zones, but only low frequency attenuation maps, provides good accuracy. This analysis requires good transducer-material interface coupling.

Other researches have studied the relationship between attenuation and velocity with porosity on sandstones and ornamental rocks [4].

The aim to develop a “High Resolution Method” was getting block tomographies. Resolution in cracks location is λ/4, this supposes <±3 cm accuracy for fissure orientation >45º and <±1 cm accuracy for <45º.

4.7. CONCLUSIONS

The inspection methods mentioned above assume a new technical tool applied for diagnosis and detection purposes on ornamental rock blocks. A percentage of success (>60 %), in any case higher than the percentage of refused blocks on factories, is obtained for a wide range of different rocks.

The mode 1 classification yielded a decrease of some percentages. This can be attributed to the difficulty in delimiting regular and unsound block states.A particular signal processing, based on parameters correlation, can be implemented in order to get the optimal orientation setting at the cutting process.

For detection purposes, low-resolution method provides a profitable tool for weak zones location. High-resolution method using pulse/echo mode is able to locate those fissures and cracks being perpendicular to the wave propagation direction. Long processing time is required to obtain a pattern of inner defects.

Research effort is needed in future work to improve the accuracy of a faster diagnosis system that decreases drastically the refused block on factories. Studies on this area are well justified as quarries and factories strongly demand an engineering tool for quality control.

References

1. White PR. and Lopes, (2000). Time-Frequency for analyzing structural response data. *ICASSP-International Conference on Acoustic Signal and Speech Processing*, Arizona 1999, p. 4.

2. Lenzi G., Limonta S., (1999). Stones Quality and Sound System (SQS): Detection of fissures in blocks by sound. *Litos*, vol. 40, pp. 46-60

3. Alcalde M., Villegas R., Vale J.F., Martin A., (1990). Diagnosis y tratamiento de la piedra, *Instituto de Ciencias de la Construccion Eduardo Torroja*, vol. 400

4. Anselmetti F.S., Eberli G.P., (1999). Velocity deviation log: A tool to predict pore type and permeability trends in carbonate drills holes from sonic and porosity and density logs, *AAPG Bulletin*, vol. 83, No.3, pp. 450-466.

5

Product Types and Selection Criteria

KOSTAS LASKARIDIS, PAOLA BLASI, MARCANTONIO RAGONE, ORAZIO MANNI,
ROSA MODARELLI

5.1. INTRODUCTION

Technological progress has made stone more competitive in terms of production but has also started off a process of product transformation. This process is bound to have important consequences in the future, especially for architects who tend to follow three different trends:

- Stone tradition
- Stone off-limits
- Stone innovation

New materials and products, able to meet end-users' requirements, are more and more often launched on international markets. Therefore, a more accurate selection, supported by a good knowledge of the properties of stones and of the products to be used, becomes absolutely necessary to use new materials.

This chapter gives an overview of new product types and analyses selection criteria based on ornamental stone aesthetic characteristics but also on physical-mechanical properties.

5.2. HISTORICAL HINTS ON STONE APPLICATIONS

The interest in stony materials has been relatively discontinuous in the course of time, probably due to problems concerning production and therefore economy. But certainly, in a relatively ripe period as the contemporary one of our culture, stony materials are getting extremely up to date, not only because of their expressiveness, which is connected to the fitting quality of the environment or the richness of chromatic and material hints, but also to an evident economic and productive development.

If stone is considered the construction material par excellence, much of this indubitable honor is due to the ancients' building know-how. In fact, the basic system on which the entire structural organism was developed, was that of the trilith, also called "three-stone", a structural system in which a horizontal element (architrave) rested its load on vertical elements (uprights). Examples of this system can be seen among the earliest megalithic monuments, which were formed of two stone blocks set vertically into the ground and topped by a horizontal slab – the famous dolmens.

To this system, used from the earliest times, was later added the arched system, which covered greater spans and achieved better results in static terms. The materials used from ancient times to create these building elements were stones: in the case of the trilith they were roughed stone elements installed without mortar and in the case of the arch they were often contoured ashlars. It is clear that these building basics never fell out of use and that even today they continue to survive thanks primarily to the special features of a material as old and as modern as stone.

Beside this primary function, during centuries the stones have been appreciated for their aesthetic properties, too; still today, in fact, a rediscovery of natural materials like marble, granite and travertine is a stylistic choice shared by many interior designers. In designing interiors there are many departure points for creating premium coverings and fixtures. The trend is to ancient materials used in unusual ways, so that advanced technological innovation and qualified design are the leaders of the new millennium. Today there is also greater use of innovative products for décor and sanitary fixtures: the new industrial workmanship on stone blocks makes it possible to create "designer objects", widening the range of use possibilities.

5.3. DATA AND STATISTICS

Before describing better the stones' applications, it is important to underline the main market trends of their production and trade, such as:

- Leading quarrying productions
- Percentage of natural stone main uses
- World consumption distribution and share
- Percentage of Italian exports of special products by country
- Expected world growth of natural stone trade
- Expected world trend of natural stone production and use

5.3.1. World consumption distribution and share

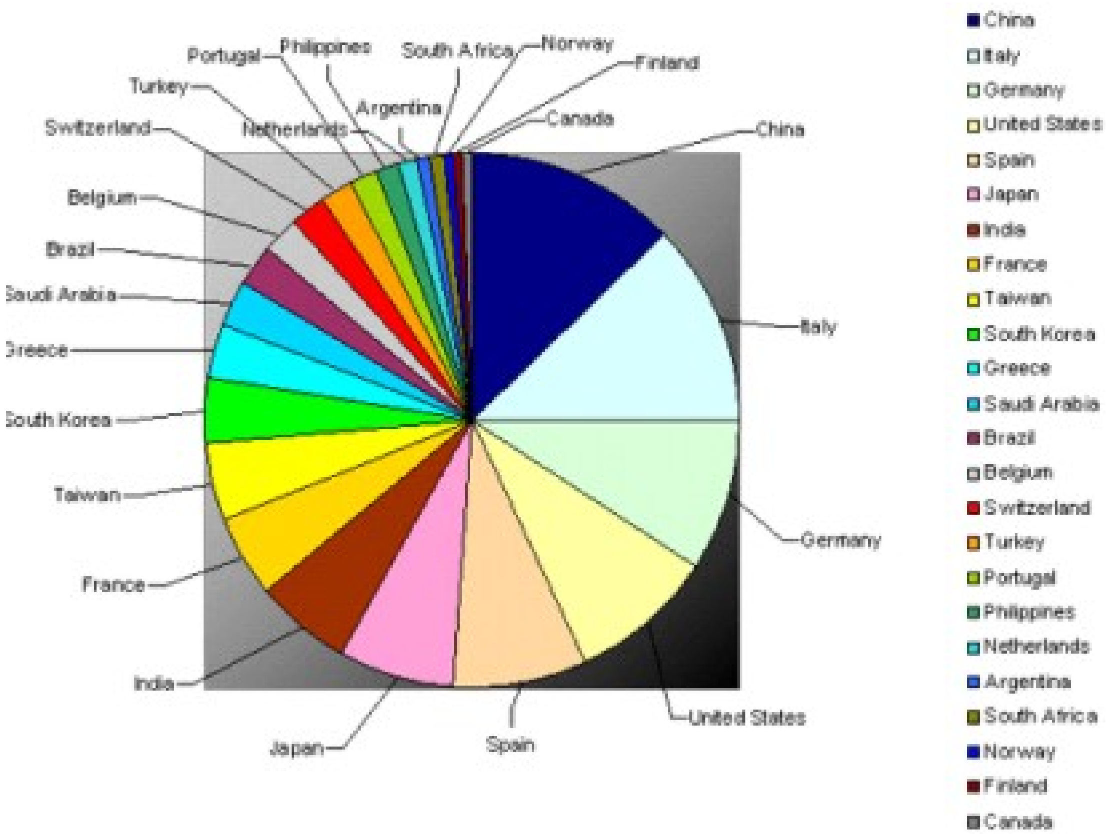


Figure 14.

*in thousands square metres at the conventional thickness of 2 cm

Table 11.

Countries	Quantities (000 tons)	Shares (%)	sq mt x 100	1999/1998
China	61.310	10.3	5,4	+ 2.5
Italy	58.130	9.8	101,1	+ 2.1
Germany	43.920	7.4	53,5	- 2.5
United States	41.920	7.0	15,7	+ 18.3
Spain	39.330	6.6	100,1	+ 12.3
Japan	33.360	5.6	26,5	+ 1.2
India	26.880	4.5	2,9	+ 7.6
France	24.510	4.1	42,3	+ 17.5
Taiwan	21.920	3.7	101,5	+ 21.0
South Korea	19.150	3.2	42,1	+ 27.0
Greece	15.120	2.5	146,8	- 3.8
Saudi Arabia	13.890	2.3	72,7	+ 10.8
Brazil	11.360	1.9	7,1	- 2.4
Belgium	11.030	1.9	108,1	- 5.0
Switzerland	10.420	1.8	146,7	+ 13.1

Countries	Quantities (000 tons)	Shares (%)	sq mt x 100	1999/1998
Turkey	9.270	1.6	14,6	+ 24.9
Philippines	6.030	1.0	8,4	+ 7.6
Netherlands	5.870	1.0	37,6	- 11.2
Argentina	4.050	0.7	11,7	+ 15.4
South Africa	4.010	0.7	10,5	+ 8.9
Norway	2.740	0.5	62,3	- 0.8
Finland	2.610	0.4	50,2	- 7.7
Canada	2.240	0.4	73,9	- 3.8

5.3.2. World Stone Industry: Leading Quarrying Productions

Table 12.

Countries	000 tons	Shares (%)
China	9.000	16.5
Italy	8.250	15.1
Spain	5.000	9.2
India	4.600	8.4
Portugal	2.350	4.3
Brazil	2.100	3.9
USA	1.700	3.1
Greece	1.650	3.0
South Korea	1.500	2.8
Turkey	1.350	2.5
South Africa	1.300	2.4
France	1.200	2.2
Germany	750	1.4
Mexico	650	1.2
Saudi Arabia	650	1.2
Finland	600	1.1
Philippines	600	1.1
Canada	500	0.9
Russia	500	0.9

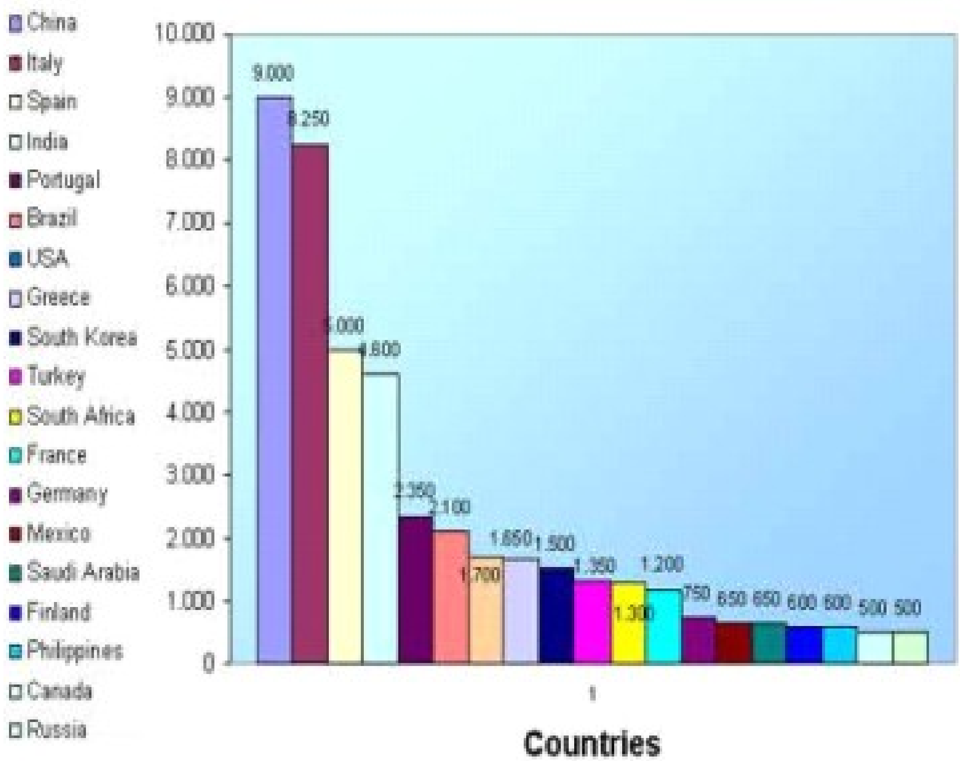


Figure 15.

5.3.3. Percentage of natural stone main uses

.

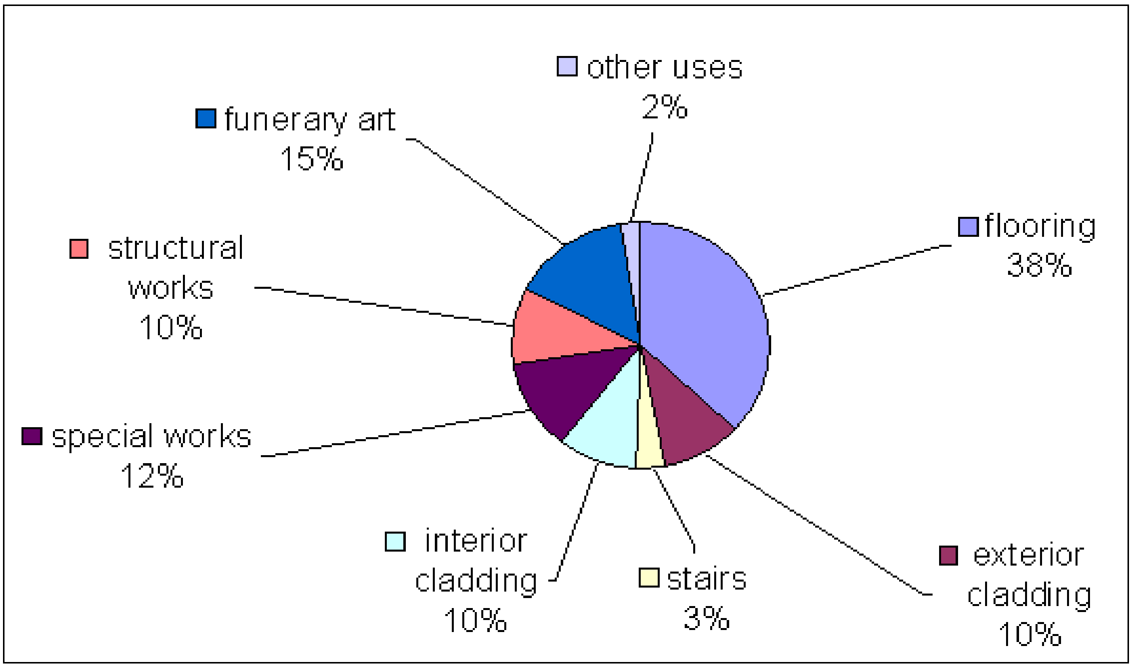


Figure 16.

Table 13.

World Net Production of finished products and Natural Stone main uses in 1999			
Uses	**000 mq**	**000 net tons**	**%**
Flooring	220150	11895	37
Exterior Cladding	59500	3215	10
Stairs	20825	1125	3,5
Interior Cladding	59500	3215	10,0
Special Works	71400	3860	12,0
Building Industry subtotal	431375	23310	72,5
Structural works	59500	3215	10,0
Funerary art	89250	4825	15,0
Other uses	14875	800	2,5
Other uses subtotal	163625	8840	27,5
Total	595000	32150	100,0

5.3.4. Expected world growth of natural stone trade

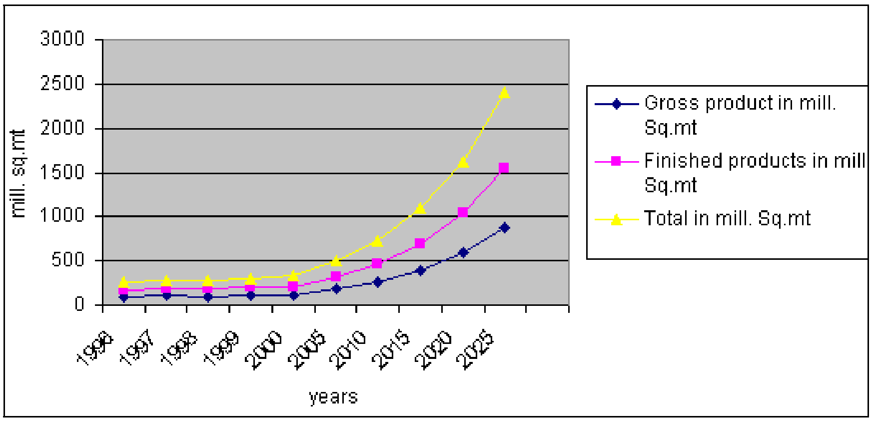


Figure 17.

Table 14.

Years	Gross product (mill. Sq.mt)	Finished products (mill. Sq.mt)	Total (mill. Sq.mt)	Annual growth rate	Ratios (%)
1996	88,4	171,0	259,4	0,0 %	84,4
1997	103,7	179,2	282,9	9,1 %	92,1
1998	96,7	181,7	278,4	-1,6 %	90,6
1999	111,5	195,8	307,3	10,4 %	100,0
2000	120,6	212,0	332,6	8,2 %	108,2
2005	179,2	315,1	494,3	9,7 %	160,9
2010	266,4	468,4	734,8	9,7 %	239,1
2015	396,1	696,2	1092,3	9,7 %	355,5
2020	588,8	1034,8	1623,6	9,7 %	528,3
2025	874,7	1538,3	2413,0	9,7 %	785,2

Average annual growth rate = 8,3 %

5.3.5. Expected world trend of natural stone production and use

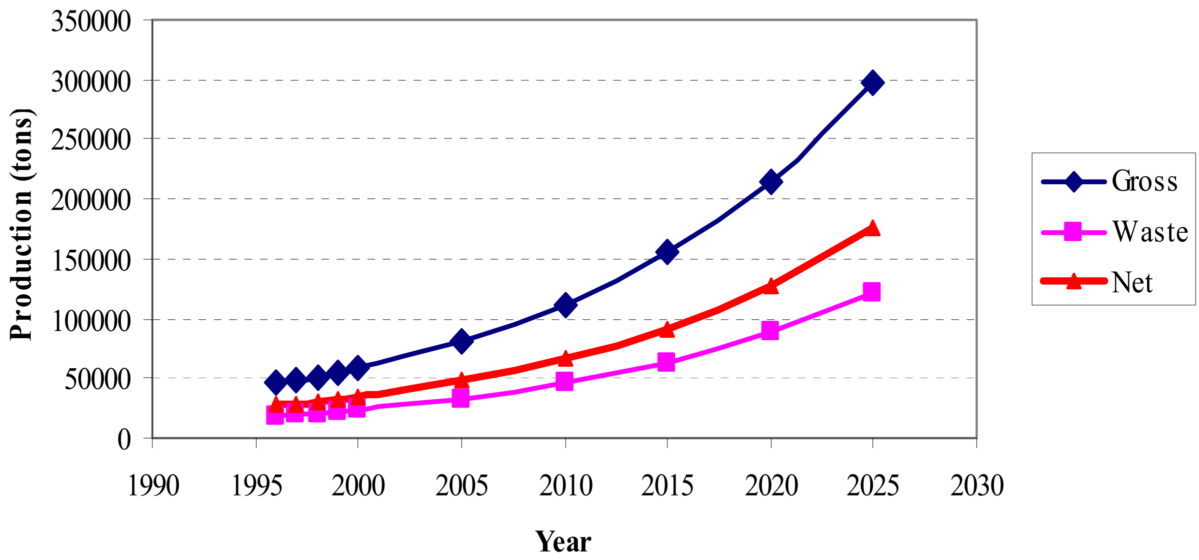


Figure 18.

Table 15.

Years	Production (000 tons)			Uses		%	Net/Gros	Waste /Gross
	Gross	Waste	Net	Mill. sq. mt	Annual increase %			
1996	46500	19070	27430	507,455		85,3	59,0	41,0
1997	49500	20300	29200	540,2	6,45	90,8	59,0	41,0
1998	51000	20910	30090	556,665	3,05	93,6	59,0	41,0
1999	54500	22345	32155	594,8675	6,86	100,0	59,0	41,0
2000	58180	23850	34330	635,105	6,76	106,8	59,0	41,0
2005	80650	33070	47580	880,23	7,72	148,0	59,0	41,0
2010	111800	45840	65960	1220,26	7,73	205,1	59,0	41,0
2015	154980	63540	91440	1691,64	7,73	284,4	59,0	41,0
2020	214850	88100	126750	2344,875	7,72	394,2	59,0	41,0
2025	297830	122110	175720	3250,82	7,73	546,5	59,0	41,0

Average annual increase = 6,86 %

5.4. STONE PRODUCTS: CLASSIFICATION AND DESIGNATION

There are three basic types of rocks in nature: magmatic, sedimentary and metamorphic. The first ones derive from the solidification of magma located below the earth surface. The second originate ones from the depositing of detritus of existing rocks and/or animal and vegetal remains. Finally, metamorphic rocks derive from a deep transformation of existing rocks, caused by physical and chemical agents (pressure and temperature).

All the rocks that exist in nature cannot be used for building: this study will only address those which can be cut into slabs and used for ornamental purposes. According to a commonly used product classification, these materials can be divided into four groups: marble, granite, stones and travertine.
Marble includes all basically carbonate rocks, with a more or less homogeneous crystalline structure, which can be polished.

Granite includes all intrusive and metamorphic magmatic rocks of silicate origin, which are solid and can be polished.

Travertine is a sedimentary calcareous rock of chemical origin, having a typical vacuolated structure; some varieties can be polished.

Stones include a wide variety of lithotypes and are generally not polished. Depending on their behaviour when processed, they can be divided into two groups, soft and/or poorly solid rocks and hard and/or solid rocks.

For further details on these commercial definitions, please refer to the European Standard EN 12440 Natural Stones – Denomination Criteria.

The situation of the commercial designation of the hundreds and hundreds of stone materials now available on the market is quite unclear. It is actually quite common, above all for new materials, to use names which have very little to do with the real characteristics of the material. For instance, a geographic reference may be added which does not correspond at all to the place which that material comes from (e.g. Bianco Italia quarried in China), or names which refer to well-known products may be slightly changed. At worst, the same name may be attributed to different materials, or one material may be defined in several different ways. This situation may cause some inconvenience, and this is why end-users in particular are asking for more clarity. In the EN 12440 a list of all main commercial varieties quarried in each UE country is enclosed.

5.5. MAIN APPLICATIONS OF STONES

Today, natural stones are basically used in the same sectors as thousands of years ago. Man has always felt the need to use these materials to build homes, palaces and places of worship, to hand down to posterity a remembrance of the dead, and to create works of art that remain through time. In addition to these three traditional sectors (or complementing them) there are now others such as urban fixtures, restoration, crafts, design, and the reuse of granulates, powders and by-products. Building – always the largest sector – absorbs 70 % of the world's production of natural stone, because different types of stone can satisfy every need for utility, beauty and functionality in various uses and are used across the board, from industrial building to religious, commercial and residential.

Stones are among the very first materials to have been used by man to build houses, monuments and other kinds of buildings. Today, the most common applications of dimensional stones are facings and floorings, both internal and external, funerary and sacred art, structural applications, special works, such as refurbishing, restorations and roofings, staircases, interior (skirting boards, doorstones, window sills) and exterior (window ledges, doorstones, copings, profiles) decoration and furnishings.

Among the most innovative applications, it is worth mentioning raised floorings, facings made of composite panels in ultra-slim stone and the structural use of pre-stressed marble or marble cut in shapes and bends. The most frequent applications, such as floorings and facings, will be reviewed below. Summarizing the main applications of stones, except those concerning the structural field are:

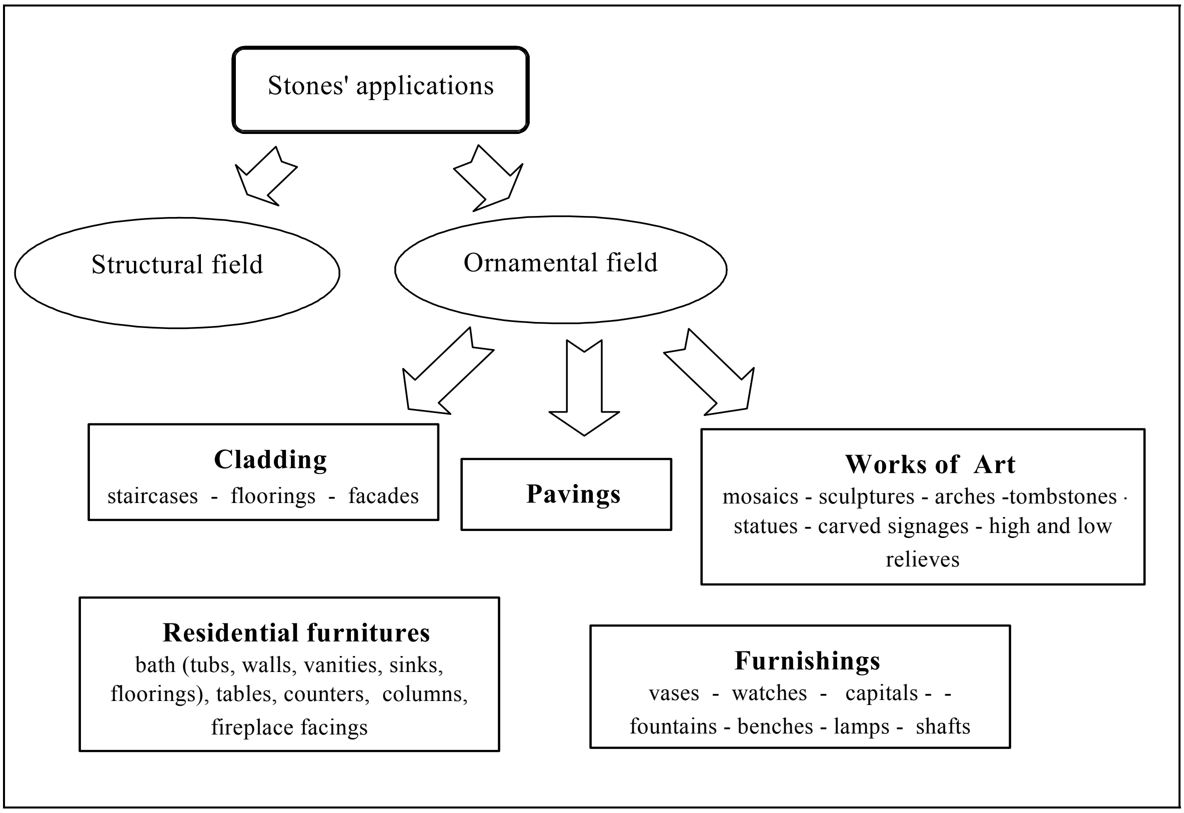


Figure 19. Main Stone applications

5.5.1. Claddings

The role of stone in exteriors is evident. It is used to pave squares and sidewalks in our cities, employed as a structural building material and also decoratively as a cladding. Stone can be used on the outside of any kind of building, from the single family home, to the huge modern towerblock. Often the skirting element round the bottom of a building at street level is made or clad with stone and likewise the stringcourse dividing one floor from another, and of course the thresholds and windowsills. Other elements on the facade frequently employing stone are balconies and door surrounds. Any attempt to cover every use of stone on building exteriors would inevitably be reductive, since every situation is different and requires special attention.

5.5.2. Pavings

Given the resistance of stone to atmospheric agents and its physical toughness, it is widely used for paving in streets and squares. This is particularly true now that the unfortunate fashion of simply covering everything with asphalt is at last coming to an end and people are beginning to appreciate the aesthetic and environmental qualities of stone. The most common shapes are squares, rectangles and rhomboids. These come in various sizes and can be laid at different distances, so that when used in combination they offer a wide range of patterns. There are also a variety of different surface finishes to suit different requirements and different kinds of stone.

5.5.3. Works of art

The most ancient cultures wanted to mark their most important and representative meeting places with stone. They wanted to counter the precariousness and inconsistency of human condition with the robustness and longevity of stone since the beginning and at all latitudes. Needless to remember even in the brightest periods of Classical, Renaissance and Baroque cultures (that developed in the heart of Europe and spread all over the world from there) stone materials were bent so much that they resulted in sublime expressiveness. Finally, even Rationalism and modern architecture wanted to entrust their tireless search for essentially and simplicity to stone.

Nowadays, new technologies have let to use stone in unusual ways, too, with the aim to emphasise its expressive values.

5.5.4. Furnishings

The use of the new technologies makes it possible to create even small objects at affordable prices, so that there was an increase in accessories' production which offers a vaste range of "mini-sculptures" made from the most interesting stone materials.

These objects, even keeping their artistic and traditional value, can be used also in the most modern interior architecture.

In particolar, colour is one of the physical characteristics which, among with other special features like veining or pattern, gives the material a unique, unrepeatable expressive value. The colour of the ground is indicative in determining the predominating colour. The range of colours that nature offers is divided into practically limitless combinations; the chromatic peculiarities of stone materials can be considered as many esthetic and expressive departure points.

5.5.5. Residential furnitures

In designing general furniture, the choice of finishing materials is significant, since today's stone sector offers a wide range of products. The use of the right material for these particular applications is a determinant factor in the good outcome of the final product design. In fact, it is fundamentally important to keep in mind the characteristics of the materials used, in relation to the prerequisites for creating these areas.

The production of elements such as bathtubs, shower plates and sinks provides valid examples of close collaboration between designers and industry. The technological development of new, numerical control machines and the automation of production processes provide for unusual applications, not only two-dimensional but also in the round, and working stone blocks leads to interesting solutions in decorative sinks.

All these applications are possible because of the stones' various properties and their effects on their relative finite products such as functionality, stylistic and expressive values, modularity and co-ordinability, costs and maintenance factors.

The rediscovery of these natural materials makes it possible to create solutions interesting in terms of aesthetic-formal "personalization" and in the technical features that make marble and granite among the materials most widely used for coverings and sink-tops.

The choose of the right stone to use in the ornamental field is, however, based on the physical aspects that influence a rock's use possibilities. In particular its:

- aesthetic features: colour, pattern, grain.
- technical properties: chemical and mineralogical composition, petrographical composition, physical-mechanical characteristics.

5.6. PRODUCT TYPES FOR CONSTRUCTION APPLICATIONS

The European regulations identify six types of natural stone products: blocks, raw slabs, slabs for internal floorings and staircases, slabs for facings, modular tiles and solid stone units. Masonry products, products for facings and units for external floorings and curb-stones can be added to the above.

As far as floorings and facings are concerned, the products supplied by stone companies can be classed as follows:

- modular tiles
- slab-edged modular units
- checkerboard
- cubes, split tiles, curbstones and kerbs
- chips, scabblings, tesserae (for the production of seminato and mosaics)
- laminated panels and pre-assembled products

Modular tiles or "modulmarmo" are generally produced through a specific process and their typical size never exceeds 60 x 60 cm. Thickness may vary from 0.5-1 cm for sizes 15 x 30 and 30x30 cm (classic size) to 1-1.5 cm for sizes up to 60 x 60 cm. The European regulation concerning these products, even if not definitive yet, limits thickness to < = 12 mm. Modular tiles are finished in the workshop.

Modular units produced by edging slabs may be cut to size, as required by the customer. Slabs used for floorings are generally 1.5 – 2 cm thick, while slabs used for facings may be 1.5, 2, 3 cm thick. Such modular units may be pre-finished in the workshop.

Checkerboard is used, instead, to make floorings or facings based on the designer's pattern. In this case, the stone units, which are often of a different nature, may have the most varied shapes, sizes and finishing. The work is generally so complex that the products must be laid in the workshop before sending them to the building yard for installation.

Cubes, split tiles, curbstones and kerbs are produced by the mechanical breakup of stone materials, which generally consist of such stones as porphyry. The cubes' sides may be from 4 to 20 cm long, in six different size classes (from 4/6 to 14/18). In most cases, the tiles are full length and their width varies by 5 cm at a time. Thickness may vary from 2 to 5 cm for ordinary ones and from 5 to 8 cm for larger sizes. Curbstones used to limit and contain floorings, but also as real flooring units, typically have a parallelepiped shape. The width of these units may vary from 10 to 14 cm, while their length may vary from 15 to 40 cm and heigth/thickness from 5 to 20 cm.

Chips, powder, scabblings, small cubes and tesserae, made of stone material generally derived from secondary processes, are used for the production of seminato and mosaics. More than products, they are compositions, which provide designers with a wide range of different possibilities.

In laminated panels and pre-assembled products, stone units (thickness 1-2 cm) are glued to a stone base and finished in the workshop (e.g. Carrara White or Travertine slabs). Sometimes, the backing slab may be removed and the units may be directly glued to one another, for instance along the edges. Such panels can also be used to create unusual multi-coloured compositions made up of even tiny units, which it would have not have been possible to create during the installation.

A special class of laminated panels is ultra-slim marble. The stone material is cut down to a thickness varying from 4 to 12 mm, then glued to a base which may come in different materials, for instance fiberglass reinforced plastic, alveolated aluminium or sheet steel, to create a fairly thick panel having suitable physical and mechanical properties for its intended use and for the type of environment or structure to be clad. The weight of the panels, which may vary from 15 to 25 kg/mq, allows the product to be successfully used in all those situations in which a light weight is important, such as in the internal finishing of buildings, lifts, ships, trains, etc.

5.7. PATTERNS

The patterns that can be used for floorings and facings can be divided into two different product classes: units made of slabs and/or solid stones, and chips, powder, scabblings and tesserae.

In the former case, the following types of composition can be obtained:

- opus incertum
- opus romanum
- modular
- cut sheet
- inlay

With chips and tesserae, the following can be obtained:

- seminato
- mosaic

Opus incertum is made of different units with varying shapes, sizes and thickness, which are placed close to each other without a precise geometrical order; it can be used to make the opus sectile, in which the randomly set units turn into an accurate and very impressive pattern, and the randomly set paving, consisting of units made from slabs all of the same thickness, with a much more accurate surface finishing.

In the opus romanum, the geometrical order stands out much more clearly: the units, even if made of different materials, have all the same thickness and a regular geometrical shape. The units are not arranged in geometrical order, but in an accurate way, to avoid creating repetitive patterns. The surface finishing may vary depending on design requirements.

In the modular class, units are arranged according to a simple geometry and colour matching. Size and thickness may vary depending on the properties of material and its intended use.

This kind of composition is particularly suitable for projects which involve large productions in short times and/or limited production and laying costs. The material may be finished in the workshop or during the installation.

The definition of checkerboard derives from the need to provide an accurate identification of all the composition units of the work to be made in a pattern, the fruit of a detailed design. Such pattern shall be used as a reference both during the processing phases and the mock-up and installation phases.

The inlay consists of a base stone slab, which is engraved or holed to accommodate some units cut according to a complementary pattern. Such pattern becomes the main element to highlight the whole work. Technology has provided a useful contribution to this kind of composition, through the “water-jet” machines, which replace or largely reduce the manual operations required to copy and profile the complementary units.

The seminato (literally: strewn floor) is made by throwing and mixing marble fragments of different sizes (5/50 mm) and colours, in the amounts desired, on a cement layer, which may sometimes be coloured. In case the grit is arranged in a precise pattern, i. e. not at random, the product is called “seminato alla veneziana”. Honing, polishing and other final treatments must be performed at the building yard to obtain an even work.

Mosaics are made of small-size, regularly-shaped, differently-coloured units (mosaic tesserae), which are laid one beside the other in a pre-established pattern. They are generally veritable works of art, which have successfully maintained their charm and value unchanged for centuries.

5.8. SELECTION BY AESTHETIC CHARACTERISTICS

Now, let us try to investigate in more detail the characteristics of the dimensional stones in which designers are most interested in and to outline the possible treatments that can be performed on the product to meet the requirements of a specific application.

The parameter designers are most interested in when using stone materials is the aesthetic appearance. It basically depends on three characteristics: colour, granulometry and structure/texture.

The colour of dimensional stones depends on the colour of the minerals they are composed of and granulometry. Sedimentary, igneous and metamorphic rocks have quite different characteristics, both in terms of colour and texture variation, and colour stability.

In particular, the pigments contained in the minerals of igneous rocks are rather stable: these minerals take on polishing well, and are resistant to aggressive atmospheric conditions, with the exception of biotite and pyrite.

Sedimentary rocks (sandstone, limestone, and other calcareous stones) come in a practically endless variety of colours and hues. These are generally very warm, but also more variable and unstable due to the special nature of the pigments contained therein. Generally, the application of such materials in external works is not, therefore, recommended, if one wants the colour characteristics to remain unchanged.

Iron plays the largest role in the colouring of sedimentary rocks; depending on its amounts and oxidization degree, it can generate colours from deep red to orange, yellow, brown, up to green, blue and black.

Rosso Verona is a classical example of a limestone the colour of which is due to the presence of iron oxides. The presence of organic matter can also produce very deep colours, from grey to deep black: the stability of these colours, which are often much sought-after by designers, depends on the level of alteration which these materials have undergone.

Finally, metamorphic rocks (slate, marble and serpentine) have colder and quite variable colours. The pigments they contain derive, especially in the case of marble, from the re-crystallisation of the pigments contained in the original rocks. These sometimes tend to concentrate, thus forming veins, sometimes very intense.

There are, therefore, some materials which can be considered as monochromatic due to the homogeneousness of their hue and granulometry, such as Bianco P or Belgium Black, to the presence of a number of minerals with chromatically close colours, and, finally, to the prevalence of one hue over the others, as is the case for some kinds of Bardiglio and green marble from Val d'Aosta.

Polychromatic materials are, instead, those which show a veined or brecciated or even "ghiandonato" (literally: acorn-shaped) pattern.

Veined materials generally consist in marble, though some kinds of granite, such as the multicoloured ones, also have veins of different colours, sizes and orientations. Larger and nicer veins can be used to create special decorative patterns, for instance "open spots".

Brecciated patterns generally belong to many kinds of marble, such as Rosso Levanto, and are due to the presence of fragments of rocks of the same or different materials, cemented to each other by some other material.

The "ghiandonato" or acorn-shaped pattern is generally produced by more or less large crystals or inclusions, soaked in a basic compound made of smaller minerals.

Other chromatic and textural peculiarities, such as the presence of inclusions or slight colour variations, are due to specific geological processes and cannot normally be regarded as material faults.

Sometimes it happens that the designer just considers the aesthetic features of a material, based only on the sampling shown by the supplier. This may cause some misunderstanding, since even the most homogeneous materials may naturally undergo some chromatic and textural variations, which can hardly be documented even by a very accurate sampling. It is advisable for the designer to visit a project, which has already been made with the material to be used, or, if that should not be practicable, to consult a specific data bank on stone materials, which may supply information also on recommended applications and projects already made.

The dimensional rocks available on the international market can certainly fulfil any kind of designers' aesthetic requirement, even if their actual availability must always be checked beforehand: some materials, such as, for instance, white marble from the Apuan Alps, can be found in large quantities, while white granite is much less common.

Finally, the processing methodologies used both for cutting and surface finishing also provide designers with an opportunity to work on the aesthetic features of the material.

For instance, polishing a dimensional stone will highlight its chromatic characteristics, while sand blasting or flame texturing (processes used to obtain a rough surface) will tend to mitigate them. The colour will not change; it is just a different way to reflect light. Nice chromatic variations can, therefore, be obtained using, for instance, one single material with different surface treatments.

Other peculiar effects can be obtained by making the most of the translucence of some kinds of marble, as in Meggen Church, Switzerland.

So far, only the aesthetic features of dimensional stones have been considered. Though very important, these are only part of the elements that a designer should consider. The identity card of each material actually includes its physical and mechanical properties as well. The latter are of fundamental importance and, in some cases, may be decisive in the choice of one material over another.

5.9. SELECTION BY PHYSICAL – MECHANICAL PROPERTIES

Natural ornamental stones i.e. marble, granite etc have been broadly used in the past and gain ground again into the construction industry, playing an important role among other building materials.

Nowadays, the applications of the natural ornamental stones in construction are unlimited and for this reason their use is broader than in past, throughout the world. The broad use of the natural ornamental stones in contemporary buildings is due not only to the aesthetic result that they offer but mainly because they can cover economical, technical, aesthetical and ecological demands. Also, by selecting to use natural ornamental stones one achieves the best relation between quality and price.

The Battelle Institute in Germany [1] performed a study comparing ten different materials with the purpose of using them in five important types of buildings for flooring. They concluded that although the natural ornamental stones belong to the expensive materials, because of the fact that they are more easily protected and cleaned, and also because of their strength, they are competitive and in a few years they can be proved more economical.

Which are though the criteria for the design and the selection of the suitable natural ornamental stone in a large project/building?

The decision of using natural ornamental stones is definitely determined by the fact that their use should give a permanent solution in terms of the achievement of a lifespan as long as that of the building itself.

The final selection of the natural ornamental stone, for the specific application that is intended (e.g. flooring, cladding etc) should take place after detailed examination of all the phases of the project and the technical – design aspects, as they are shown in the flow diagram (Figure 20). The example of Figure 20 shows the criteria and the selection stages of the natural ornamental stone for exterior cladding of the building. However, these criteria are valid in general and not only for exterior cladding.

The first stage of natural stone material pre-selection can reached only after taking in account the architectural design and the aesthetic presentation of the building, after completing an evaluation of the macroscopic characteristics (aesthetic appearance, presence or absence of veins and their arrangement, presence or absence of inclusions “spots”) of a big variety of natural ornamental stones of different colours, as well as after presentation of the building’s drawings.

The factors that affect the final selection of the natural ornamental stone are mainly the following:

- Availability of required amounts and the required quality of the material needed for the whole project.
- Ability to apply suitable surface treatment technology to achieve the desirable treated surface on the selected material.

- Knowledge of the chemical – physical – mechanical properties of the rock that should fulfill the standards, in order to avoid influence of the material by the climatic and environmental conditions of the area where it is going to be placed and finally
- The total cost of the coating.

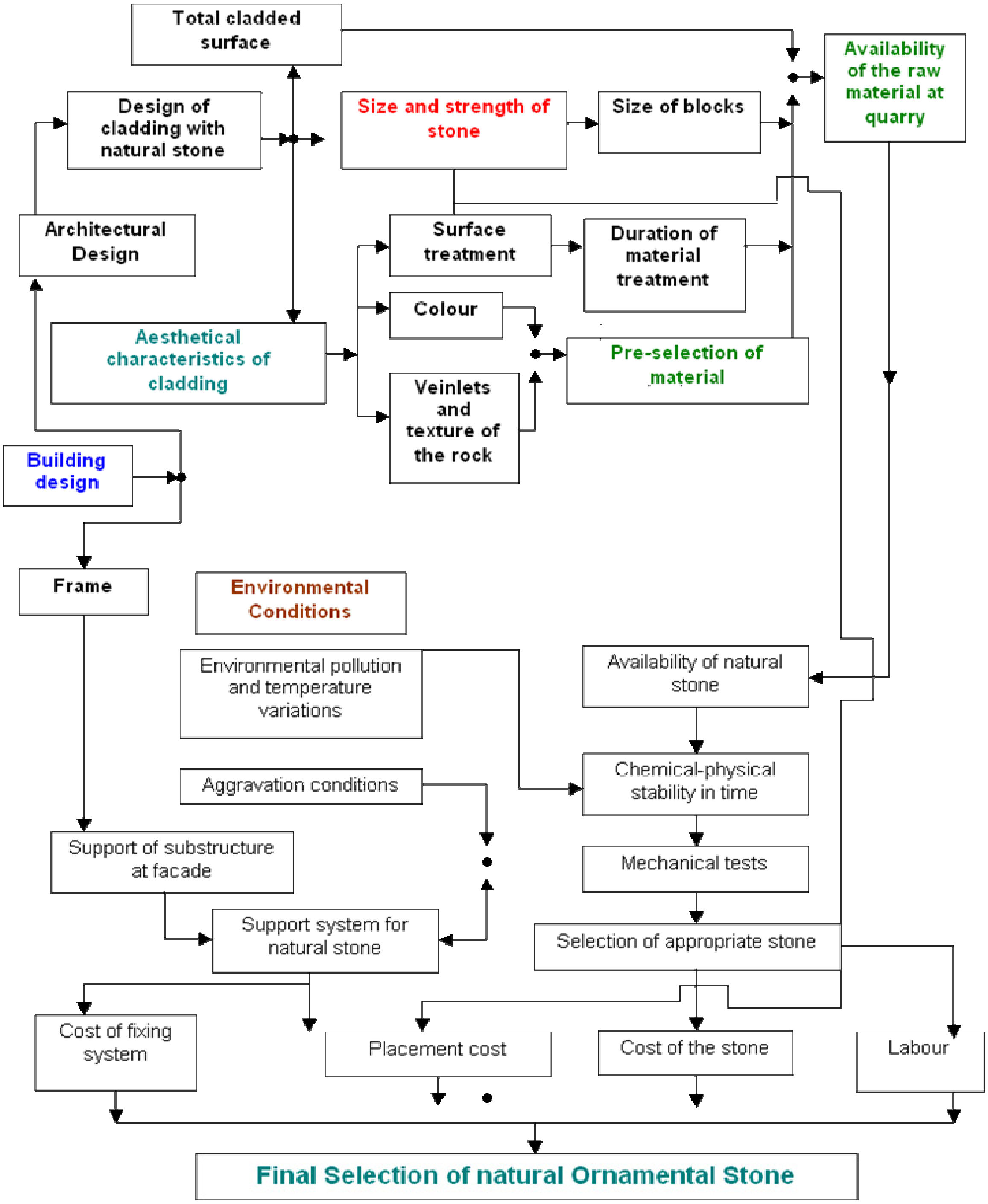


Figure 20. Selection criteria of natural ornamental stones for use for external cladding

From the above mentioned, one can see that certification of the rock's quality is demanded, after the examination of its physical – mechanical properties from which depends its ability to resist the environmental pollution and the mechanical effects, considering the climatic conditions of the area where the project is taking place.

The examination and the certification of the material's suitability are conducted through laboratory research after a series of tests that take place in specialized laboratories. The properties of the rock to be measured and evaluated depend on the final application.

Knowledge of the physical – mechanical and technical properties of natural ornamental stones gives also the opportunity to predict the rock's behaviour in a building, as time goes by. In the laboratory environment, all rocks under investigation are subject to strain-stress tests in order to estimate their mechanical, physical, technical and environmental properties.

Until now, tests are conducted according to the international standards ASTM, DIN and UNI for the natural ornamental stones. However, during the last years, the Technical Committee prepares new European standards EN for the natural ornamental stones, and the first specifications are in charge, while at the same time the Committee prepares the rest.

The above-mentioned categories of the natural ornamental stone properties that should be examined in order that the material's identity is certified are presented in the following paragraphs.

5.9.1. Physical Properties

Specific Density

It is the ratio of the rock's weight to its bulk. Because of the fact that the natural ornamental stones include pores, cavities and voids, there are two measured bulks: the apparent, which i.e. is the bulk of the rock together with its voids and the actual, which i.e. is the one without the voids. Thus, there are two specific gravities for each rock: the apparent and the actual. The one that characterizes the rocks is the apparent specific density and is expressed in Kgr/m^3.

By the same procedure used to determine the apparent specific density we can also determine other rock indexes such as the density grade (ratio of the dry apparent specific density to the specific density), the porosity and the compact (ratio of the apparent specific density to the actual specific density), used in specific cases.

Water Absorption-Coefficient of Impregnation

The term water absorption refers to the rock property of water saturation. The water absorption of the natural stones is the difference in mass between the sample saturated with water and the dry one. When it is expressed in % it is called coefficient of impregnation.

In Table 16 indicative values of the physical properties of different natural ornamental stones are shown.

5.9.2. Mechanical Properties

Unconfined Compressive Strength

The compressive strength of a rock is defined as the ratio of the total load applied on a sample to its area intersection and it mainly depends on the characteristics of the rock's consistency and structure.

The most important factors that influence the compressive strength of a rock are:

- Porosity and the density
- Particle size and shape
- Anisotropy
- Mineral composition

Table 16. Mean values of physical properties of various ornamental stones

I. Apparent specific density		
Dolomitic marble	A.S.G ~ 2820 kgr/m^3	
Serpentine and ophycalcite	A.S.G ~ 2780 kgr/m^3	
Marble	A.S.G ~ 2710 kgr/m^3	
Granite	A.S.G ~ 2600 kgr/m^3	
Travertine	A.S.G ~ 2400 kgr/m^3	
II. Representative values for porosity		
Argil - Clay	44 – 50 %,	extremely porous
Psammite	7 – 34 %,	very extremely porous
Volcanic Tuff	20 – 30 %,	extremely porous
Travertine	5 – 10 %,	quite porous
Compact limestone	0,4 – 2,0 %,	small porosity
Granite	0,4 – 1,5 %,	small porosity
Compact Basalt	0,2 – 0,9 %,	compact
Serpentine	0,1 – 0,6 %,	compact
III. Water absorption		
Compact limestone and pure marble	∑y=0,06-0,34 %	
Granite and related rocks	∑y=0,35 %	
Common limestone and ophycalcite	∑y=0,4-0,45 %	
Porous limestone and travertine	∑y=1,15 %	

When a rock is strained it goes through different states (elastic-plastic-brittle). According to the international standards the minimum compressive strength of a rock, for various uses, is 510 Kgr/cm^2. In Table 17 indicative values of compressive strength for different ornamental stones are tabulated.

Table 17. Representative values of compressive strength

Type of Rock	**Compressive Strength**
Granite and related stones	R =2000 kg/cm^2
Ophycalcite	R =1500 kg/cm^2
Pure marble and compact limestone	R =1500-900 kg/cm^2
Fractured limestone – Breccia and travertine	R =900-650 kg/cm^2

Flexural strength

The resistance in tensile strength of the natural ornamental stones is the ratio of the bending moment during the breaking to the section modulus.

The bending strength of any rock also depends on its composition and structure. According to the International Standards the minimum bending strength of a rock for flooring is 68 Kgr/cm^2. Table 18 presents indicative values of bending strength of rocks used as ornamental stones.

Table 18. Representative values for Flexural strength

Type of Stone	Flexural Strength
Psammite	R= 30-100 kg/cm^2
Travertine	R= 40-100 kg/cm^2
Limestone	R=50-200 kg/cm^2
Marble	R=60-200 kg/cm^2
Granite	R=75-200 kg/cm^2
Basalt	R=100-250 kg/cm^2

Modulus of Elasticity

The Modulus of Elasticity, E, or Young's Modulus is a rock constant and is equal to the ratio of the stress increment to the strain increment (E=Δ∑/ΔEL). The modulus of elasticity is mainly used for the determination of elasticity of slabs that are placed horizontally or at an inclining position.

5.9.3. Technical Properties

Abrasion Test

This property expresses the rock's resistance in friction (caused by the circulation of humans, vehicles etc).

As abrasion is defined the progressive loss of material, from the surface of a stable body, caused by mechanical causes

Impact Strength

This test expresses the rock's resistance in breaking and particularly the fractures caused by the free fall of objects. The impact strength is expressed as the minimum height in cm that a sphere of particular weight falls and causes breaking.

Knoop Micro-hardness

This property expresses the relation between a particular load applied by a diamond point, KNOOP type, and the surface of impression that causes on a polished surface of an ornamental stone. The Knoop micro-hardness in combination with the mineral composition and the petrographical determination of the rock provides details concerning the marble's behaviour in wear, treatment etc.

Coefficient of Thermal Expansion

The coefficient of thermal expansion expresses the elongation in mm per running meter of a natural ornamental stone, caused by the temperature's increase by 1 ^oC.

The knowledge of this property is particularly important, when the marble is used in countries with intense temperature changes.

5.9.4. Environmental Tests

Almost all ornamental stones after being excavated, treated, and placed in open areas and are under the continuous influence of environmental conditions, which have as a result their partial erosion and subsequently the reduction of their strength. It is known that there exists no rock, which is absolutely time proof, which means that the law of loss is applicable even on rocks.

Thus, ornamental stones that are going to be placed in exterior areas, where they shall be constantly exposed to physical, chemical and biological factors as well as the climatic conditions, should be tested as far as their resistance is concerned. Environmental tests include:

- Resistance in frost (cycles of freezing and refrigeration). The ornamental stones' testing in frost resistance, gives us information concerning the materials' strength in weathering and it is crucial in the determination of the behaviour of the materials which are going to be used in humid and cold climates. The resistance of a rock in frost depends directly on its coefficient of impregnation.
- Resistance in erosion (accelerated aging). Knowing the natural ornamental stones' resistance to erosion caused by atmospheric factors is crucial for the behaviour of the material meant to be used in exterior areas. The atmospheric oxygen that causes oxidation to several minerals, the dissolving action of rain water together with the CO_2 as well as the other atmospheric pollutants such as SO_2, SO_3, NO_2, Cl, that are contained in it and produce the dangerous photochemical smog and the corrosive for the rocks acids (carbonic, sulphuric, nitric, hydrochloric acids) are the main chemical influences of the atmosphere on rocks.

The rock's accelerated aging is also connected with the ultra violet radiation and the violent changes of the weather.

5.9.5. Conclusions

Revising, it should be mentioned that the selection of appropriate ornamental stone for a particular application is subject to various conditions, which should be considered and combined, in order to attain a proper, safe and aesthetic result.

In general, the basic prerequisites for the construction with natural stones of a technically and aesthetically perfect work, which can stand through time, are two:

1. Strict selection of materials according to their physical –mechanical characteristics, depending on their application, which means that an accurate laboratory testing should take place.
2. Appropriate planning and analysis of the project, before the beginning of the construction.

Concluding it should be stressed that knowledge of the physical-mechanical characteristics of any ornamental stone can act as an identification card for the stone. One should consider the material's identity, in order to be able to use it accordingly, thus avoiding bad usage caused by the material's selection.

5.10. LIFE CYCLE

The attention of designers and more generally of all those who use stone for decorative purposes must be drawn to the uniqueness of this material. In particular, it is extremely important to highlight that each dimensional stone, whether marble, granite, travertine or stone, has its own personal identity card, which one must perfectly know, especially if one wants to use it in large quantities.

Inherent properties, as well as the quarrying, processing, installation and preservation processes which stone may undergo during its life cycle, may strongly affect the behaviour of a stone material: from raw material to finished and laid product to be maintained.

The life of any dimensional stone product, whether a modular tile, facing panel or kitchen top, starts at the quarry, or even earlier, during the location and characterisation of the deposit.

In the past, new deposits were often discovered by chance or were related to the finding of ancient development areas.

Today, geology, experience and the technologies available make it possible to take, especially in countries and/or areas that are new in terms of stones, a veritable inventory of minerals, in order to evaluate the presence and extent of dimensional rock deposits. Careful surveys of stone deposits have been conducted in such countries as Madagascar, the Philippines, the province of Cordoba, in Argentina, and the Ontario Province, in Canada. These surveys also provide an evaluation of the characteristics and potentials of a deposit before opening a quarry, to avoid useless investments.

Once a quarry is opened, the quarrying activities must be carefully planned. The peculiar characteristics of the material can already be seen in the quarry, both in terms of fracturing level of the outcrop and in the arrangement of crystals, which affects some important mechanical and aesthetic parameters. Stone materials are never isotropic, and, therefore, even with the most homogeneous rocks, the orientation of the quarrying front must always be carefully checked in order to obtain the best material and avoid useless waste. An irrational quarrying activity, as in the case of boulder deposits (erratic blocks), may require a time- and money-consuming selection of material. Actually, these blocks, which initially belonged to one single rock, split over time and often took on different orientations, following tectonic and alteration phenomena. Depending on the cutting directions they have taken on, they look different in terms of texture and colour (sometimes even ornamentation).

Of extreme importance are also the machines and quarrying technologies used: they differ depending on the type of material (marble, granite, stone), on the characteristics of the deposit and quarrying site, with special reference to the presence of water. Choosing a wrong quarrying method may cause serious damages. For instance, an indiscriminate use of explosives or the use of a wrong amount of explosive charge (especially for granite) may cause microscopic damages to the material and deteriorate, therefore, its physical and mechanical properties. Many and important deposits have been made practically unserviceable by an extensive use of explosives. The effects of this technique can also be very deceitful: the block may still look sound and, therefore, be sent to the cutting operations, which are often located very distant from the quarrying site, resulting in high transport charges. Once in the sawmill, the block may “collapse” during the main cutting operation, or the slabs cut from the block may break up as they are polished.

The characteristics of the quarry are very important for designers as well, especially if they intend to use large quantities and/or special sizes of material. The availability of a dimensional stone, both in terms of quantities and maximum slab size obtainable, is, therefore, closely related to the nature of the deposit and to the technologies used to quarry it. There are actually very rich and homogeneous deposits in nature, for instance those in the Apuan Alps, Roman travertine and many kinds of granite, but, next to these, there are also very many others which, though they sometimes contain very valuable material, are definitely smaller and less homogeneous. It is, therefore, up to the designer, based on specific requirements, to decide what materials should be used, bearing in mind that nature can offer him all he needs, both in terms of quantity and characteristics of material.

Once taken out of the quarry, the dimensional stone block is carried to the workshop, where it is processed until it becomes our well-known end stone product.

The processing technologies used and the workers’ experience and professional skills are extremely important as well.

Over the last two decades, the processing technologies have provided the opportunity to achieve very important results. Among the most significant ones, let us mention the improvement of block cutters, which make it possible to obtain useful material even from the so-called shapeless, i.e. non squared, blocks. This results in remarkable savings, even for quarries, since material, which would be otherwise sent to a dumping ground, can now be recovered. Great results have also been obtained in the processing of thin materials and for the possibility to use diamond wire to cut curved lines.

In addition, during the processing phase, materials undergo different processes depending on their characteristics. Special attention is paid to the most delicate materials, such as coloured marble, and to the most valuable ones. The processing techniques, especially surface finishing, as we shall see in the next section, may be extremely important for a designer who wanted to obtain different aesthetic and functional results.

The processing phase ends with the packaging of material, after carefully checking the characteristics of the manufactured articles obtained. In the particular case of mass-produced products (tiles, steps, etc.) and in those works where an even colour is essential, workers carefully check the aesthetic characteristics of the material (colour and veining) to obtain well-distinguished lots of finished products. The purpose of this operation is to maintain a certain level of homogeneousness, even in the range of aesthetical differences that naturally occur in dimensional stones. As previously mentioned, there are some materials which are naturally more homogeneous than others, and, in these cases, therefore, the selection will be much faster, and, above all, there will be definitely less rejected material, resulting in remarkable savings.

The concept of homogeneousness is always to be taken in a very elastic way when talking about stone materials, since the highest value of these products lies just in their natural variability. The ceramic industry, which has always been very keen on reproducing somehow the beauty of nature, has also recently launched some products which try to reproduce the heterogeneousness of marble and the charm that each stone product carries with itself: that of being unique!

Finally, in the case of cut-to-size products, it is very important that the mock-up and piece-mark be performed before delivering the pieces to the building yard, for an easier installation.

Finally, for the fullest enhancement of the product, laying and maintenance techniques are of fundamental importance.

The work will actually turn out well and the customer/user will be fully satisfied not only when the product has been properly selected and sized, but also when it has been laid using proper technologies.

Improper application techniques and/or unsuitable maintenance and cleaning treatments may cause different damages to the material.

The foregoing shows how important professional skills and experience are to ensure a perfect matching between the product obtained and its intended use.

5.11. EXAMPLES OF INNOVATIVE STONE PRODUCTS

Innovative controlled production processes have been introduced aiming at obtaining products suitable for heavy duty and specialized uses for the building industry. These are composite materials consisting mainly of marble, quartz and, clay, cotto too. The production process entails mixing inert materials (quartz, marble and cotto) of differing granulometry (5-6 mm in the dust to grit range), organic dyes and polyester structural resin (approximately 7 %).

In addition to its bonding action, the latter material bestows to the finished product excellent values in terms of bending resistance, impact strength and soaking resistance. In more general terms, it makes it possible to reconstruct the mass of the recomposed material with physical qualities and performance characteristics better than those of the initial natural product.

Thanks to a computerized industrial process entailing vibro-compression in a vacuum at high pressure, hot-catalyzed polyester resin makes it possible to also compact large format slabs (120 x 120 cm and 120 x 300 cm) in a range of different thickness (0,6/1,3/2/3 cm). Such products can be used to satisfy different application requirements.

The production cycle makes use of single-slab compacting, thus overcoming difficult, costly off the block sawing – which is typical of the entire natural stone sector. Usually the body is initially mixed and homogenized by means of computerized control units.

It is the dosed – according to production thickness values – between two sheets of paper on a conveyor that sends the product (still non-solid) for pressing into slabs. The slabs are hardened in the catalysis chamber, which consists of a towel block with a set of heated surfaces. These surfaces are maintained at a temperature of 80-85 °C, and are able to solidify the body pressed into slabs in about 30-40 minutes – half of the time available for the entire production cycle required for a single slab. The slabs thus obtained are then finished in various ways: the two main faces are flattened, the slabs are calibrated, polished, cut, chamfered and, if necessary, their edges are treated according to specific final use.

When the slabs are finished, they can be supplied in large quantities, with controlled, certified characteristics: uniform weight, thickness, compactness, design and colour of the exposed surface.

Another innovative mail order's technology of natural stones permits to produce thin, light and reinforced composite materials preserving, however, the natural stone's precious characteristic: its unequal beauty. The final product realized with this new technology is a natural stone integrated with new components during the processing step. These different technologies can be applied before cutting the stone blocks, in order to allow the transformation of beautiful but, sometimes, poor resistant materials.

Thanks to the particular productive processes, it has been possible to realize large format slabs (over 3-4 square meters), but with a thickness of few millimetres: these slabs are light but resistant. A different strengthening technology has been studied, according to the different materials and the possible applications: from traditional flooring to external or internal covering, from furniture to particular objects.

The natural stone, processed with the above-cited technology, became an industrial product, a salvaged raw material without negative characteristics, able to spread the natural stone's use all over the market.

Luxurious yachts can be a new application field for versatile form and thin natural stone products. The natural stones can be used for covering ceilings and walls of e.g. halls, the pizzeria, the wine-bar, the disco, the stern's theatre, the library and other different shops. Beside the possibility of operating with different geometric forms, there is also the possibility of obtaining very thin ornamental stones, of about 5-6 mm, thanks to a particular and innovative technology: slabs, with a thickness of 5 mm, are cut directly from the original block and, then, they are reinforced with a carbon fibre's fabric so that it possible the polishing and the cut in modular dimensions.

The reduced weight of these elements permits to use natural stone also in aeronautical applications, especially because of the ideal fire-resistance properties of natural stones.

In the last years, stone materials can be coupled, during the production or the application steps, with other different materials, such as:

- **wood**: before coupling with stone, the wood must be smoothed and positioned, because it is more ductile than the stone material. In this way it's possible to avoid spots due to the production of powder
- **ceramic and cotto**: if stone materials are coupled with ceramic or cotto, it's possible to obtain elements with large surfaces and small thickness
- **glass:** the smoothed stones can be coupled with glass in two different ways: by realizing a guide profile or a direct groove, less resistant but cheaper;
- **metal:** the metal is put in special grooves created in the stone; in this way it's possible to avoid joints.

Agglomerate stone products are another innovative application. These new materials, originating from natural stones, satisfy the market's request for innovative products that also meet environmental requirements. The starting materials are aggregates obtained either by fragmentation of various industrial minerals (e.g. quartz) or waste from extraction of ornamental rock (e.g. marble, granite), or from natural sand. Small proportions of organic or inorganic binders are added to these materials. Since these products are manufactured industrially, it has been possible to continuously improve their physical and mechanical characteristics over the years, making them consistent and competitive with natural stone. Agglomerate stones are semi-finished products produced in slabs or blocks. They have a wide range of applications: in building, as floor and wall coverings in interior and exterior areas such as facades, stairs, windowsills, etc., and in interior design applications in general, such as kitchen and bathroom surface tops. The wide range of colours available also contributes to satisfying aesthetic requirements.

Agglomerate stone is an environmentally friendly product. When natural stone is extracted from quarries, a large quantity of waste is produced and this is normally sent to landfill. However, this waste can be used as a raw material for the production of agglomerate stone.

5.12. FUTURE TRENDS IN NEW PRODUCTS

The development of the production process has led to increasingly advanced machines, which can now cut thickness under 6 mm. Thus, stone maintains its unique ornamental qualities but loses its solidity.

Such exasperation is the result of competition. For stone to compete against rival materials, in addition to its range of unique colours and vein patterns, it needs to be lightweight too and this has become its most modern attribute. The reduction in thickness has also led to a reduction in the size of individual units, which can now be considered standard products able to complete with stone's main rival, ceramics. So, the design criteria behind the use of these products are less focussed on specific uses since they can be used without specific references.

Finally, there is another unprecedented trend currently gaining ground. This stems from the processes of technological innovation that highlight stone's mechanical properties. Stone is therefore being used as structural material again, but taking advantage of the new machinery and processes available. The innovation lie not only in the machinery, but also in a new philosophy which choose to combine stone with other materials and products to create a unique product exploiting each material's prime vocation.

As already mentioned, the success of entire stone industry on a more commercial scale relies to a large scale extend on producing thin stone pieces, and with the new technology it is now possible to cut pieces just 4 mm thick. Obviously products of this thickness need to be reinforced with appropriate supports though; otherwise the stone would be too fragile. Products over 7 mm thick, however, do not necessarily need supports, since they can guarantee the assistance required to withstand external stress factors. These products can be divided into standard marble and standard granite products, where stone has no support and composite panels of thin stone where the stone is reinforced. The thickness obviously varies according to the material and maximum size of the products is 600 x 600.

In addition, given their reduced thickness, the surface finishing of standard of marble and granite products is carried out during processing in the workshop because there would be the risk of breakages or damage if this were carried out after laying. Finally, again in view of the reduced thickness, it is not advisable to finish the surface of these products with percussion tools (bush-hammers) or using thermal shock treatment (flaming). Hence, standard products are almost always pre-polished or pre-honed. This can be an ideal solution for the refurbishment of old buildings, where they was frequently used, since they can be laid on top of existing floors and facings thanks to their thickness, with considerable advantages in terms of cost, laying time and yard management. Moreover, they are available in a wide range of materials, colours and surface finishing, which guarantee great scope for architects. Although the fixed size is a limit, in no way does this hinder compositional freedom, even in the experimentation of new formal solutions.

The ultimate frontier in thin stone however is composite panels. Current production possibilities depend not only on the type of stone but also on the kind of support and products available on the market within the region of 15 to 25 kg/m^2. Such products are remarkably light. Yet, the stone's innate properties remain intact and in some cases are even improved. For example, stone is known to be unsuitable in condition of bending stress – with a support it acquires resistance to this stress. The panels are made by gluing the thin stones to various supports such as fibreglass, aluminium honeycomb, sheet steel; the subsequent process of honing, polishing and cutting are carried out using the same technology used for standard semi-finished products.

Cutting stone so thin requires more sophisticated tools than those normally used with traditional technology, such as diamond disks, whose cutting edge can easily chip the edge of the product or break it completely because of the pressure applied. High pressure water jet technology has solved this problem since it can cut without chipping and applying pressure only on the cutting groove which is no wider than 1.5 mm. In addition to precision cuts, water jet technology can perform circular and round cuts (much more difficult with diamond disks) and cuts at fractions of an angle which no craftsman, however qualified, could ever do. This has led to a new lease of life for traditional work in the stone industry such as inlay work. The latter has mostly been abandoned due to the gradual disappearance of skilled craftsmen who alone could keep the tradition alive. Among other things, thanks to this technology, which can perform perfect cuts in stone, up to 5 cm thick. The cutting speed varies according to the thickness of the material. This kind of work on stone represents a totally new frontier, which still has not been explored to the full, but which already looks as if it will become an interesting field of application in view of the highly personalised solutions it can provide designers.

A better-explored area is the enhancement of stone's natural translucency. This is not a recent rediscovery but one that has not been fully exploited yet, apart from in ornaments. Examples in architecture where convincing, evocative results have been archived include a church in Switzerland where the cladding in white marble, 2.8 mm thick, vibrates with the light which crosses it, almost as if it were organic matter; a large pink marble wall that illuminates the hall of a building in Sydney, Australia; the curtain wall in white Arabescato marble on the Rare Book Library at Yale University. Yet, not all natural stone material can be translucent. Translucency is an attribute of crystalline marble varieties only, whose special texture allows the light to pass through. Limestone, granite, stone and travertine, on the other hand, are not permeable to light. Alabaster and onyx are lightly translucent materials too, but they are not used in buildings at all and so are just mentioned for the sake of completeness. Thin stone, now widely used in architecture, can no longer be considered innovative. What is innovation today, however, is the tendency to reconsider stone's material nature, thereby using thick stone and exploiting its exceptional resistance to ageing, weathering and compressive stress, i.e. its chemical-physical-mechanical properties more than ornamental proprieties, even if the two go hand in hand and are mutually enhanced .Yet, this is not meant to refer to the renewed use of columns and entablatures, but rather to the wide range of uses, mostly still in experimental stages, which rediscover the intrinsic value of stone by way of totally innovative projects. In most cases, from the architectural point of view, such projects involve to use of stone combined with steel cables and structures.

The first attempt date back to the mid 60's when Eng. Cartei in Pisa produced a footbridge with a load-bearing frame in girders made of reinforced H-shaped marble ashlars end Arch. Cecchini and Eng. Zorzi in Verona produced the monumental stairway to the Monuments Trust in Verona in the St. Fermo Cloisters, again in pre-stressed marble. Neither of these show any particular innovation in terms of actual stone processing but both stand out for the combination, entirely structural, of stone and steel tie rods used, exploiting their primary vocations, with the stone resisting the compressive stress and the steel the tensile stress. The stone/steel tie rods formula was used again a few years' later in highly interesting projects by some of the most celebrated names in contemporary architecture. The Pavilion of the Future, for example, by Peter Rice, built for the1992 Seville Expo, features a portico 260 m long and 30 m high, consisting of a stone structure (in Pink Porrino granite) to which a system of cables and tie rods is connected which induces compressive stress only on the granite modules. The stone structures was made entirely in the workshop and consists of solid modules 20x20 x 140 cm applied to plates of the same materials using epoxy resin to make "standards units". The engineering experience from the Pavilion of the Future most probably made an important contribution to Renzo Piano's project for the New Liturgical Hall in the Church of Father Pius at S. Giovanni Rotondo. The building's prominent feature is its arches, twenty in all, some with spans of up to 50 m, in blocks, contribute to the creation of a typical pre-stressed structure able to support the entire roofing of the building.

In the above examples, the architects' first interest is based on the study of the stone/metals systems, systems in which the stone is appreciated for original properties of strength and coarseness despite the refined engineering. Other approaches to the subject of structural stone concentrate on the peculiar characteristics of the material, on the experimentation of traditional and new uses of stone with the new innovative production technology available. Angelo Mangiarotti is a prominent figure in this field in which he has worked intensely over the past ten years, taking advantage of the productive framework and opportunities offered by the Apuo-Versilian district. He has focussed his attention in particular on exploring the possibilities of a new shaping machine that cuts stone using a diamond wire as a tool. The special feature of this machine is its ability to cut curves, yet without destroying the material, formerly an inevitable drawback with the "comb" technique. One of the first examples, of an eminently experimental value, is the "cono-cielo", a cone in white Carrara marble, 11 m high, composed of eleven ashlars in the shape of truncated cones placed one on top of the other, decreasing in thickness from 12 cm at the base to 2 cm at the top. This prototype is made entirely out of one block of marble 2.5 x 2.4 x 1 m reduced into the 11 ashlars by concentric cuts. Moving on to more practical applications, Mangiarotti, again with the help of this machine, designed the roof of the new IMM Carrara Spa head offices, which was completed and installed in 1993. The roof measures an approximate 750 sqm overall and consists of a series of vaults in white marble assembled together and placed on solid-web metal girders. Each vault is made up of two semi-vaults connected on the centre line with a male-female joint so that they work like a triple-articulation arch. Each module is 1 m wide, 5.5 cm thick and has a clear span of 4,30 m. Continuing his research, Mangiarotti has subsequently produced various prototypes in white marble, including the monolithic flights of stairs 1.10 m wide composed of four steps 4 cm thick. Again this testifies to the excellent performance of the diamond wire-shaping machine, with its capacity to make the best use of the block, reducing processing waste to the minimum or eliminating it altogether.

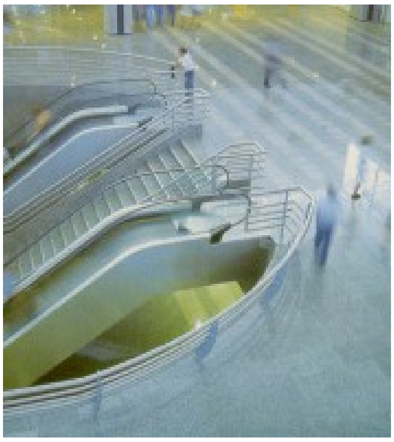
It is superfluous to state that the "two schools of thought" mentioned above, far from annihilating each other, can continue to develop separately from each other or even exist side by side if required by the project. Both, however, demonstrate the enormous progress, on an industrial scale, achieved by the stone sector which is one of the few sectors which has fully modernised to suit today's applications and market requirements. In this sense, technological innovation in the sector has made a decisive contribution to both concepts of natural stones as a mineral and natural stone as a product, making them more competitive with rival materials and allowing them to be used for new applications at the same time, with obvious benefits in terms of higher consumption. Another important factor as regards stone innovation is its duality. On one hand it has increased the automation of production processes, now almost totally computerised, and on the other hand it has improved craftwork where the professional skills of those who carry out this work continue to be a necessary and decisive factor in achieving quality results.

5.13. Appendix – Photographic Demonstration of Main Dimension Stone Applications

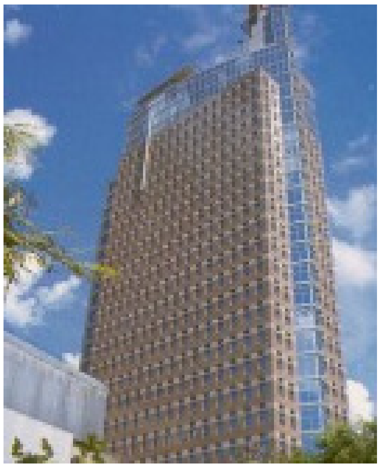
5.13.1 Claddings





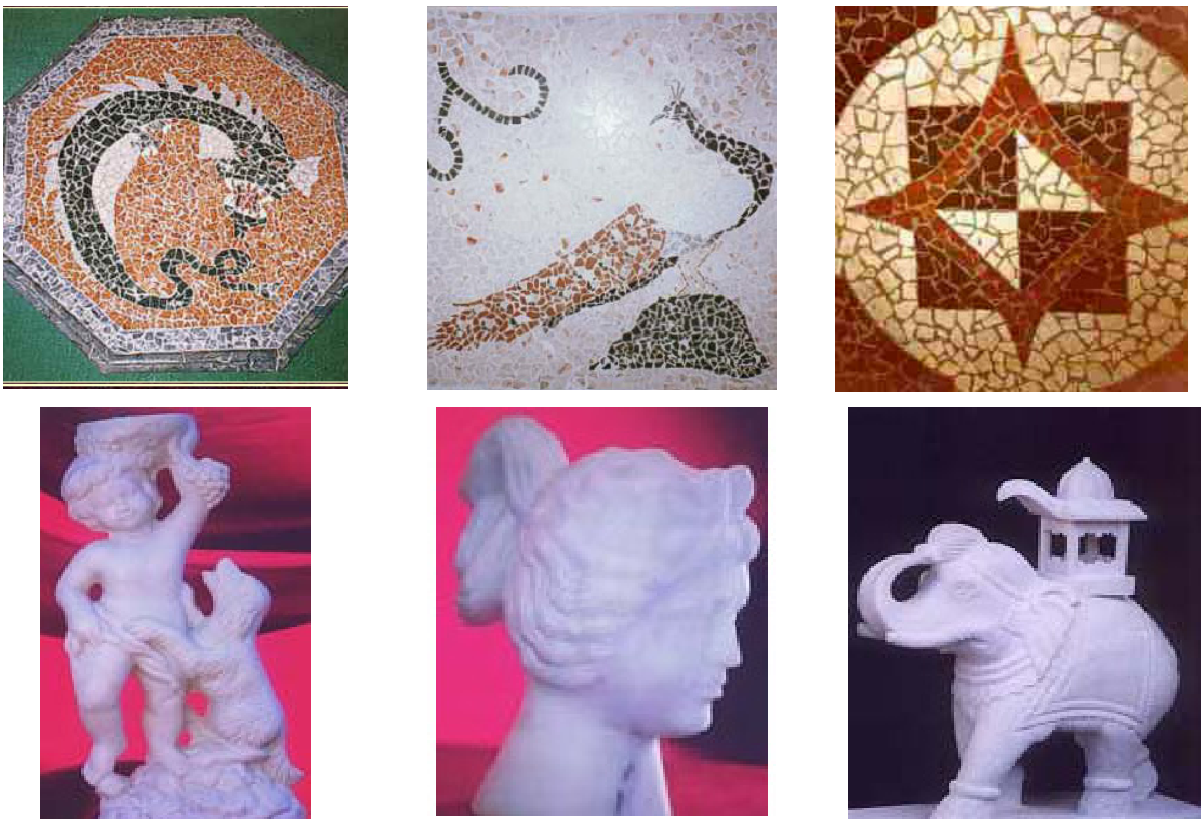


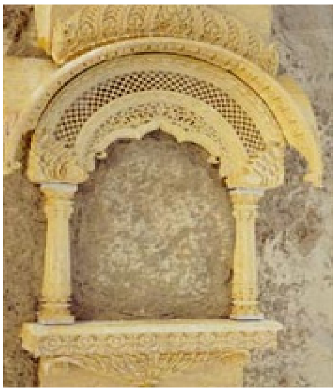
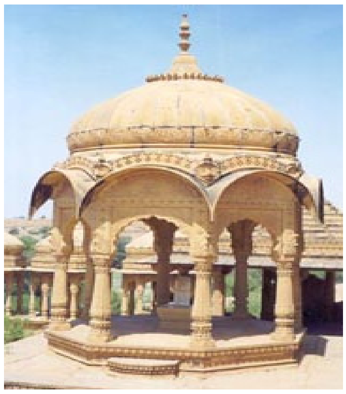
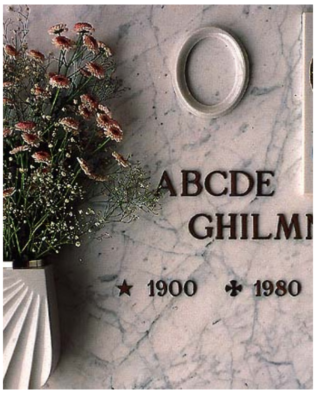
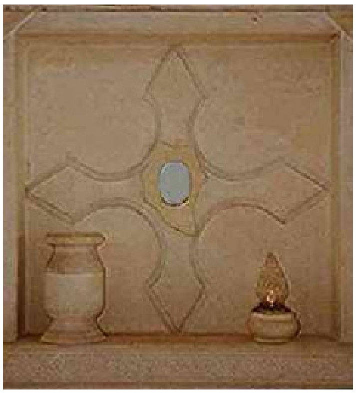
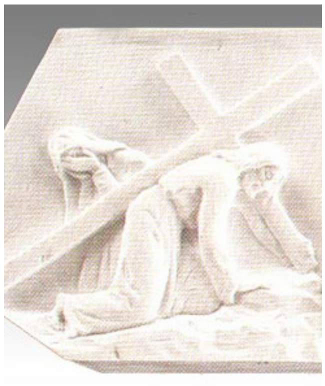


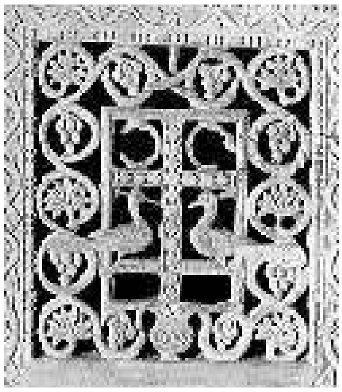


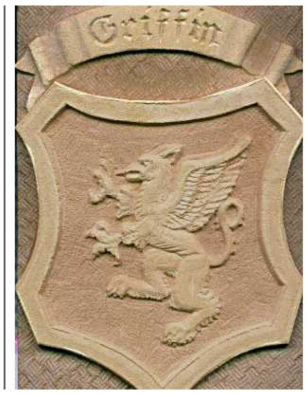
5.13.1. Pavings

5.13.2. Works of art







ABCDE
★ 1900 ✤ 1980



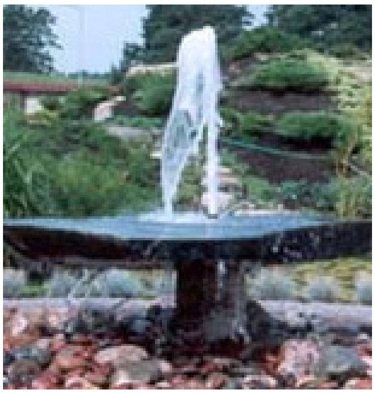


Griffin

5.13.3. Furnishings

















5.13.5 Residential furnitures











References

1. AA.VV., (1982). Marmi Italiani (Italian marble), *Technical guidebook*, F.lli Vallardi,
2. ASTM C119, (1988). Standard Definitions and Terms relating to Natural Building Stone, American Society for Testing and Materials
3. Bradley F., (1998). La Scelta delle Rocce Ornamentali in Architettura (*Choosing dimensional stones in architecture*), Studio Marmo
4. Calenzani L. e Corbella E. (1989). *Manuale dei Marmi Pietre Graniti (Manual of marble, stones, granite)*, F.lli Vallardi
5. EN 12440; (2000). Natural Stones – Denomination Criteria, European Committee for Standardisation
6. Grassi E., (1993). I Rivestimenti Esterni – SEI Prima parte (*External facings – SEI, Part One*), *Internazionale Marmi e Macchine Carrara*
7. Mignani A. e Quadrelli S., (1993) Pavimenti e Rivestimenti Interni – SEI Seconda parte (*Internal floorings and facings – SEI, Part Two*), *Internazionale Marmi e Macchine Carrara*
8. Morandini F. A. e Sanvito M.; (1997). La Caratterizzazione Tecnica delle Rocce Ornamentali: Normativa e Prove Tecniche (*Technical characterisation of dimensional stones: regulations and technical testing*), GEAM
9. UNI regulation 8458; (1983). Prodotti Lapidei Terminologia e Classificazione (*Stone products: termininology and classification*), Ente Nazionale di Unificazione (*National standardisation board*), Milan
10. UNI regulation EDL 173; 1987, Pavimenti Lapidei, Terminologia e Classificazione, (*Stone floorings: termininology and classification*), Ente Nazionale di Unificazione (*National standardisation board*)
11. Winkler E., (1994). Stone in Architecture, Springer-Verlag Berlin
12. Battelle Institut e.V., (1991). Bodenbelage - Ein Vergleich von Anforderungen und Kosten - Bericht für Deutscher Naturwerkstein - Verband e.V., Würzburg, p. 109.
13. Deutscher Naturwerkstein - Verband e.V.(1996). Bautechnische Information Naturwerkstein 1.5, Fassadenbekleidung, Würzburg, p. 66.
14. Deutscher Naturwerkstein - Verband e.V.(1996). Bautechnische Information Naturwerkstein 2.1, Fußbodenbelage innen, Würzburg, p. 27.
15. Greek Marble (1999). *Market Guide*, 19th Annual Edition, Athens, p.473.
16. Grassi Ennio (1993). Die Aussenbekleidung, veröffentlicht von Internationale Marmi e Macchine Carrara S.P.A., Regione Toscana, p. 53.
17. Papaioannou N. & Vidakis E., (1995). Quality control – criteria – specifications for ornamental stones. *Course organized by the Technical Chamber of Greece on: "Exploitation and management problems of quarry materials*", p.14

6

Stone in Pavements

SYMONS RAY, DEREK FORDYCE, HERIOT-WATT, KADHIM KHWEIR, M. J. MCHALE, ROD KIMBER

6.1. THE PERFORMANCE AND BEHAVIOUR OF STONE ELEMENT PAVEMENTS

Natural stone paving is being used to create high-quality streetscapes with many city centre refurbishment schemes. The lack of use of natural stone in Britain over a 40-year period at the end last century has left a skills shortage and a lack of development in the knowledge of natural stone paving construction. This chapter is a review of natural stone paving construction based on a study carried out on behalf of the SCOTS Natural Stone Paving materials Working Group. The SCOTS Working Group has published a 'Natural Stone Surface Good Practice Guide'. This chapter summarises the types of natural stone paving element used in roadway and footpath construction, it identifies the manner in which the construction can behave, and it identifies the factors that should be addressed to achieve adequate service performance.

6.1.1. Introduction

Stone element paving in the form of slabs was the first surface used for the movement of people and wheeled transport. The slabs formed a stable surface under all weather conditions. The construction formed the first roadways; they were used principally by the military. Smaller elements in the form of cobbles, sets and cubes provided surfaces within urban areas for civilian use. In Britain cobbles and sets have been the more common form of stone element paving construction. The invention of tar macadam in the early part of the 20^{th} century, and finally the post war expansion and modernisation accompanied by the removal of the tram network in urban areas, saw the end of roadways constructed using stone elements.

Footpaths were also converted to lighter and more regular shaped elements formed by concrete, or surfaces were formed by asphalt. The late 20th century has seen the resurgence in the use of stone to form streetscapes. This has been the consequence of the need for urban streets to be living environments and the need to consider sustainability. The resurgence in the use of stone for streetscapes has required a better understanding of the behaviour of stone element pavement construction when subject to modern traffic loading.

Stone element paving can be divided into deep and shallow construction, greater and less than 100 mm in depth of element. The plan area of elements then subdivides the elements into cubes, tiles and flagstones, all less than 100 mm in depth; and cubes, setts, blocks and slabs, all greater than 100mm in depth. Shallow stone element paving is flexible and can fail through the bending of the surface as a layer; deep stone element paving is stiff and can fail by the shearing and vertical movement of individual elements forming a surface.

With setts and cubes individual elements are stabilised by being bedded into an aggregate layer and the joints between elements being filled with an aggregate. Where a graded aggregate is used for the bedding layer and joints the stability of elements depends on the packing of the aggregate surrounding the individual elements. When well packed, the aggregate locks the elements together to form a flexible surface layer. With this form of construction the elements have a limited stability. When subject to heavy loading and traction forces deep elements can rotate and can be displaced. This does not reduce the load carrying capacity of the layer, but it results in the need for constant maintenance. The aggregate forming the joints can also be plucked out by traffic action and mechanical street cleaning operations; this also leads to the need for constant maintenance of a surface. Stabilising a joint aggregate with cement potentially provides for a maintenance free surface layer. A cement-stabilised joint creates a rigidly bonded surface layer; the layer is brittle and will deform little before fracture. Because such a surface can move little before fracture a stiff bedding layer is required when the loading is other than light traffic, this layer is formed by cement stabilised aggregate. Failure of a rigid construction is either by the shear of individual elements with a deep surface layer construction, or by flexing with a shallow surface layer construction.

A uniform and stable aggregate layer constructed over a soil foundation should support a flexible stone element pavement layer. Such a construction is flexible and moves under traffic loading. There is a limit to the load carrying capacity of this construction; the soil deforms continuously under repeated loading, leading to the deformation of the pavement surface. A cement stabilised aggregate layer constructed over a soil foundation should support a rigid stone element pavement layer. When the layers are bonded together, and are of adequate thickness, this construction can take the highest traffic loading. Bituminous macadam can form the support layer with a rigid construction when the traffic loading is less heavy.

Flagstones should be used for footways only. The bedding layer better supports flagstones; joints with flagstones should not be filled with cement mortars, as they will always fracture due to over stress; flagstones are best bonded to a cement stabilised bedding and support layer.

Stone element paving was first used to provide a stable and durable surface for the movement of people and horse drawn transportation. Stone was quarried initially by cutting into and then splitting sedimentary rock beds; large slabs of stone could be produced in this way. The slabs formed paved ‘ways’; paved ways were a common form of construction used by the Romans.

Slabs were a suitable method of constructing large flat surface areas, such as large open areas where people could congregate, or roadways, which were linear. Flat surfaces formed by stone slabs required the formation of a flat supporting surface. Roadways were raised above the surrounding ground level to ensure adequate drainage of surface water and as such a flat supporting surface could be created. For more general surface construction smaller elements were used, which could be quarried from vertical rock faces and hand worked to form regular shaped elements of varying size. Cubic elements in particular were used to form surface mosaics.

Slabs are naturally stable elements; accuracy in cutting allowed them to be fitted together with a dry joint on top of a flat prepared surface formed by a graded aggregate or processed soil. Smaller elements cannot be easily worked to repeatable accurate shapes. Smaller elements require to be stabilised in the construction of a surface; the elements require to be bedded into a graded aggregate layer and the joints packed by a graded aggregate.

In Britain, examples of roadways and mosaic stone surfaces are the historical remains of Roman occupation. The industrial revolution and urban development saw the resurgence of stone element paving construction in Britain. The primary form of roadway construction was a 'setted' construction formed by cuboid shaped stone elements; the elements were stabilised by being bedded into, and joints packed by, a graded aggregate. The surface shape of elements were rectangular, commonly 75 mm to 125 mm in width and anywhere between 100 mm and 350 mm in length. The depth of elements was anywhere between 100 mm and 300 mm. A setted construction was formed by laying the stone elements, or setts, across the width of a roadway in a bonded pattern. The width of a stone sett was around the size of a horse's hoof; this enabled horses to gain grip on a stone paved surface, particularly on inclines. Footway construction was historically formed by small element, or slivers of stone from the quarrying operation, often incorrectly referred to as horonizing. True horonizing is formed by thin elongated stone elements recovered from riverbeds.

The late 19^{th} and early 20^{th} centuries in Britain saw developments in the art of laying stone element paving. Slabs, or flagstones, were split from sedimentary rock beds, but were now sawn into rectangular shapes; smaller elements, setts and cubes, were mechanically cropped from blocks of stone. Cropped setts were hand finished where a more regular shape was required. In Scotland, where hand finishing was applied to create a very regular pattern with a setted construction the elements were described as nidgers, the hand finishing being the process of nidging. The supporting construction with stone element paving was improved to provide greater stability and uniformity as the weight of vehicles using the roadways increased, particularly with the advent of pneumatic tires. The maintenance of surfaces was reduced with the use of tar pitch to seal joints, and cement stabilisation of bedding and joint aggregate to provide stronger surfaces capable of sustaining the heavier loading from commercial and public service vehicles.

The invention of asphalt at the beginning of the 20^{th} century was the start of the demise of stone element paving in Britain. The evenness of surface profile that could be achieved with relative ease by asphaltic products along with the higher skid resistance and thus greater road safety saw, by the 1950's, a reduction in the use of setted pavements. The road reconstruction programme after the decommissioning of urban tramways in Britain saw the end of stone element paving, other than the maintenance of streets that had escaped the reconstruction programme.

There was a renewed interest in stone pavement construction in the late 20^{th} century; the renewed interest was the consequence of a change in perception of society in the developed world. Society today in the developed world is one that values quality of life, part of which is the quality of the living environment. There is also recognition for the need to exist and develop within a sustainable environment, part of which is a reduced dependency on non-renewable resources such oil and oil based products- asphalt, and using systems the elements of which can be reused in some form. The change in perception and values of society means that systems, such as roadways and footways, have to be coasted differently: for example, the ability to use the elements of a system after decommissioning or at the end of their service life has to be part of the cost equation.

The renewed interest in stone element paving has brought with it the need to better understand how such pavements behave, particularly when subject to modern traffic loading from commercial and public service vehicles running on new tire technologies, such as quieter tires and longer lasting low profile tires. Urban environments reconstructed for a different distribution of traffic flow, with more pedestrian and more restricted vehicle movements, has created a greater intensity of loading on roadways and the need to consider a greater likelihood of vehicle over-run on footways.

6.1.2. General considerations

Stone element paving is used to provide the surface to footways and roadways. Elements have to be capable of being maneuvered readily for transportation and construction, and also for removal and replacement where there is a need to access services beneath a roadway or footway. There is therefore a weight limitation, and consequently a size limitation, on the size of elements. Elements vary in shape; different element shapes have specific descriptions. Elements can be divided into two categories: those with a depth less than 100 mm, and those with a depth greater than 100 mm. The two categories relate to how the stone elements behave as a surface layer in response to surface loading.

Table 19.

Element plan area (10^3 mm^2)	Element depth <100 mm	Element depth >100 mm
>90	Flagstones	Slabs
20-120	Tiles	Blocks
2.5-35	Cubes	Setts and Cubes

Elements less than 100 mm in depth have little flexural stiffness as a surface layer and will try to deform, as individual elements (flagstones) or as a layer, and bend in the form of a dish under an applied surface load such as a vehicle wheel. The quality of a supporting construction is critical with shallow paving elements. Lack of support by the bedding layer will cause localised flexing and the fracture of individual flagstones or the cracking of transverse joints with cubes, for example. Lack of foundation support will cause more widespread flexing and the cracking of joints parallel to wheel paths, but beyond the actual path of a wheel.

Elements greater than 100 mm in depth have greater flexural stiffness as a surface layer; here the stability of individual elements forming a layer is much more significant. The quality of a supporting construction is important to the behaviour of the surface layer, but it is less critical than with shallower paving elements.

The pattern of paving elements in relation to the direction of vehicle movements is critical to the behaviour of deep and shallow paving elements.

With small paving elements such as cubes and setts, which can be laid by one person and without any mechanical lifting aids, the elements are bedded into a granular layer to provide initial stabilisation; the joints are then filled with a granular aggregate to provide full element stabilisation. The granular bedding layer and joint matrix may themselves be stabilised using a rigid or flexible binder, such as hydrated cement or bitumen, or a flexible polymer. The inclusion of a binder with the bedding and joint aggregate provides greater stability to paving elements, and creates a surface layer that can act as a composite system. The behaviour of the composite layer is directly related to the nature of the binder used. A hydrated cement binder used with the joint aggregate creates a rigid surface layer, one which will flex little before fracture occurs at the joints; a bitumen or polymer binder used with the joint aggregate creates a flexible surface layer, one which will deform under load. Joint aggregate bound by hydrated cement, bitumen or polymer also creates a surface that is potentially maintenance free.

With large paving elements such as flagstones the elements are laid onto a bed of fine aggregate; the manoeuvring of elements may require the use of a mechanical lifting aid. Here the elements behave as independent units and composite action is difficult to achieve. Joints may be formed to allow for thermal movement of individual elements and for size tolerance. Where joints are formed they may require to be sealed to prevent the ingress of water into the support structure of a pavement. In such circumstances a flexible joint is more suitable; rigid joints formed by cement mortars cannot absorb the movement of large paving elements under load or thermal movement.

With a stone element pavement a stable support structure is required. A natural soil seldom can provide uniform and stable support to a stone surface layer; at least a stabilised soil foundation is required along with a bedding layer. Good practice requires a construction layer over a natural soil to provide a high quality and uniform support to a stone surface layer. There may be a need for a sub-construction layer for frost protection, or where the natural soil is particularly weak. Where a rigidly bound surface layer is used the primary support layer requires being rigid, through the use of a cement-stabilised aggregate or concrete.

6.2. STONE ELEMENT PAVING FORMED BY SETTS AND CUBES

Historically, setts and cubes were bedded into a fine graded aggregate, the joints were flooded with fine graded aggregate and the individual elements compacted by a heavy mandrel. The act of bedding individual elements provided the initial stabilisation of the elements, and it provided the initial compaction to the fine aggregate directly supporting the elements. The bedding layer also enabled a surface profile to be formed.

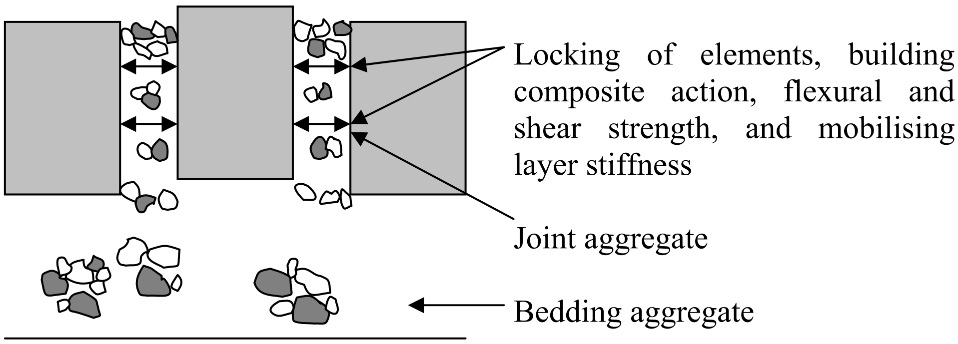
In the 19th and early 20th centuries it was common the construct a stone element paving directly onto a natural soil, the soil first being profiled and stabilised by rudimentary compaction. The granular bedding layer was often formed by fire bottom ash, which was an accepted form of recycling. The joints may have been flooded by fire bottom ash, or by a graded fine aggregate. Traffic action provided the final compaction to the bedding and joint aggregate; and any lack of support in the soil foundation was remediated by reprofiling the surface layer.

6.2.1. Flexible construction

The historical construction described is flexible by nature. The bedding aggregate and the soil foundation support individual elements; the joint aggregate stabilises individual elements.
Surface layer construction: With shallow elements formed by cubes less than 100 mm side dimension, an arc-shaped patternation was found to provide a surface layer with enhanced stability and enhanced stiffness; the most common patternation found in Europe is described Bogan, shown in Figure 21. Deeper elements, greater than 100 mm in depth, are formed by setts and can be formed by cubes; setts rather than large cubes are found in Britain. Deep

elements are normally always laid in stretcher bond pattern, as shown in Figure 21. On mainland Europe, the joints with deep setts are commonly formed in two stages. Initially the joints are filled with a coarse graded fine aggregate; after compaction the joints are then filled with a fine graded fine aggregate (dust) which is washed into the joints (the latter process may be carried out by nature). This process is adopted because of the difficulty in fully compacting a joint using a graded aggregate; the setts are allowed to 'rock' to orientate and pack the coarse graded fine aggregate that 'locks' the elements in position.

The locking of the setts together builds composite action with the surface layer; the potential stiffness of the layer can therefore be mobilised and the layer builds flexural strength. The locking action also provides resistance to vertical movement of individual elements; shear capacity defines the resistance of individual elements to relative movement. The shear capacity of elements forming a surface layer is related to the flexural strength and stiffness of a layer.



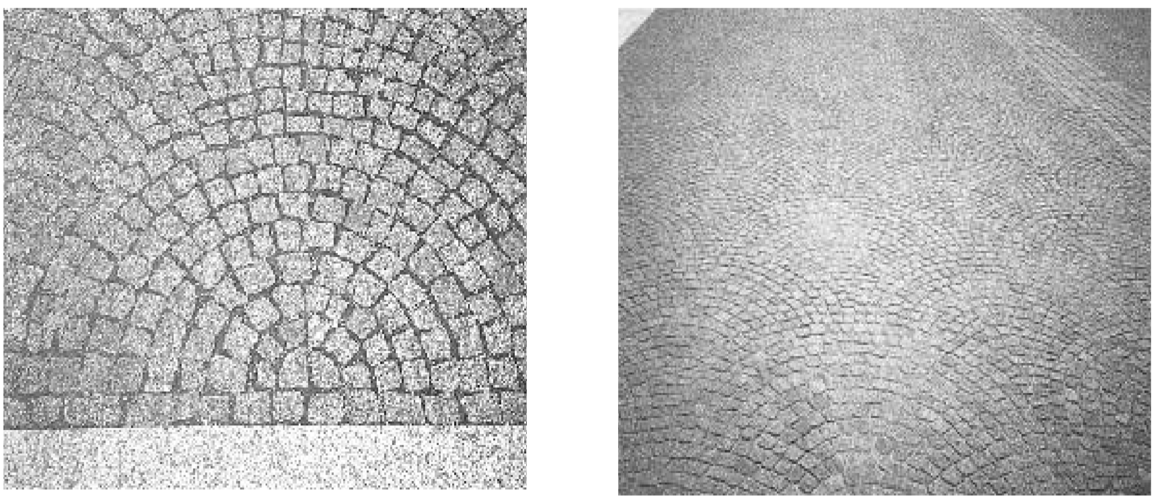


Figure 21. Bogan patternation with small cubes

Figure 22. Stretcher bond patternation with setts

The unbound nature of the surface layer leads to flexibility: the layer deflects when loaded as the aggregate particles can individually move, albeit by a very small amount. The surface is also ‘live’ in that permanent movement can occur but the surface will act as a composite layer and perform unaffected. Permanent movement occurs when the shear capacity of a joint has been exceeded. Where movement is recovered the behaviour is described as ‘elastic’; where shear occurs and the shear strength and behaviour of the system is unaffected the behaviour is describes as ‘plastic’.

Measurement of the shear capacity of setts laid in the late 19th century has provided a value of around 100 kN/m^2 (kPa); this translates to one sett being able to sustain 1 tonne weight before relative movement occurs between the loaded sett and adjacent setts.

Figure 23 shows the movement of setts as a result of the shear capacity of the joints being exceeded. The figure demonstrates the more critical shearing action with setts: rotation under the action of traction forces from vehicle wheels. This occurs on inclines and at the approaches to, and within, junctions. This effect is more critical where thinner setts are used, 100 mm or less. Large cubes are much more stable and can mobilise support from the bedding aggregate when subject to traction forces. In central Europe large setts are employed in high stress locations: 160 mm and more in width and depth, and 200 mm and more in length.

Flexible surfaces are permeable in their early life, and moisture is commonly applied to a surface during layer compaction. As such, the support structure is made permeable to avoid moisture becoming trapped within the pavement during construction, and during the early life of the pavement.

6.2.2. Support conditions

A flexible surface layer is best constructed on a stable and well-compacted aggregate support layer, laid over a soil foundation. The compacted aggregate layer provides a uniform quality of support to the surface layer. Stabilisation of this layer is critical. A stable layer is formed by a fully compacted well-graded aggregate. A well-graded aggregate is one where the coarser fractions of the grading form a load bearing skeleton, and the particles forming the skeleton are restrained (stabilised) by the finer fractions which fit into the void space within the skeleton. A well-graded aggregate can produce a dense layer; a dense aggregate layer can trap moisture and without care in the grading, through limiting the fine aggregate fraction sizes, the layer can be frost susceptible. Frost susceptibility is moisture freezing and expanding within the fine pores of an aggregate structure; the result action is described as frost heave.

Aggregate layers deflect and can deform when loaded. Deflection is movement which is recovered, and is the result of elastic behaviour; deformation results from the particles forming the load bearing skeleton reorienting and repacking themselves, and the layer further compacting itself. Particle reorientation and 'secondary' layer compaction can occur as a result of traffic vibration rather than direct loading. Deformation should be avoided.

With a flexible construction, although the support layer should not further pack itself, it is important to ensure that neither the layer itself, nor the natural soil foundation, is over stressed. The over-stressing of a support layer will lead to aggregate crushing, or distortion of the layer in an extreme case. Over-stressing of a natural soil will result in additional packing of soil particles, and soil deformation. The effect of a surface load from the wheels of a commercial vehicle penetrates much more than 1 metre below the surface of a flexible pavement Increasing the thickness of the aggregate support layer(s) reduces over-stressing of a soil foundation. But, a build-up of permanent movement of a soil foundation is inevitable with a flexible pavement construction. The rate of build-up of movement in a foundation is a function of the stress applied and the number of load applications from the passage of vehicle wheels; the vehicles of importance are heavy commercial vehicles and public service vehicles. With a flexible construction the build-up of deformation in a foundation soil as a result of repeated stress is a 'fourth power' relationship. The distress caused by a vehicle is measured conventionally in terms of axle loads rather than wheel load (an axle load being approximately twice a wheel load). The relative distress caused by axle loads is given by the expression: (axle load/80)*4, where the axle load is measured in KN. With this relationship the effect of the passage of one public service vehicle is, for example, the same as the passage of about 160,000 cars.

Figure 23. Rotation of setts as a result of traction forces

6.2.3. Support layer stiffness

The stiffness of a pavement layer describes the potential of the layer to flex under load; the thickness of an aggregate layer provided with a flexible pavement is directly related to the stiffness of the layer. Stiffer layers are able to spread a surface stress over a greater area and thus reduce the stress transmitted to a lower layer. The stiffness of a layer is a function of the depth of the layer and the 'elastic modulus' of the material forming the layer. The depth function is the cube of the depth: double the depth and the layer stiffness is multiplied by a factor of eight. Elastic modulus is the ratio of applied load to deflection resulting from the applied load. With aggregate layers the particles deform under load, and they have a limited ability to rotate. With permeable aggregate gradings the aggregate skeleton is less well stabilised: compared with a dense grading the deflection is that much higher, and the elastic modulus and therefore the stiffness of a layer is that much lower.

6.2.4. The performance of flexible construction

Additional packing of an aggregate support layer and any sub-layer, and additional compaction of the soil foundation are events, which have an impact on the longer term behaviour of a flexible construction. Both events lead to a deformed surface profile; the aggregate joints between stone elements forming the surface layer shearing to allow the surface layer to follow the deformed profile of the support layer and soil foundation. The load carrying ability of a deformed pavement should be unaffected The pattern of deformation with a surface indicates the layer, or layers, within which aggregate movement has occurred. The deformed profile will follow wheel movements; the profile will be in the form of wheel track 'rutting' where canalised traffic flow exists. Canalised traffic flow exists where vehicles are restricted to very precise pathways. The wider and shallower the rutting, or any surface deformation, the lower the layer within which movement is occurring.

Given the nature of a flexible construction it should not be specified with heavy and canalised traffic flow regimes, or specified in areas where there are high traction stresses without careful design.

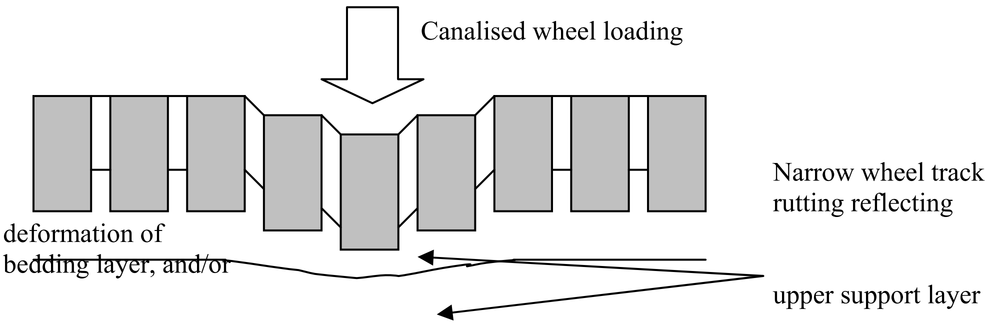


Figure 24.

The use of appropriate plant and time is needed to fully pack an aggregate forming a support layer; an exposed and profiled soil foundation should always be compacted prior to the placement of any construction layer. On mainland Europe there are examples of situations where a mechanically compacted support structure is left open to traffic action prior to the placement of the stone surface layer. This action provides additional 'secondary' compaction where that may be needed. One key issue with the placement of an aggregate layer is the moisture content of the aggregate; the moisture content should be that to achieve maximum material density with the compaction energy applied, this moisture content is described as the optimum moisture content.

Permeable support layers have reduced stiffness compared with dense support layers; more permeable support layers require to be laid thicker than dense layers otherwise the soil foundation may be over stressed. One detail used in Europe to reduce the risk of an over-stressed foundation soil with a highly permeable construction is to use a stiff sub-layer formed by bitumen-stabilised aggregate skeleton- open grade bituminous macadam.

Under-compaction of the surface layer is a possibility with smaller cubes. In such circumstances the elements will de-pack and rise out of the surface. The joint aggregate will work its way under individual elements. A poorly graded joint aggregate, too fine an aggregate, or an aggregate that lacks a degree of angularity can also cause this effect.

Confinement is critical to the effective compaction, and therefore stability of a surface layer. The bedding and alignment process with stone elements provides the initial compaction of the bedding layer. In this process a skilled operative will be seen to hit surrounding elements with their hammer, this is to hear the uniformity of compaction of the bedding layer. A vibrating plate compactor rather than mandrel carries final compaction today. It is important that the weight of the compactor is consistent with the size of surface elements being used. It should also be recognised that the degree of compaction achieved with a surface layer is directly related to the energy of compaction applied, through the weight of the compactor used and the time spent by the compactor on a surface. But compaction of an aggregate can only occur with confinement. The edges of a surface being compacted require to be effectively confined. Kerbs to a roadway provide confinement; confinement can be achieved where a free edge exists by not compacting close to the edge. A temporary edge may be constructed to provide full compaction of a surface layer. Kerbs and temporary edges require to be fully fixed to provide the confinement required. Patternation to some extend can provide confinement, as it does with concrete blocks, but this has to be carefully designed for.

The amount of compaction applied to a surface layer can be quantified. Compaction should be to refusal: no further compaction can be achieved. The surface to a pavement will have a defined profile, particularly transverse profile to ensure adequate surface water drainage. Ideally the bedding layer should be of uniform thickness and the surface profile formed by the surface of the support layer. This is often impractical. The consequence is that the bedding layer is used to create the surface profile; the bedding layer is also used to accommodate the variation in depth of stone elements and the variation in profile of the support layer. The compactibility of a bedding aggregate can be measured using a drop hammer to compact an bedding aggregate sample confined in a circular mould. Pre-compaction can be applied to represent the bedding process; the aggregate can be compacted to refusal. The vertical movement of the aggregate in the compaction process defines the difference between the bedded height and finished height of a surface. A uniform bedding layer thickness may be specified as laid to 70 mm, compacted to 50 mm: the surcharge height of the surface is 20 mm with an initial bedding height of 70 mm. Compaction is applied to achieve the specified surface profile. But, with this form of specification a 20 mm reduction in surface height would not be appropriate where the bedding layer is laid too thick, or too thin. Too thick a bedding layer will result in under-compaction of the bedding layer and deformation under traffic action. Too thin a bedding layer will not allow the amount of compaction expected and may result in the crushing of the bedding aggregate.

Aggregate used for pavement construction should be angular or sub-angular. Angular aggregate is derived from the crushing of quarried rock; sub-angular aggregate is obtained from the upper reaches of a river where some tumbling of particles has occurred. Any aggregate should have a minimum crushing strength, be well graded but have a control on the fine fractions (material less than 75 microns in size). Where greater permeability is required this should be achieved by limiting the content of fine fraction sizes: such a grading will ensure an aggregate skeleton is formed, but one with limited stability and reduced elastic modulus.

6.3. Surface Layer Aggregate Qualities

The aggregate used to create a flexible surface layer should be sub-angular, or a mixture of sub-angular and angular.

A more continuous aggregate grading leads to enhanced layer stability and stiffness; a more continuous aggregate grading improves layer compaction. All aggregate needs to be moist when compacted, to maximise the effect of the compactive effort applied. What should be recognised with larger stone elements forming a surface layer is that the elements are highly stiff. The bedding layer is confined. The consequence is that the aggregate around the edges of the element will rapidly become locked, but not necessarily in the most tightly packed state. The consequence is that elements will lack support under their central area. This is observed readily if large elements are removed after bedding compaction, the aggregate around the edges of the element is apparently well packed, the aggregate around the centre of the element is apparently under-compacted. The actual situation is that the aggregate around the centre of an element has been fully packed, by vibration, whereas the aggregate around the edges has locked itself into a skeletal structure that is not fully packed. This situation is not necessarily an issue with setts, but is an issue with flagstones.

It should be recognised that keeping an aggregate at its optimum moisture content for compaction is difficult, and requires skill and care in the storage of materials on site. In terms of the bedding aggregate it is common practice to wet a stone surface prior to final compaction, ‘to lubricate the aggregate’ and achieve ‘good’ packing. This approach is never likely to ensure the aggregate is at its optimum moisture content, and therefore optimum compaction is unlikely ever to be achieved by this procedure, other than by extreme skill, or by chance. Some movement of a surface layer is likely with any flexible construction; but such movement can readily be corrected by removal and re-bedding of the stone elements.

The maximum size of a fine aggregate forming a bedding layer requires to be related to the thickness of the compacted layer. The compacted thickness of a layer should be around 6 times the maximum size of aggregate used to form a grading. Bedding aggregate needs to have a maximum size of around 6mm with a compacted layer thickness of around 40 mm. Bedding layers laid too thick may become unstable under heavy loading resulting in the distortion of the surface layer. With joint aggregate, the ratio of size of joint to maximum (or single) aggregate size used to form the skeleton locking the stone elements should be between 3-6.

6.3.1. Support layer aggregate qualities

The aggregate used to form a support layer, or sub-layer, should preferably be angular. The grading requirements that apply to a bedding layer apply to a support layer, in terms of maximum particle size to compacted layer thickness, and the manner of creating layer permeability.

The need for the aggregate to be at optimum moisture content is important; whereas moisture is added to a surface layer prior to layer compaction, this is not generally the case with the support layer. The compaction plant requires being capable of fully packing an aggregate structure to maximise material properties, and thus ensure little or no secondary compaction occurs. The compaction of this layer is critical to the performance of a flexible construction.

What should be avoided with a flexible construction is the specification and use of a rigid support layer, or the use of a layer material with a high elastic modulus. The danger with such a layer is the potential de-compaction of the surface layer. The reason for this is the effect of the stress wave within the construction with the passage of a vehicle wheel. A stiff layer reflects a surface stress wave rapidly, both ahead of a moving load and behind the moving load. The nature of a stone element construction is the macro-roughness of the running surface; this increases the dynamic loading on the pavement structure. High dynamic loading and high stress reflection will 'test' the stabilisation of surface elements. Where the stabilisation is poor de-compaction may be a consequence; elements become loose and can work their way out of the surface layer.

6.4. Key Issues with the Construction of a Flexible Pavement

- All aggregate should be angular or sub-angular.
- An aggregate should be well graded.
- Permeability of a compacted grading should be achieved by using a washed crushed rock fine aggregate, a river sand fine aggregate, or by screening the finer fractions out of a fine grading.
- Permeability of an aggregate grading is needed to avoid moisture becoming trapped within a pavement structure.
- Joint aggregate with deep setts may be applied as a single size aggregate which is packed by vibration, followed by washing in a fine dust to stabilise the single size aggregate.
- Maximum aggregate packing should be achieved by material layer compaction.
- Compaction energy should be applied until refusal, or through calculation of vertical movement to achieve maximum aggregate packing.
- The moisture condition of an aggregate should be at or close to the optimum for the compactive effort applied to a layer.
- Wetting a bedded stone layer prior to bedding layer compaction should provide adequate moisture to maximise the compaction of the layer; the support layer must be permeable to allow excess moisture in the bedding layer to drain through the construction.
- All aggregate must be protected from contamination and excess moisture variation whilst being stored; this is the single most ignored needed in the construction of a flexible pavement.
- The thickness of a layer must be consistent with the moisture content of the aggregate and the compaction energy applied.
- The maximum aggregate size forming a grading is related to the thickness of the compacted layer: ratio of compacted layer thickness to maximum aggregate size should be around 6.
- The ratio of joint thickness to maximum aggregate size should be between 3 and 6.

- The thickness of a bedding layer is critical to the performance of a pavement. Excessive variations in layer thickness due to poor control of the surface of the support layer and too great a variation in the depth of stone elements can lead localised deformation due to a variation in layer compaction.
- The thickness of a support layer and the provision of any sub-layer should ensure that the stress applied to the soil foundation results in a slow accumulation of vertical deformation leading to the loss of a surface profile.
- The surface layer will have, or will build, stiffness as a result of the packing of the joint aggregate locking the elements together; patternation creates layer stiffness.
- The stiffness of a layer increases with depth of element used, or through patternation with shallow elements such as cubes. Pavements subject to heavier loading require a stiffer surface layer through the use of deeper surface elements: double the depth and 8 times the stiffness.
- A flexible construction should not be used there is canalised traffic flow without carrying a structural analysis, and care is required in design through patternation and width of element where there is a demand for high traction stress from cornering, braking and acceleration.
- The principal advantage of a flexible construction is sustainability

6.5. RIGID CONSTRUCTION

The significant advantage of a flexible 'small element' pavement construction is the ability to readily repair any surface deformation. Once one element has been removed additional elements can be extracted relatively easily. The bedding can be refilled and the surface layer reinstated with little wastage of material and to a quality of finish that the repair is not obvious. But, with a flexible construction the aggregate at the top of the joint is difficult to stabilise. With little trafficked roadways moss can grow in the joint; the root system can effectively stabilise the joint aggregate at the level of the running surface. Roadways subject to heavy traffic loading can result in the aggregate being plucked out by tyre action; surface water movement can remove exposed joint aggregate, and mechanical street cleaning operations where brush and vacuum is applied can disturb and remove the exposed joint aggregate. A flexible construction can therefore require a degree of maintenance of the joint aggregate, unless the joint aggregate can be stabilised.

All aggregate has a potential of bonding to a degree when subject to high compressive force; limestone aggregate can have a 'natural' cementing quality and when tightly packed at the top of a joint can provide a stable joint system. To provide a low maintenance surface, cement stabilised aggregate or cement mortar can be used to form the joints between stone elements. A cement mortar also seals a construction to the ingress of moisture, thus reducing the potential damage caused by frost action. In addition, a more stable surface is needed where there is high stressing caused by traction. Narrow stone sett construction on inclines commonly shows the elements rotated and particularly when the joints are wide. A more stable construction under such conditions is required.

For reasons of enhanced element stability, frost damage and low maintenance, cement mortar joints were developed. Commonly stone elements are bedded in the same manner as with a flexible construction, the bedding mortar being moist to maximise compaction effort. Joints are then filled with a cement mortar; the cement mortar is commonly applied as a slurry, the mortar being spread and filling the joints with the use a squeegee. Prior to the application of the slurry a surface is wetted, to allow the slurry to flow into the joints more easily. Where a moisture bedding mortar is used the surface is commonly wetted after the bedding of the stone elements to compact the mortar at the bottom of the joints. The joint mortar forms the top to joints, sealing and stabilising the surface construction.

The key performance issue with the use of cement mortars, and concretes, is that they are brittle materials. Where a joint mortar is used with stone elements a rigid surface layer is formed; little movement of the surface will fracture the bond between the joint mortar and the stone elements. Where a rigid surface layer is constructed over a flexible support, or, more critically, a low stability bedding created by an unbound graded fine aggregate, then failure of the surface is likely through layer flexure or joint shear. Unless a stone element pavement is lightly loaded, where cement mortars are used to form joints the bedding requires to be well stabilised through a use of a well-graded aggregate, or preferably, a cement stabilised aggregate. The support layer requires being cement stabilised, preferably. No secondary packing of the bedding layer aggregate or support layer aggregate should occur. But, where cement stabilisation is used with a bedding aggregate and support layer, the rigid binding of hydrated cement should not be taken as a way of stabilising an under-compacted aggregate structure.

The key issue with a rigid surface layer is that the joints control the behaviour of the surface layer, this is the consequence of the joint mortar being effectively unable to deflect without fracture. The most vulnerable part of the joint construction is the interface between the joint mortar and the stone element.

- With a deep surface layer construction the shear capacity of joints is most critical.Because of the limited movement of individual elements in shear the compressive strength of the bedding layer is little mobilised.
- With shallow surface layer construction, the rigid composite action of the surface layer results in it acting as a thin plate under the action of a wheel load: the surface layer flexes under load. The stiffness and stability of the supporting construction, including the bedding, is critical to the behaviour of a thin rigid surface construction.

Shear failure with a rigid construction is evidenced through cracks forming around individual elements: a punching action. Flexural failure is evidenced as linear or radial cracking along joints; these cracks are normally top-down surface cracks as the surface 'stress relieves' itself.

6.5.1. Surface layer construction

With a rigid construction the process of bedding stone elements and then filling the joints to fully stabilise the elements is a two-stage process.

6.5.2. Bedding

Cement stabilised bedding layers are commonly treated in exactly the same manner as graded aggregates. The material requires being at its optimum moisture content for compaction.Optimum moisture content is achieved when a semi-wet mortar is at its 'fluff point', or maximum bulk volume. The easier qualitative test to apply is to squeeze the mortar in the palm of the hand and the ball formed should be cohesive, but with no free moisture visible. When used as bedding the matrix is subject to initial compacted by the bedding process, and subsequently by the compaction of the stone surface using a plate compactor. The bedding mortar is normally allowed to gain initial strength before the joints are filled with cement mortar; this is achieved by leaving the surface open but untrafficked for at least

36 hours. As such it is good practice to wet a surface after compaction to pack the bedding mortar at the bottom of the joints and maximise the depth of the joint filled by the joint mortar.

The difficulty with the use of a semi-wet bedding mortar is the ability to keep the workability of the mortar after mixing and during the period of laying a surface: a retarded set mortar is commonly used on mainland Europe as a consequence of this. Because of the difficulty in maintaining workability, and because of the difficulty of keeping the surface of the stone elements free from bedding mortar, which can stain a surface, a practice commonly used in parts of Britain is to use a semi-dry bedding mortar. Fine aggregate and cement are mixed and used ‘dry’. After compaction the surface is wetted to ‘activate’ the cement in the bedding mortar. This is not good practice. The addition of cement to a fine aggregate is to make denser the grading. When fully packed a ‘dry’ bedding mortar has low permeability. Wetting a surface after layer compaction to flood the joints results in migration of the cement within the bedding layer, and leads to poor hydration of the cement. The consequence is a low compressive strength and variable strength bedding mortar being formed. Measured compressive strengths with this practice have been found to lie between 1 N/mm^2 and 7 N/mm^2 (MPa). Measurements in other countries have found similar values. Practices used to improve the quality of a dry bedding mortar when setts form the surface layer elements are to lay and initially compact elements, the elements are then lifted and water sprayed onto the mortar bed and the stone elements re-bedded. Commonly no layer compaction is applied to the surface as a whole with this approach; thus the consequence is still a low compressive strength, and variable compressive strength, bedding mortar.

With heavily loaded pavements which employ deep stone elements, or possibly stone blocks, compaction by vibrating plate is ineffective in compacting the bedding material and it can damage the surface of the stone elements. Here a stiff cement mortar is used to form the bedding. Stone elements are located and bedded using a heavy rubber maul; no further compaction is applied to a surface layer. The mortar bedding is cohesive and the action of bedding compaction is to displace and deform the mortar rather than compact it. With deep stone elements and blocks the use of a semi-dry bedding mortar will create variable packing under the elements as a result of lock of the coarser particles forming the loading bearing skeleton around the edges of the element, as described with flexible construction.

Whichever type of bedding mortar is used, and which should be related to the pavement loading and therefore depth of surface elements specified, the thickness of the bedding layer must ensure that the bedding aggregate can be fully packed.

6.5.3. Jointing

Joint mortars require to flow into joints and fully fill the joints, wetting out the faces of the stone elements fully to maximise contact area and therefore maximise bond strength, and therefore tensile strength (for flexure), and shear strength. More fluid mortars are formed by the addition of cement; more cement requires more moisture and therefore more fluidity. No compaction is applied normally to joint mortars; joint mortars require, ideally, to be self-compacting, to maximise density and compressive strength. The selection of the aggregate in terms of shape and surface texture and the design of the aggregate grading with a joint mortar are critical to the placement performance of the mortar.

Joint mortars are exposed to the environment and therefore require being durable and not degrading with repeated cycles of freezing and thawing. The density of a mixture is critical to durability; this is achieved with the correct blend of cement and aggregate. The blend of cement to fully fill an aggregate grading and achieve maximum density is particular to an aggregate source, or aggregate design.

High quality joint mortars come mainly from mainland Europe and are the result of experience with more aggressive winter conditions. High durability translates directly to high compressive strength, therefore high bond and therefore high shear and tensile strength. But, the negative side with high strength commonly is limited movement before failure with little or no warning- brittleness: the term used to quantify movement is strain- movement related to original dimension. Rigid systems are controlled by strain limits, not load or stress limits. The stiffness and stability of support layers is critical to the behaviour of rigid surface layers; the shrinkage of joint mortars can also be critical to the behaviour of rigid surface layers.

It is common to use proprietary joint mortars with rigidly bound stone element to achieve the control needed in joint mortar quality. Proprietary mortars are normally pre-bagged blends of aggregate, cement and any powdered additives to assist workability and minimise or compensate for shrinkage. Proprietary mortars are carefully designed mortar systems. They are designed normally to be water tolerant for site use, but in Europe site mixing plant is available which can meter the water into a pre-blended mixture, for both bedding and jointing mixtures. This approach achieves maximum control on mixture quality.

Much of the chemistry used to design cement joint mortars has come from grouting technology. Water reducing agents and shrinkage compensation agents come from this chemistry.

6.5.4. Support conditions

The bedding layer provides the direct support for a rigid surface layer construction. This layer is most critical when a shallow surface layer is constructed. The surface layer lacks stiffness and will deflect as a layer under traffic loaded. Any lack of compressive strength or stability of the bedding layer will be critical to the performance of the surface layer.

With a deep surface layer construction the quality of the support layer is also important. Although the surface layer will act as a stiff construction any deflection of the support layer as a consequence of the use of a material with a low elastic modulus may allow sufficient flexing of the surface layer to cause flexural cracking. A stabilised aggregate should be used to form the support layer under a rigid surface layer construction. Ideally, the support layer should be cement stabilised aggregate, and one in which the aggregate forming the layer is fully packed through compaction energy. Rigidly bonded deep surface elements supported and bonded to a high quality cement stabilised bedding layer and cement stabilised support layer forms a highly stiff pavement construction suitable for heavy traffic loading.

With all but the heaviest loaded pavements bitumen may be used to stabilise the aggregate forming a support layer. Bitumen is not a rigid binder; the binding provided by bitumen depends on speed of loading. With fast moving surface traffic a bitumen stabilised aggregate layer can respond in a manner to a cement bound or stabilised layer. Under slow moving traffic a bitumen bound layer will respond as a well compacted unbound aggregate layer. Bitumen mixtures are laid hot when the bitumen acts as a lubricant to the aggregate, similar to moisture with cement stabilised or unbound aggregate. As hard a bitumen as possible should be used with a support layer to maximise the stiffness of the layer. Bitumen stabilised layers should be thicker than an equivalent cement stabilised layer, but thinner than an unbound aggregate layer.

With a rigid surface layer there is a need to ensure composite action occurs with the layers forming the pavement. f this does not happen then each layer acts as an independent layer when the pavement flexes under vehicle wheel loading. This can generate high values of tensile strain in each layer as each layer flexes independently. Where bonding between layers does not, or may not, occur as with a bitumen stabilised support layer, then the support layer requires to be laid thicker to ensure adequate layer stiffness.

For light vehicular traffic loading and for foot traffic loading, where the loading is 'light', it is not critical to provide cement stabilised bedding or support layer. The cement stabilised joint proved for a durable, low maintenance surface. In such circumstances the bedding and support layers should be formed by a well-graded and well-compacted aggregate; layer stiffness is created by density and layer thickness. It is important with such a construction to ensure the joints are not over filled with bedding aggregate, otherwise the joint mortar topping will not be able to provide then stiffness to the surface layer. The result will be flexural cracking of the layer.

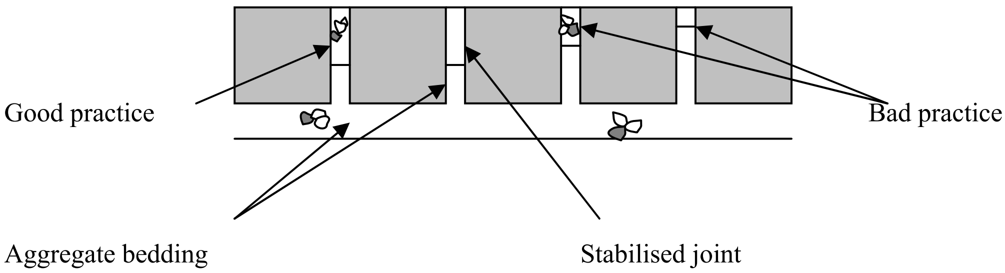


Figure 25. Support Conditions

6.5.5. Performance of rigid construction

The behaviour of composite surfaces formed by the use of cement mortar joints is complex.

6.6. DEEP SURFACE LAYER CONSTRUCTION

With deep elements the composite formed is a stiff continuous surface layer, a surface applied load is transmitted between elements by joint shear. The bedding layer should be of uniform quality and well compacted. But, with a deep surface construction, any vertical movement of an element will generate joint shear well ahead of any compressive stress generated in the bedding layer. Although a degree of under-compaction of the bedding layer will have some impact on the shear generated in the joint, the more critical issue is the limited area of joint mortar subject to shear. The bedding process results in the bedding material filling the bottom of joints. The bedding mortar should fill the lower joint to provide initial stability and enable the surface to be compacted to complete the full compaction of the bedding layer where a semi-wet mortar is used. The residual bedding material in the joints should be recompacted by the wetting of the surface. But, lack of care or skill can result in the bedding material filling a significant proportion of the joint with individual elements, or a series of elements. The same care is required when a stiff mortar is used to form the bedding with highly loaded pavements.

The shear stress generated in a joint is the wheel load divided by the joint perimeter sustaining a wheel load times the depth of the joint mortar: load divided by the area sustaining the load. The patternation of surface elements can have an impact on the joint perimeter sustaining a wheel load. Joints under-filled with joint mortar have a reduced area sustaining an applied wheel load; a greater joint shear stress is generated. A high strength joint mortar that has the ability to generate a high shear capacity can be over-stressed as a result of a lack of joint mortar depth. The consequence of over stress is shear failure around individual setts, as shown in Figure 26.

The situation is made more complex in that shear failure is seldom the result of a single passage of a vehicle wheel load, unless a surface is opened to traffic movement to early before the joint mortar has cured sufficiently. Failure of cement mortar systems is the result of fatigue failure: failure resulting from repeated stressing at a level below that to cause single load failure. The fatigue strength of joint mortars is complex, but is directly related to the strength of the joint mortar and to the bond that can be achieved with the surface of a stone element.

With deep setts, if they fail in shear then the effect of a poorly compacted bedding aggregate is bearing failure of the bedding mortar and loss of surface profile. The latter is accompanied by the flushing out of the failed bedding mortar. Here surface water moves into the interface between an element and the bedding through the crack in the joint mortar, the water is pressurised when the elements are subject to a vehicle wheel load and is jetted out of the joint along with the failed bedding mortar. The result is a continual loss of bedding material and a continual movement of stone elements into the bedding layer. The process stops when the surface of the bedding mortar has adequate compressive strength to avoid further bearing failure.

The concept of the joint mortar only filling the upper portion of joints has resulted in the development of high quality, proprietary joint mortars. The shear capacity of some proprietary mortars is over 3000 kN/m^2 (kPa); this is 30 times the shear capacity of aggregate stabilised surfaces. But, where the joint depth can be maximised with 'good practice' then the shear capacity of a joint mortar-stone element composite system can be reduced significantly.

A similar form of distress can occur as a result of a lack of joint mortar fluidity. In such circumstances the joint mortar does not fully fill the joint spaces and it does not fully 'wet-out' the surfaces of elements. A lack of mortar density and reduced contact area reduces the shear strength of joints: shear, or punching failure, is again the consequence. The wetting out of the face of stone elements to maximise shear capacity is linked to the texturing of the surface of stone elements; texturing the surface of stone elements increase the area of contact between a mortar and the stone element. The shear capacity of a stone element is halved when the surfaces are sawn as opposed to being textured through cropping or sand or shot blasting. As with the partial filling of joints with joint mortar, the quality of joints is not evident from the quality of a finished surface. But, this can be checked with coring of joints.

Figure 26. Shear failure of a single sett

Where the quality of joints forming a surface are generally good, the failure in shear of one element is not critical and the failure is not likely to be progressive. But, without an assessment of the general quality of joints forming a surface them progressive failure cannot be ruled out.

Distress can occur with rigid composite construction as a result of not allowing adequate curing of the cement mortar in the bedding and jointing. With deep elements a weak joint mortar will lead to shear failure and possibly failure in bearing of the bedding layer. Cement mortars gain strength and will build shear strength and composite action with time. A minimum strength is required before a roadway is opened to vehicular traffic, to avoid irrecoverable damage to the joint mortar. Excessive water in a joint mortar to provide fluidity may lead to excessively high moisture content at the top of joints. This can provide a material area with high voids content and potentially low durability; the effect can be a rapid degradation of the joint with frost action and tyre action.

6.6.1. Shallow surface layer construction

The partial filling of joints is more critical with shallow elements such as cubes less than 100 mm in side dimension; in addition, the quality of a bedding mortar is also more critical with such elements. Critically, if the joints are only partly filled and the joints account for a significant proportion of the volume of a surface then the depth of the joints will impact on the stiffness of such a layer. Where the stiffness of the bedding layer is low as a result of material under-compaction, or as a result of no inclusion of cement into a bedding aggregate, then the thin plate formed by the shallow stone elements will flex under wheel loading. This will result in flexural cracking at the interface between the joint mortar and the stone elements. The pattern of cracking will relate to the laying pattern of the elements. Where a Bogan pattern has been laid over an unstabilised aggregate bedding layer and the joints were only partly filled, radial cracking was evident around the Bogan pattern along, but at and at right angles to, the wheel path. From work carried out by TRL in their Pavement test Facility (PTF), where a similar situation occurred but the cubes were laid in rows and columns, or in stretcher bond, the cracking was along either side of the wheel path. In both cases from cores the cracking was found to be 'top-down', a classic flexural tensile failure. The surface was in effect stress relieving itself.

One type of proprietary laying system grouts the bedding layer through the joints prior to filling the joint with a viscous mortar; the grouting operation and the final joint filling operation is carried out as the surface is compacted by vibration. In such a circumstances, and with cubes, a full cement stabilised joint is achieved; accompanied by a Bogan patternation this process can create a stiff layer that can sustain significant traffic loading with shallow elements. With such a system the surface layer can behave in a manner reflecting a thicker construction layer.

6.6.2. Impact of support conditions

The durability of joint mortar and bedding mortar is critical in climates where frost penetration is deep. In such climates it is common to make the bedding layer material and support structure permeable to ensure there is no moisture trapped within a construction after construction which then can cause frost heave during a winter period.

With a rigid composite surface construction it is important that the support structure is also rigid, or has adequate stiffness in relation to the stiffness of the surface layer. It is important that with any layer a low stiffness is not created as a result of under-compaction. This can lead to the additional compaction of the layer and fracture of the surface layer in flexure, or bearing failure.

6.6.3. Material issues with a rigid construction

The aggregate used to form a cement-stabilised bedding layer is the same as with a flexible construction: angular and sub-angular. But, the aggregate to form a cement-stabilised joint is different to that with a flexible construction. Mortars that can self-compact when they flow into a joint require the selection of aggregate with appropriate shape and grading. From mainland Europe some proprietary joint mortars are formed with river aggregate of particular geological origin; but an aggregate grading can also be assembled from single size fractions. In either case the joint aggregate can be expensive as a result of the exact qualities looked for. A high quality mortar is required when the depth of the joint is, or may be, limited as a consequence of the depth of joint taken up by the bedding mortar. But, where a 'full depth' joint can be formed then a lesser quality can be accepted from a mortar.

Above all else, joint mortars require being durable; this is achieved by material density. Maximum density is achieved when the hydrated cement fully fills the fine aggregate structure. To ensure adequate wetting out of a stone surface the cement paste should just overfill the aggregate structure. As each aggregate source implies a different shape and grading of aggregate, the cement content is particular to an aggregate source, or aggregate grading. For durability, the aggregate to cement ratio should be between 2:1 and 3:1.

Lime may be added to a cement stabilised joint mortar. Lime can enhance the compressive strength and adhesion qualities of a cement mortar. But, care is needed in the quantity of lime added to a mixture; excessive lime can cause greater brittleness in a mortar.

As with a flexible surface construction, where the bedding mortar is semi-wet and final compaction is achieved through the use of a vibrating plate compactor applied to the surface of the stone elements, adequate edge restraint is required to be provided to elements. Without adequate edge restraint confinement of the bedding mortar does not exist and full compaction cannot occur. Edge restraint is provided in the same manner as with flexible constructions: kerbing, temporary edge restraint during construction; the option of only compacting close to a 'free' edge is not an option with a mortar bedding. But, breaking a surface into panels through the provision of details that can provide the action of an edge restraint is good practice.

Shrinkage and allowance for movement is an important issue with rigid constructions. With surface layers, either contraction joint details require to be provided every 8-10 m, or joints mortars are used which are flexible to allow tensile strains built up within the surface layer to be relieved. Contraction joint details can be used as restraining edges for the compaction of the bedding layer through the use of stainless steel angles fixed to the support layer. Alternatively, joint mortars can be 'shrinkage compensated', by the use of additives in the mixture. In such circumstances no shrinkage joints are required, but construction joint will always be used and there may be a need for expansion joints with large surface areas. These joints may be filled with a flexible mortar, such as one formed by a polyurethane binder. Where the support layer is a high strength concrete construction, movement joints will be required in this layer, unless it is continuously reinforced. Where movement joints exist within a support layer the joint should be taken through the surface layer as well, as good practice.

Edge restraints are critical with a rigid surface layer construction. All free edges must be adequately restrained against movement, particularly where wheel loading can act at or over an edge. Concrete logs provide one form of restraint as long as they are large and cannot be dislodged. The critical locations are around ironwork in the carriageway, such as value covers and access shaft covers. These details are often flexible in terms of their construction and reaction to wheel loading. A concrete ring detail integral with the support layer and that is separate to the ironwork may be the only way of providing adequate edge restraint.

6.6.4. Key issues with the construction of a rigid pavement

- Joint mortars control the behaviour of a rigid pavement construction.
- Joint mortars above all should be durable.
- Shear capacity is the critical property of heavily loaded pavements that employ deep surface elements.
- Flexural strength is the critical property of lightly loaded pavements that employ shallow surface elements.
- Joint failure is generally results from fatigue.
- There should be as great an area of contact between a joint mortar and the stone elements forming a surface. Joint mortars should fill as much of the depth of a joint as is practical for the laying of a surface; joint mortars should wet out the face of the stone elements.
- The surface of stone elements should be textured to maximise the contact area between the mortar and the stone element.
- Joint aggregate should be sub-angular and cubic.
- The grading of joint aggregate should allow self-compaction where the mortar formed flows into joints.
- The cement paste in a joint mortar should fully fill the space with the aggregate structure, to maximise joint durability and joint strength.
- Joint mortars may include additives for shrinkage compensation and to reduce the water content.
- Bedding aggregate should be angular or sub-angular.
- Bedding aggregate should be well graded.
- Bedding mortar may be used semi-wet when it should be compacted through the compaction of the surface layer.
- Where the traffic loading is heavy and large surface elements are used a stiff bedding mortar should be employed which does not require material compaction.
- The use of semi-dry mortars does not create uniform quality bedding mortars of adequate compressive strength.
- Bedding mortar should not over-fill a joint and limit the depth of joint mortar.
- Edge restraint is critical to the compaction of a semi-wet bedding layer and to ensure any edge to a rigid construction is fully supported.

- With heavily loaded pavements using deep surface elements that form a rigid surface layer the bedding layer and support layer should be stabilised using cement; with less heavily loaded pavements bitumen may be used to stabilise the support layer.
- Composite action is important with heavily loaded rigid pavements, through bond between the bedding layer and the surface elements, and the bedding layer and the support layer.
- With lightly loaded pavements the bedding layer and the support layer may be stabilised through the full packing of a well-graded aggregate, but care is required to ensure that joints are fully filled and there has to be recognition that over loading the surface will result in flexural failure.
- Where there is no shrinkage compensation used with the joint mortar contraction joints should be detailed.
- Expansion joints and construction joints require to be detailed. These should be filled with a flexible joint mortar, or a sealant is used with an edge restraint.
- Any joint in a concrete support layer should be taken through to the surface of the pavement.
- Restraint of all free edges is critical using a rigid edge detail around ironwork.

6.7. SEMI-FLEXIBLE CONSTRUCTION

It is possible to construct a semi-flexible construction. This uses a binder that behaves somewhere between hydrated cement and an unbound aggregate. Two binders are used to form the joints with a stone element paving: bitumen and polyurethane.

6.7.1. Bitumen filled joints

Commonly bitumen filled joints are used with a cement stabilised construction, the bedding mortar fills a substantial proportion of the joint and the joint is then sealed using bitumen. On mainland Europe bitumen joints seal a flexible construction particularly around tram tracks where there is significant vibration. The strain limit of bitumen is much greater than hydrated cement and the strain limit can be extended by the use of additives to the bitumen. Without additives the bitumen does fail in fatigue at the interface with stone elements, and the bitumen ages with time, which reduces the fatigue capability of the sealant.

Bitumen may be used to flood a single size aggregate forming a joint. The difficulty is the depth of penetration of the bitumen. The bitumen needs to be at a high temperature, but it cools rapidly in contact with cold aggregate surfaces. Bitumen will not bond effectively with damp aggregate surfaces.

6.7.2. Polyurethane joint and bedding systems

Polyurethane has high adhesive properties and can be designed to achieve a range of elastic modulus values with a graded aggregate. Polyurethane has been used to form mortars with graded aggregate that can be used for the bedding with stone elements. With joints the polyurethane can flood out an aggregate filled joint. Polyurethanes have difficulty with wet aggregate surfaces but they can operate with damp surfaces without detriment to bond.

The advantage with a polyurethane system is flexibility with strength. Shear tests with stone elements has resulted in the face of the stone disbonding. With a polyurethane system, elements operate in a similar manner to a flexible construction: the bedding layer supports elements, but the enhanced shear strength of joints allows the system to be used, potentially, in high stress locations.

Polyurethane joints can be used to construct movement joints in rigid construction.

6.7.3. Stone element pavements formed by flagstones

Flagstones form the surface to footways; they should not be used to form the surface to roadways. Flagstones may be laid on unbound aggregate bedding, or on a cement-stabilised aggregate or cement mortar bedding. Joints are formed between flagstones to take up any tolerance in the dimensions of the elements, and to seal the construction. The walls of flagstones are generally sawn; the top and bottom faces are riven where the element has been split along a bedding plane.

6.7.4. Flagstones laid on an unbound aggregate bedding

The weight of flagstones normally requires them to be laid by mechanical aid, either with a vacuum pad to allow operatives to lift elements into position, or by the use of a mechanical lifting frame. The weight of the element often limits the effect of compaction using a heavy rubber headed mall.

The key issue with the laying of flagstones is the event of the locking of the aggregate skeleton around the edge of the element as a result of the confinement of the bedding aggregate. The fine aggregate forming the bedding layer is commonly dense to allow some movement and ability to take up differences in element thickness. Between the need to take up differences in element thickness and the locking of the bedding aggregate the bedding layer has the potential to deform.

The joints between elements are commonly ‘sealed’ with a dry, cement sand, fine aggregate mixture brushed into the joints; liquid grouts may be used but the narrowness of the joint makes the operation difficult. The thickness of the joint results in high shear stresses being generated in the joint when the flagstone is loaded. Even although a high strength grout is used the dimension of the joint will lead to high shear being generated; the smoothness of the joint wall limits the ability of the joint to mobilise the full shear strength of a mortar grout. In addition, the thermal movement of elements can result in high compressive stresses and tensile stresses being built-up in the joints. The consequence is joint failure in almost all cases. Moisture can now enter the bedding layer; in addition the bedding rather than the joint, now supports the element, but the primary support provided by the bedding is still at the edges of the element.

Elements loaded near their middle are always in flexure, the depth of an element requires to be great enough that the loading does not cause tensile failure and fracture of the element. When moisture enters the joints it migrates to the bedding layer. With a dense aggregate grading moisture can be retained within the bedding layer, loads applied near the edge of elements can flush out the fine aggregate fractions and edge support can be lost. The result is that the flagstone can rock.

What should also be recognised with the use of an unbound aggregate bedding layer is the event of secondary compaction as a result of traffic-generated vibration.

6.7.5. Flagstones laid on cement stabilised aggregate bedding

As with concrete blocks, limiting the fine fraction sizes in the bedding aggregate can allow drainage and limit or eliminate the loss of bedding material if moisture enters an unbound aggregate bedding layer. But, drainage within a construction may not be possible. Stabilising a bedding aggregate is often seen as a way of maintaining an impervious construction and avoiding the loss of bedding material. Stabilising a bedding aggregate can also be viewed as a way of minimising any secondary compaction from traffic vibration.

Where semi-dry cement stabilised bedding mortar is used the difficulty is activating the cement. The reason for the limited compaction achieved with an unbound aggregate exists with a semi-dry system. The lack of complete hydration results in a variable quality of bedding mortar being formed; most hydration will occur around the edges of a flagstone as a result of surface wetting. There is little advantage in the use of a cement stabilised bedding unless the loading is very light. Any lack of hydration, or limited hydration of the bedding mortar around the edges of flagstones may result in bearing failure. Loss of support results when the failed bedding mortar is flushed out of joints.

A semi-wet mortar may be used as a bedding layer. This approach can ensure a more uniform quality of mortar as a result of more uniform hydration. The difficulty is in achieving adequate densification of the bedding mortar. Densification will be greatest at the edges of flagstones; the flexural strength of elements is critical under any vehicular loading. Joints, if filled with a cement mortar, will again sustain all the loading until failure in shear when the joints become permeable, but bearing failure at the edges of the flagstone may be greatly reduced with this construction.

A stiff mortar-bedding layer may be used particularly with a lower cement stabilised support construction. Providing a bond coat to the underside of a flagstone with this design can ensure composite action of the layers forming a construction. Failure of a brittle joint may have limited impact with this design; this design can also sustain limited vehicle loading.

6.7.6. Design for bedding support

The joints with flagstones should not be filled with a brittle mortar unless pedestrians only load the pavement. Flagstones bonded to a semi-wet or stiff cement stabilised bedding layer and support construction is better practice; joints should be filled using a flexible mortar which has little resistance to movement and which can adhere to the smooth surfaces of joints.

6.8. CONCLUSIONS

Natural stone roadway and footpath construction is not a simple technology, albeit that the technology has been used for more than a millennium. The key issue today is the severity of traffic loading, in terms of the physical weight of axles and therefore wheel loads, number of axles per vehicle and the canalisation of traffic on a roadway. In terms of footpaths there is an increasing use of footpaths by vehicles when they service commercial businesses. The consequence of vehicular traffic loading has been an increasing frequency of failure with natural stone constructions: in a number of occasions significant failure has occurred a very short time after construction.

Historically, natural stone construction used unbound aggregate to stabilise elements; the support construction was also formed by unbound aggregate. Although such construction is 'sustainable', and cubes can produce a stiff surface layer even when less than 100 mm in depth, heavy canalised traffic results in permanent deformation of the construction.

Maintenance of roadway surfaces can also be high as a result of plucking of the aggregate from the joints.

Today in major cities across Europe cement mortar joints are more common with stone roadway construction. This is a result, primarily, of a need to reduce the maintenance with such surfaces. But, the event of using cement mortar joints is to attract shear and bending stresses to the surface layer. Such a construction is sensitive to the quality of the cement mortar joints, and sensitive to the stiffness and stability of the supporting structure. Although ‘thin’ surface layer construction (less than 100 mm in depth) is more sensitive to flexure, deeper construction can also be sensitive to flexure where the higher strength, more durable cement mortar forms a topping to the joints. Deeper construction is generally more sensitive to shear failure seen initially as a punching failure. Heavier more canalised loading requires a deeper surface layer construction with joints fully filled with high quality cement mortar. With such a loading condition the bedding also requires to be a plastic cement mortar, and the base preferably should be a cement stabilised aggregate. Such a construction is highly stiff which will act as a composite system where the bond between layers remains in tact.

With heavily trafficked roadways, semi-flexible composite systems can be designed which employ a joint and bedding mortar using a polymer binder rather than a brittle cementitious binder; polyurethane is a cold applied system and is more useful that a bitumen system. Polymer modified cement mortars are available and can provide some degree of hybrid behaviour.

Flagstone construction cannot easily sustain heavy vehicular traffic loading; this is a consequence of the difficulty in construction of obtaining uniform direct support through the bedding layer, and as a consequence of the dimension and nature of the joints. The bedding layer, not the joints, controls the behaviour of flagstones. The elements behave as independent units and the inherent strength of the stone and depth of the elements control flexural strength, unless composite action can be achieved with the support structure. The figure below shows the behavioural relationship between stone elements forming a surface layer construction with roadways and footpaths. Such a diagram is a qualitative guide to the use of natural stone with roadway and footpath construction to match modern-day traffic needs.

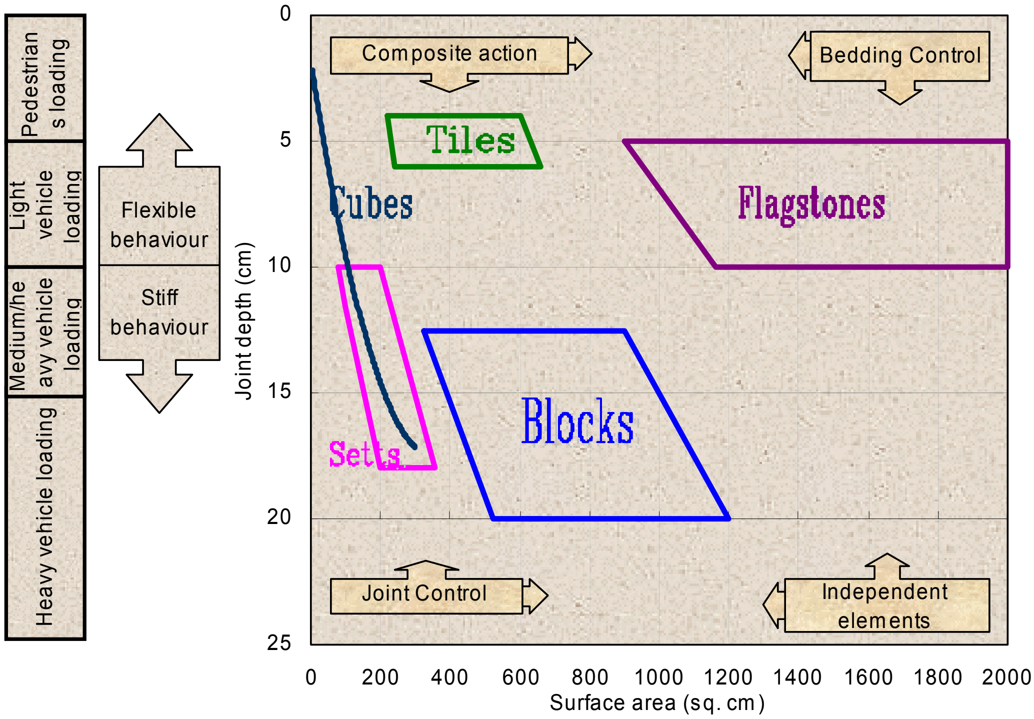


Figure 27. Qualitative guide to the use of natural stone with roadway and footpath construction

References

BS EN 1341 (2000). Slabs of natural stone for external paving, *Requirements and test methods*, BSI, London.

BS EN 1341 (2000). Setts of natural stone for external paving paving, *Requirements and test methods*, BSI, London.

Copyright Transport Research Laboratory 2002. All rights reserved

McHale M J., Fordyce D., (2000). Use of natural stone materials: Stage II Interim report. *Unpublished SCOTS Report*

SCOTS (2000). Natural Stone Surfacing, *Good Practice Guide*, Society of Chief Transportation Officers in Scotland. [Free download at www.scots-website.org.uk]

7

Key Issues in the Design and Specification of Stone Surfacing

SYMONS RAY

7.1. INTRODUCTION

The success of a natural stone-surfacing project will ultimately depend on good communication between the designer, the client and the contractor. The designer's responsibility is to formulate the pavement design, prepare drawings and provide a detailed specification of all the materials to be used. A clear understanding of how the work is to be carried out is also required. This paper reviews some of the design and specification issues that need to be addressed when using natural stone as a surfacing. They include the following:

- Design approach
- Load applied to the surfacing
- Selection of stone
- Choice of construction

- Layer thickness and properties
- Road layout
- Detailing
- Risk assessment

7.2. DESIGN APPROACH

The main purpose of the design is to ensure that the pavement is fit for its intended purpose and does not fail prematurely. Most pavement design methods are empirical and are based on observations of real roads under a variety of traffic conditions. Recently more fundamental design procedures based on structural theory have come into routine practice. This method is commonly used to improve, or extend the conclusions reached from experimental work and is known as semi-empirical. It results in a combination of recipe and end-product specifications. The former defines the physical properties of ingredients and their proportions, and the latter states performance targets that must be met. Although less commonly used, a purely theoretical design procedure can be adopted. The method uses structural theory and information on the behaviour of road materials under repeated stress. Provided the appropriate inputs are used, a mathematical model can be used to determine the relevant critical strains or stresses for different designs. The technique encourages innovation and may produce cost savings. Performance testing to demonstrate the approach agrees well with full-scale experimental evidence is normally necessary. Experience and expertise are required in the application of this method.

7.3. LOADING

The primary factors influencing the design of the surface layer, and the support structure, are the magnitude, frequency and type of loading applied to the paved area. In the SCOTS Guide (SCOTS, 2000), rigid pavements are designed for the maximum axle loads they are likely to carry. The magnitude of loading is based on axle weight, and the type of loading by the layout and geometry of a particular site, e.g. gradients, junctions, road width and other factors. The two conditions combine to define the load applied to the surface for design purposes.

7.4. SELECTION OF STONE

The selection of stone is an aesthetic matter and is likely to be influenced by the streetscape setting, historical records etc. However the stone elements need to be durable and provide adequate skid and slip resistance. Guidance on selecting appropriate stone is given in the

SCOTS Guide (SCOTS, 2000) and BS EN 1341 & 1342 (BSI, 2000). Surface texture is also an important characteristic for all faces of the stone. Apart from influencing skid resistance, research has shown (McHale and Fordyce, 2000) that the texture of the side walls is important for achieving bond with the adjacent mortar. Similarly it can influence friction and adhesive characteristics with the bedding. For heavily trafficked sites, element side walls should be sawn and then fine textured by fine picking or sand/shot blasting.

7.5. CHOICE OF CONSTRUCTION

The designer has the choice of selecting either a flexible or rigid pavement construction. The former is an older, traditional form of construction that involves stabilising stone elements with unbound aggregate. The latter uses mortar to fix the stone and is a more modern development resulting from traffic growth and inner city cleansing regimes. In both cases it is important to ensure that the lower pavement layers are compatible with the upper surfacing layers in terms of stiffness.

7.6. Flexible Construction

Flexible construction involves stabilising stone elements with unbound aggregate. The elements are bedded into a layer of fine rock aggregate, and the same material is used to fill the joints between the elements. The effect is to 'lock' the elements together by friction between the aggregate and stone and the interlock created by the laying pattern. The most significant benefit in using unbound aggregate to achieve surface layer stability is sustainability. All the surface components can be reused, and any loss of surface profile can be rectified simply. Other benefits associated with constructing a flexible stone surface include:

- Lower cost
- No curing period allowing early opening to traffic
- No staining problems associated with using mortar
- Allowance for small movements without loss of stability
- Can be lifted and re-laid seamlessly following excavation as part of utility activities

The main disadvantage is its limitation in load carrying capacity. Flexible pavements will deform under heavy loads and are not recommended for use in severe stress sites. Permanent movement will occur in the various pavement layers when the applied stress exceeds the shear strength of the aggregate matrix. Permanent movement will occur until equilibrium is reached. Increases in stress will result in additional permanent movement until a new equilibrium point is again reached. This effect is seen where roads formed by a flexible stone construction are stable for many years (>100) until heavier vehicles use the carriageway, e.g. as a result of re-routing buses. There is also a need for early life maintenance with unbound systems. Joints require to be topped up with fine aggregate as the system 'shakes-down' and 'stiffens up' under traffic loading. Joint aggregate can also be lost as a result of surface cleaning operations.

Key issues that should be considered when specifying a flexible construction are as follows:

- Flexible pavements will deform under heavy loads and are not recommended for use in severe stress sites
- Cubes should be laid in curved patterns such as Bogen, or arc pattern, in vehicular trafficked areas
- All stone elements should have textured faces
- The support structure must be compatible with the surface layer
- Compaction of support materials is critical to ensure a uniform and adequate support for the surface layer.
- Edge details are critically important. Rigid support must be provided at all edges to a flexible pavement construction.
- The moisture content of the bedding aggregate during compaction should be at, or close to, optimum.

- The need for joint topping up depending on traffic type, volume and environment.

7.7. Rigid Construction

Elements can be stabilised through the use of mortar and the binding action of the hydrated cement paste forms a rigid composite between the mortar and the stone elements. The depth, strength and width of joints are the primary factors controlling resistance to loading. The main advantage of rigid construction is its potential to provide a long life with minimal maintenance. Disadvantages of a rigid stone surfacing relate to construction and aftercare issues. Cement staining can be a problem during filling of joints and there is also an environmental issue with joint filling, as surplus mortar can be washed into drainage systems. Staged construction can be difficult with rigid pavement design. This relates to achieving level, variations in bedding depth, variable curing where an edge is exposed along a construction joint and adequate compaction of the bedding along the construction joint.

Rigid surfacings are difficult to repair following failure or access by PU providers. Repairs can be time consuming, expensive and it is often difficult to match the existing surface or maintain a uniform appearance following repairs.

Key issues that should be considered when specifying a rigid construction are as follows:

- Rigid pavements can fail under a critical single heavy load, or in fatigue under repeated lighter loading
- With the exception of flagstones, strength, depth and width of joints will be the primary factors controlling resistance to loading
- If sawn elements are used all surfaces should be textured by ‘picking’ or shot/sand blasting
- The support structure must be made compatible with the surface layer, i.e. possess a high stiffness
- The thickness of the bedding layer is critical to the stiffness of the direct support provided to the surface layer. It should be compacted at its optimum moisture content
- The apparent strength of a cementing action with an aggregate should not be taken to replace the need for material stability achieved through full compaction
- Joint mortars should be specified to fill a defined depth of joint
- Time to opening to traffic can be an issue with a rigid construction. The aim is to ensure that the mortar achieves an appropriate strength prior to trafficking.

7.8. Layer Thickness and Properties

Stone elements come in all shapes and sizes and these factors influence the supporting mechanisms of the completed pavement. Common types of stone element are shown in Figure 28.

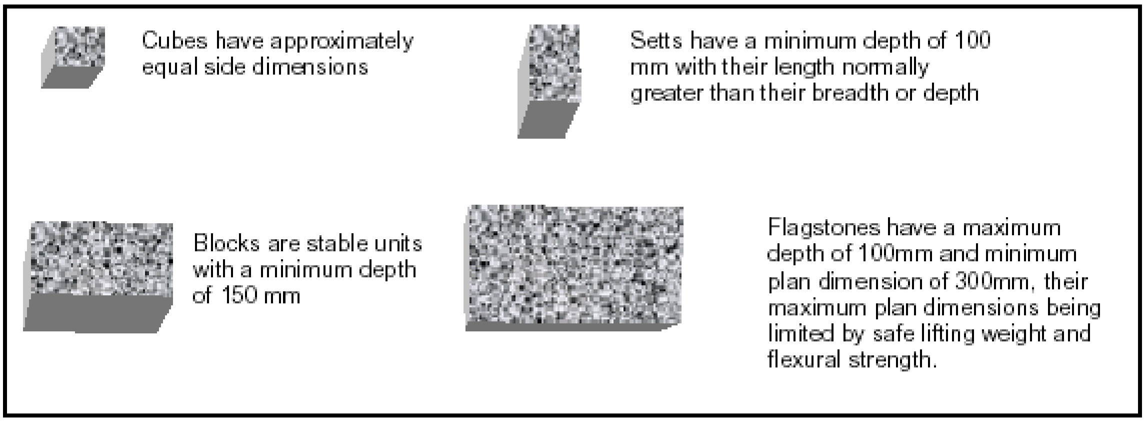


Figure 28. Common types of stone element

The influence of element depth was examined in TRL's Pavement Test Facility, and eight different full-scale panels were constructed and tested. The testing showed that stone element surfacing can be divided into deep and shallow construction: greater and less than 100 mm depth respectively. Shallow construction has limited stiffness and can fail through the bending of the surface under load. Deeper elements provide greater stiffness and are more likely to fail through shearing and vertical movement (punching) of individual elements under direct wheel loads.

It is recommended that stone elements up to 50 mm in depth be used for pedestrian loading only. Elements between 50 mm depth and 100 mm depth are capable of being designed to sustain light to medium vehicular traffic loading and elements between 100 mm depth and 150 mm to sustain medium to heavy vehicular traffic loading. Elements greater than 150 mm in depth are capable of being designed to sustain heavy vehicular traffic loading.

Guidance on the selection of stone elements, bedding and jointing properties is given in the SCOTS guide (SCOTS, 2000).

Key issues that should be considered when specifying layer thickness and properties are as follows:

- Elements need to be sorted into appropriate size and shape groups prior to laying to achieve the desired joint width tolerances
- Flexible
- Bedding material must be permeable.
- The profile of the surface of the support structure should follow the intended profile of the finished surface layer to within a tolerance of no more than 5 mm over a 3 m length in any direction.
- The bedding layer must be neither too thick nor thin.
- With flagstones, joints should not be filled with cement mortars.
- Rigid
- No more than 20 mm rise of bedding mortar permitted within joints.
- Water cement ratio of joint mortars should not exceed 0.7; mortars must be sufficiently workable to fill joints and to leave no voids.
- The use of cement in aggregates does not remove the need for adequate compaction.

- With cement-stabilised roadbases, expansion and contraction of the layer must be considered. Bituminous roadbases need to be well compacted to avoid secondary compaction under traffic.
- A minimum joint mortar compressive strength is required before opening to traffic.

7.9. Road Layout and Geometry

In common with all good road construction, appropriate cross falls are required to allow drainage of water. This is required to ensure safety and maximise the longevity of the stone element surfacing.

Local knowledge should be used to identify areas of vehicle over-run due to carriageway width or restricted delivery access to commercial properties. Allowances should be made in the design for channelisation effects and vehicle over-run onto pedestrian areas.

The laying pattern with stone element surfacing is an aesthetic choice, but also contributes to the stability of the elements under trafficking, particularly with a flexible construction. Cubes used in vehicular trafficked areas with a flexible construction should be laid in curved patterns described as Bogen, or arc, the arc being in the direction of the traffic flow, or uphill. On inclines and high stress areas more stable elements (cubes or setts with a minimum depth of 150 mm) should be used. Elements should be laid in stretcher bond pattern at right angles to the direction of vehicular travel.

With rigid construction, the laying patterns described above will improve element stability, but the influence will be secondary to the depth, strength, width of joints and workmanship.

7.10. Detailing

Detailing of stone element paving is particularly important, as poor detailing can often result in early life defects and failure. Careful attention should be given to edge details, change of surfacing, street furniture and the need to allow for thermal movement. The following should be considered when designing and specifying details:

- Edge haunches need to adequately support and restrain paved surfaces
- Interfaces between different types of surfacing to minimise cracking and movement caused as a result of differential material responses to temperature.
- Street furniture – quality grey iron or heavy gauge ductile iron is recommended
- Expansion and contraction joints for concrete support layers.
- Movement joints in the surface layer above joints in the roadbase.

7.11. Workmanship

Poor quality, consistency, placing and compaction of fixing materials have been highlighted as major recurrent problems. The consequence of this is that some designers are attempting to compensate for this by using proprietary products. It is important that these products have a proven track record and have been 'tried and tested' in the streetscape environment.

It should be remembered that no bedding or jointing material will serve its intended purpose if it is not applied properly. A grout or mortar is only a single unit within a pavement structure and it must react not only with stone elements, but also other materials it comes into contact with. The appropriate mixing, consistency, placing and compaction of materials are essential if the material is to perform as intended.

7.12. RISK ASSESSMENT

Many factors need to be considered in producing a successful stone surfacing design. In order to ensure that all of the factors have been considered correctly, a failure risk model can be used to check the design. The aim of the risk model in the SCOTS guide is to provide a rapid check on the suitability of the design for its intended setting. The model also considers some of the factors that are not quantified in the design process (e.g. workmanship).

The risk assessment is essentially a parametric analysis in which the most significant parameters influencing the performance of a stone element pavement are considered. The calculation process employed in the model derives a value that has been termed the Natural Stone Paving Failure Index.

A simple calculation template is used to insert the appropriate parameter values from relevant tables. The calculation process derives a value for the Index. If the Index value is below ten then there is a low risk of significant failure occurring. If the value is above 10 then it is likely that at some point during its life the natural stone pavement in question will suffer failures. As the value increases above ten there is increasing risk of failure and increasing risk of that failure occurring early in the life of the pavement and / or being severe and widespread.

It should be noted that in the case of unbound surfacings the model assumes that regular, appropriate maintenance of the surfacing is carried out. If this is not the case then a more severe failure than indicated by the index value could occur.

The risk model is not intended as a definitive statement on the condition or likely performance of a pavement. It is intended to act a guide to those responsible for making decisions associated with the design of stone paved roads. The Index could also be used to evaluate the risks associated with existing schemes and the need to make provision for maintenance works at some future date.

7.13. FUTURE RESEARCH NEEDS

The use of stone as a quality surfacing in the streetscape is growing rapidly. Cities are competing with ‘American style’ out of town retailing. They are also competing against each other to attract inward investment from the business community. For these reasons, the market for quality streetscapes looks encouraging. Some of the benefits of using stone include:

- preserving historical character
- attracting new investment
- improving the environment and quality of life

The desire to retain the traditional appearance of old is unlikely to diminish. But there is also a growing interest in the use of natural stone in contemporary urban architecture. This is undoubtedly because of the durability, flexibility and high aesthetic content of natural stone. Quality streetscapes increase civic pride. In turn this can bring additional benefits in reducing vandalism, and enhancing the safety and security of public spaces.

However, it is important that the future of stone is not guided by fashion alone but takes full and proper account of the engineering. Research is required to demonstrate that stone is the best choice for prestigious streetscape projects. It is needed to ensure stone can conform to today's often demanding engineering standards and compete with man made products. Robust design guides and specifications are required to ensure a stone surfacing is fit for its intended purpose.

There is more to do if stone is to compete successfully with other products. Research is required to provide a fuller understanding of stone surfacing if they are to continue to play an important role in future streetscapes. It is important that they are used in the most appropriate locations that maximise their many benefits to society. Key research areas include:

- Quantifying benefits of stone
- Improving and refining design methods
- Enhancing material performance
- Detailing
- Identifying training needs
- Maintenance issues

7.14. QUANTIFYING BENEFITS

The benefits of using stone need to be examined and quantified. Many benefits are of course not readily quantified in purely financial terms - for example historic character, amenity value, use in traffic calming, enhanced profile and image – and a broader approach is needed.

The UK Government states that sustainable development means meeting four objectives simultaneously (DETR, 1999):

- Social progress which recognizes the needs of everyone
- Effective protection of the environment
- Prudent use of natural resources
- Maintenance of high and stable levels of economic growth and employment.

Put another way this asks the question, “Can stone generate wealth and human well-being without destroying the environment?” Stone surfacings have the potential to meet most of the above objectives through:

- Producing a quality environment shared by all
- Having the potential for high-value reuse and recycling
- •Supporting high levels of economic growth and employment (indigenous stone).

Stone is a primary resource, but used in a certain way it offers potentially unlimited reuse as for example in unbound construction.

Much stone is currently imported from countries such as China and, although cost effective in direct financial terms, the process cannot be viewed as sustainable. Clearly there is a need to re-examine the potential for producing indigenous stone with the obvious energy resource efficiencies, and at the same time generating local employment.

7.14.1. Improved performance

Our approaches to designing stone surfacings are still at an early stage when compared to other materials such as asphalt and concrete. Information on the performance of stone pavements needs to be collected, analysed and used to further develop existing design methods. Equally fundamental testing of materials under repeated stress would assist in the development of analytical tools.

One example of a knowledge gap is in the use of large plan area elements, or flagstones. This type of surfacing is preferred by pedestrians, but is regarded as a high-risk option if required to carry medium to heavy traffic. Robust flagstone designs are required that are both economic and can work under traffic loading. Work is required to understand the behaviour of flagstones.

7.14.2. Materials

Recent research carried out under the SCOTS project (SCOTS, 2000) showed that the texture of stone surfacings has an influence on the structural behaviour of the pavement under load. Laboratory and full-scale (PTF) testing showed that increasing side wall micro-texture produced enhanced shear and bending resistance. Further work is required to investigate and quantify the influence of texture on the bond between stone and mortar. This information will also assist quantifying the effects of using recycled stone materials, e.g. stone setts.

The slip and skid resistance of natural stone is an area of considerable concern and debate. This is because there is little guidance available. Stone surfacings do become slippery, although it is likely that their physical appearance particularly in the wet, influences driver behaviour and results in reduced vehicle speeds. It is a national objective that accident rates are reduced. Monitoring of stone surfacings is required to quantify and measure their safety record.

Stone from different geological sources varies greatly in terms of its polishing and wear properties. Currently the PSV test (PSV - BS812:1989) is used as an indicator of the likely skid resistance of road materials. There is some doubt about the applicability of the test as it measures the polishing resistance of aggregate fragments rather than a single flat surface. A new test, the polished paver test is based on the resistance to polishing of flat paver surfaces, but some in-service testing has shown that PPV values may be over optimistic. Work is required to identify appropriate testing methods to standardise measurements of initial slip and skid resistance.

A wide variety of instruments have been devised to measure the routine in-service skid resistance of roads, e.g. braking force trailer, Griptester and SCRIM. These tests have been developed for asphalt and concrete surfaces. Research is required to determine whether they can be used to assess stone surfacings. Routine monitoring is important to establish in-service threshold levels that need to be maintained to ensure safe passage by all road users.

7.14.3. Detailing

The streetscape consists of different materials and forms of construction, which require careful detailing. For example problems are often encountered at the interface between stone, street furniture and different surfacings such as asphalt. Guidance is required on the differential material responses to temperature and loading that can cause deterioration of the surfacing

7.14.4. Training Needs

European experience stresses the importance of using skilled personnel to construct stone surfacing schemes. It is likely that training falls into the ‘chicken and egg’ category in that industry is unlikely to invest in long-term training until there is a strong market. Common complaints include a lack of good craftsmen and that current training schemes do not produce trained personnel.

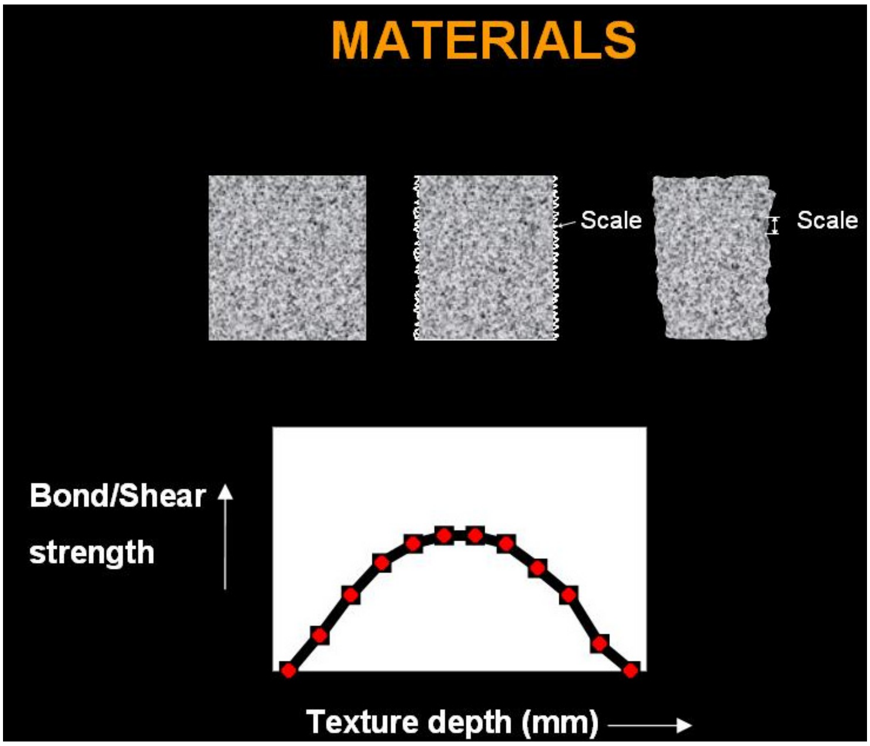
Research conducted on behalf of utility companies has shown that the principles of highway engineering need to be put across simply to workers. An awareness of the implications of ‘cutting corners’ is not always fully understood. Knowledge of sustainability issues and recycled materials also needs to be included in training courses.

7.14.5. Maintenance issues

Stone surfacings require major investment and it is important that they are protected and sustained through an effective maintenance regime. Owing to the high visual quality of stone, effort is required to ensure surfaces are maintained as they were originally constructed and provide a safe passage for all road users. Research is required to address the following areas:

- reinstating road openings
- cleaning surfaces
- carriageway markings
- re-texturing stone

Utility companies are required under the New Roads and Streetworks Act to reinstate any openings with materials matching those removed. However, the shortage of skilled labour experienced in laying stone often leads to inexperienced contractors carrying out the work poorly. Some authorities are encouraging partnerships in which a dedicated contractor with proven expertise is used. This type of initiative needs to be monitored and reviewed.



The various cleaning systems available on the market need to be assessed. The strengths and weaknesses of the various techniques needs to be understood so guidance can be given on the most appropriate methods for a given situation.

Carriageway markings are required to enforce parking restrictions. Aesthetically they can clash with stone and are known to de-bond from the surface. Research is required to develop improved materials and explore alternative ways of managing traffic.

As stated earlier today stone surfaces can become slippery due to vehicular or heavy pedestrian traffic. Existing texturing methods are available but again need to be reviewed in terms of their effectiveness in restoring skid and slip resistance. Re texturing also needs to be considered in terms of finished profile and its effects on noise and vibration. Equally the effects of reducing the depth of stone need to be considered in terms of structural performance.

7.14.6. Conclusion

The use of stone is growing. Research is required to:

- Quantify and promote the benefits of using stone
- Understand the material
- Improve design, specification and detailing
- Identify training needs
- Develop maintenance regimes and techniques

This offers big potential returns in the form of:

- Increased economic turnover
- Improved environment and quality of life
- Secure future for the use of stone


TRAINING NEEDS

References

Restricted range of relevant European texts, Guides and Standards

1. NORME P 98-335: Chaussees Urbaines. Mise en Oeuvre des Paves et Dalles en Beton, des Paves en Terre Cuite et des Paves et Dalles en Pierre Naturelle (1993). Paris, AFNOR
2. Les Pierres Naturelles en Voirie Urbaine – Guide de Mise en Oeuvre, (1995). Lyon, CERTU
3. Degradations des Chaussees Urbaines Revetues de Paves ou de Dalles, (1998). CERTU, No. 76
4. 'Katalog Vozovek Pozemnich Komunikaci' TP 78, Ministerstvo Dopravy, The Czech Republic, 1996
5. Merkblatt fur Flachenbefestigungen mit Pflaster und Plattenbelagen, (1989). Forschungsgesellschaft für Straßen- und Verkehrswesen, Arbeitsgruppe Mineralstoffe im Straßenbau, Ausgabe
6. Richtlinien fur die Standardisierung des Oberbaues von Verkehrsflachen, (1986). RstO 86, Forschungsgesellschaft fur Straßen- und Verkehrswesen, Ausgabe
7. Praxistips fur die Pflaster – und Verbund – Steinverlegung, (1994). Verfasser: Sepp Rixner, Wacher-Werke GmbH and Co. KG
8. Legal Loading, (1999). Weight and dimension limits for heavy vehicles, Swedish National Road Administration
9. The Road Vehicles (Authorised Weight) Regulation 1998, Road Traffic, Statutory Instrument No. 3111
10. Shoji K., Ryusuke A., Katsutoshi S., (1993). Application of Cement-Asphalt Emulsion Mortar for Construction of Natural Stone Pavement, *First World Congress on Emulsion*, Volume 3, Paper Number 4, 1b 063
11. Fordyce D., Khweir K., (2001). The Performance and Behaviour of Stone Element Pavements, *Natural Stone Surfacing 2001 Conference and Exhibition*, One Great George Street, Westminster, Surveyor Publication
12. SCOTS (2000). Natural Stone Surfacing – Good Practice Guide, Society of Chief Officer for Transportation in Scotland, Dundee City Council, 2000
13. British Standard, (2000). Specification for Dressed Natural Stone Slabs, BS EN 1342,
14. British Standard, (2000). Specification for Dressed Natural Stone Setts, BS EN 1343

15. British Standard, (2001). Natural Stone Setts and Cobblestones – Code of Practice for Construction of Pavements, BS7533, Part 7
16. British Standard, Natural Stone Setts – Structural Design of Trafficked Paved Areas, BS 7533, Part 10, in preparation
17. DETR (1999). A Better Quality of Life: a strategy for sustainable development for the UK.
18. SCOTS (2000). Natural Stone Surfacing, Good Practice Guide, Society of Chief Transportation Officers in Scotland, Dundee City Council.

Acknowledgements

The work reported in this chapter was carried out in collaboration with TRL (Scotland). The authors wish to thank the SCOTS (Society of Chief Officers of Transportation in Scotland) Natural Stone Paving Materials Working Group and Scottish Enterprise for funding the study. The work has been included in the 'Natural Stone Surface Good Practice Guide ' published by the SCOTS Natural Stone Paving Materials Working Group.

8

Stone Decay and Conservation

ANGEL M. LOPEZ-BUENDIA, CELIA GUILLEM. KONTODIMOS KOSTAS, FOUNTI MARIA

8.1. INTRODUCTION

Stone has been a traditional building material in all of the human history. The older and better-conserved buildings date back to the Neolithic era. However, Ancient Egypt was the place of the first truly industrial use of quarries at big scale. Egyptians had the knowledge how to polish sculptures on basalt that Greeks and Romans could not reproduce with same efficiency. While Greeks started the massive usage of stone, the Roman Empire improved it and spread over the Mediterranean influence in most of Europe. Romans used marble extensively as pavement and covering in slabs. The Middle Ages, characterised by technological and cultural drawback, also affected the stone industry. An exception in stone industry of Europe during the prime Middle Ages was the Arabian culture in Iberia.

Although rock materials are normally considered to be resistant to weathering, almost none can be found in equilibrium with the environment in which they are placed; this leads to changes in their original properties. These changes, within certain limits, can often be advantageous: a stone can mellow in appearance and acquire surface qualities which confer certain aesthetic value and slow down the action of weathering agents. In more aggressive environments, however, building stone can suffer more severe changes, which can develop into a progressive deterioration coupled with a serious loss of aesthetic qualities.

Stone is a geological material originating under different environmental conditions of pressure-temperature and physical-chemical equilibrium different than in buildings. In the same way that in nature a rock mass suffers changes in contact with other material, in building there are interchanges and alteration when in contact with other materials.

It is under these conditions that the study of the durability of rock materials, the deterioration processes, the methods and the products of conservation and the experimental work on the future behaviour of systems stone treatment acquire special importance.

8.2. CHARACTERISATION OF ROCK MATERIALS AND INTRINSIC PARAMETERS THAT CONTROL DURABILITY.

Factors that hinder the straightforward characterization of rock materials include the presence of discontinuities and anisotropies, the normally poly-phase nature of rocks and their inhomogeneities. It is, therefore, very difficult to apply the principles of materials science to rocks, especially where the petrophysical interpretation of the results of alteration studies is concerned.

From the petrophysical point of view, the essential pretrographical components that characterise a rock and allow interpretation of its physical properties are texture and mineralogy. With regard to the deterioration and durability of rock materials, the importance of voids as textural components must be emphasized, and the three dimensional form of the pore system must be analysed. This analysis provides understanding of the degree of connectivity of the microfissures and the pore channels, the pore throat radii, the localisation of pores in relation to mineral components, etc.

These characteristics control the circulation of fluids (principally water) through the rock and consequently, a whole series of hydraulic properties, which, in turn, control the processes of alteration and physical and chemical decay of the rock. A clear relation can be recognized between the chemical alteration of the rock, the mean grain size, and the associated inter-granular porosity. Other important textural characteristics are those that relate to the rock components spatially, such as the grain boundaries, the type of cement, or matrix, the presence of textural granulometric anisotropies, etc. The nature of grain boundaries controls applicability and durability of building stone, rocks being classified petrophysically as either crystalline or cement. Both rock types have very different physical properties, cemented rocks showing greater variations in the values of key parameters and suffering greater alteration.

On other hand, the physical properties of the different stone types present in a building must be evaluated and interpreted petrographically as an essential prerequisite for assessing the diverse alteration processes talking place. Each of the key rock properties and the corresponding method or standard test recommended for its determination is briefly described bellow:

a. Properties which characterise the appearance and physical nature of rock materials: colour, density of mineral grains, apparent density of dry rock, porosity, by means of mercury porosimetry injection techniques, and approximation to the pore system can be obtained.

b. Properties which characterise the circulation of fluids through the pore system of the stone (hydraulic properties); Absorption and desorption of water, absorption and evaporation velocity, capillary suction, permeability to water vapour, expansion due to water uptake, etc.

c. Properties that characterise the deformation behaviour (uniaxial compressive strength, elastic module, specific heat, thermal expansion, etc.

It is dangerous to generalise and devise fixed behaviour models for the diverse rock types (limestones, sandstones, marbles, granites, etc) given that the physical properties can vary as their clearly do. For the correct interpretation of the various alteration processes that occur, it is, therefore, necessary to determine for each case at least the fundamental physical properties.

The determination of key physical properties is also necessary in the field of stone conservation in order to establish recommendations for treatment, since the effectiveness of many conservation procedures, such as cleaning, consolidation or hydrofuging, is controlled to a large extent by these properties.

8.3. DECAY

The durability of building rock depends on the nature of weathering agents (Bell, 1993). One of the factors that influence the nature of the weathering is the climatic conditions, other is the environment (urban, rural, coastal or inland), and another the degree of exposure of a stone in a building.

8.3.1. Nature of the ornamental rock. Lithological influence

Carbonatic rocks

Deterioration of carbonatic rock is influenced mainly by dissolution, salt crystallization and freeze-thaw activity (Bell, 1993). The pH has a strong influence in carbonatic rock weathering, thus, for example, a direct relationship between the amount of rainfall and its pH value an the degree of surface recession. Nevertheless, damage due to crystallization of salts is more significant in terms of stone decay.

Sulphur dioxide is one of the major pollutants in the atmosphere and can have influence in deterioration, mainly in sulphatation process. This is produced by change of atmospheric sulphur dioxide (or of sulphur which is oxidized in atmospheric conditions to sulphur dioxide) to sulphuric acid (very rarely thought sulphidric acid), under the reaction:

$$2SO_2 + O_2 \leftrightarrow 2SO$$

and in humid conditions

$$SO_3 + H_2O \leftrightarrow H_2SO_4$$

The reaction with calcite is:

$$\underset{calcite}{CaCO_3} + H_2SO_4 \leftrightarrow \underset{anhydrite}{CaSO_4} + CO_2\uparrow + H_2O \xleftrightarrow{+H_2O} \underset{gypsum}{CaSO_4{\cdot}2H_2O}$$

The acidification of water by carbonic acid, can be enough to dissolve calcite, following the reaction:

$$\underset{calcite}{CaCO_3} + \underset{carbonic\cdot acid}{H_2CO_3} \leftrightarrow \underset{calcium\cdot bicarbonate}{Ca(HCO_3)_2} \leftrightarrow Ca^{2+} + HCO_3^-$$

This reaction is moved toward the right by formation of carbonic acid, which is influenced by organic matter activity and humidity:

$$H_2O + CO_2 \leftrightarrow H_2CO_3$$

Calcite migration is a typical pathology in calcarenites and sandtones with calcitic cement in building structural rocks. Precipitation on the surface creates an apparent resistance, although, - on the contrary- it is a diagnosis of internal mechanical weakness. In the epresence of pyrite the alteration can be very crucial due to formation of sulphidric and sulphuric acid.

Frost effect in carbonatic rock tends to be confined to those with pore sizes <5 μm and the effects are most notable in those climatic regimes where temperatures frequently move above and below the freeze point of water.

Granites

Deterioration on granite is very influenced by hydrolysis, thermal changes and oxidations. Acid conditions can affect punctually if there are organic activity on the surface. In that situation, water can have values of pH<4, and ca be produced dissolutions of silicates.

In granite, alteration has an associated losing of hydrolysed minerals and oxidised minerals. Minerals as feldspars, micas and chlorites, even amphibole, the resultant minerals are smectites, kaolin, opal and iron oxides and hydroxides. In this way, alterability in granites follows the inverse of the Bowen reaction series:

Discontinuous series of alterability:

Olivine>Pyroxene>Amphibole>Biotite>Orthoclase>Muscovite>Quartz

Continuous sequence of alterability:

Calcium feldspars>calcium-alkaline flds>alkaline feldspars>Orthoclase>Muscovite>Quartz

Chemically, there is a migration and an impoverishment of Na, Mg, Ca, K, Sr, and an enrichment of Fe, Al, Ti (Molina, 1993).

Other detected phenomena in granite are the oxidation from Fe^{2+} to Fe^{3+}, with a migration and destruction of its crystalline structure, mainly in biotites, but also in other many ferric minerals.

Due to high variations in dilatation coefficients between quartz and the other components, the effect in environments with high and fast temperature variations is very evident. In this way, can be spectacular the granite alteration after a fire in a building.

Sandstones

Weathering in sandstone depends of the mineralogical composition and cement. In that way, in siliciclastic sandstone with silica cement freeze-thaw and thermal shock will be the main risk. If cement is calcitic, thermal shock is less important and the pH effect is more important. In calcarenites the behaviour is similar to other carbonatic rock. As porosity of sandstones is, commonly, very high, weathering is more evident. It is due to higher surface contact with the external environment, as well as due to increased vulnerability to salt crystallizations.

Slates

Deterioration in slates is very commonly associated to freeze-thaw, thermal shock and sulphides oxidation. Water can be easily introduced within the foliation and, as it is a mechanical weak plane, it can produce a flake off effect. Thermal shock has also a similar effect, due to the differences of dilatation between surface and internal part of the slate, or in other words, different dilatation coefficient between the external side of the foliation plane and the internal side.

Sulphide oxidation has one of the more common and negative effects in slate, not only because of the originating iron oxides, but also because of volume change during oxidation process. The reaction can be expressed as:

$$2FeS_2 + 3H_2O \leftrightarrow 2SH_2 + Fe_2O_3$$

As sulphidric (that changes to sulphuric in short time) is a strong acid, the alteration is locally intense, even with partial dissolution of quartz.

8.3.2. Interphase Boundary phenomena

Main variations take place in the interface between materials (e.g. skarn formations) in the same way as in the geological behaviour of rocks. The contact between different materials can be:

- **Rock-rock**. It can be important when there are different lithologies in contact, where oxidation or alteration can give a new alteration zone in the interface. This is, for example, the case of interface of acid-basic, metamorphic-sedimentary, organic rich-carbonatic rock types, of oxidised compounds domain-reduced compounds domain, and between others.

- **Rock-mortar**. One of the more evident examples is the contact between Portland cement based mortar and volcanic rocks and, in general, any rock with amorphous silica or heulandite type zeolites. An alkali-rock reaction is produced in this case, which can be summarised as follows:

$$\underset{\substack{amorphous\\silica}}{SiO_2} + \underset{soda}{NaOH} + \underset{portlandite}{Ca(OH)_2} \longrightarrow \underset{hydrated-alkaline-silicates}{n_1Na_2O \cdot n_2CaO \cdot n_3SiO_2 \cdot n_4H_2O}$$

Other examples may occur by de-dolomitisation of dolomitic rock by interaction with alkali from Portland cement. In this case the reaction is as follows:

$$\underset{dolomite}{(CO_3)CaMg} + 2\underset{soda}{NaOH} + \longrightarrow \underset{brucite}{Mg(OH)} + \underset{calcite}{CO_3Ca} + CO_3Na_2$$

- Rock-ceramic. Depending on the ceramic type, some interaction with alkaline rocks can be detected.
- Rock-soil. When rock is placed in contact with soil of very different nature, an important interaction can result (e.g. limestone in organic kaolinitic soil, or basalt with alkaline an carbonatic rich soil). Reactivity is normally increased by humidity effect and salts migrations.
- Rock-metal. Metal is commonly used in construction in combination with stone. Mainly iron, steel, aluminium (aluminium-nickel), or lead are used depending on the age and style of the construction. Chemical changes can be observed in this case during the oxidation processes (Eh and pH variations) as well as ion diffusions effects. Particularly important are resulting differences in the thermal conductivity, dilatation coefficient and electrostatic charge.
- Rock-wood. In some cases, wood can have interactions with stone, mainly if it is coated (Figure 29)

Figure 29 Example of an interaction between wood and rock in a building. Coatings from wood provide a higher pH, humidity concentration and reactions in contact.

8.3.3. Environmental effect

The emplacement of the rock in a new environment from quarry to building can increase dramatically the vulnerability to alteration. Generally, the principal agents of deterioration are: moisture, soluble salts and atmospheric pollutants.

Water

Water is, itself, one of the most important agents of alteration, and serves to facilitate the deteriorating action of others agents. The effects or damages caused by water (moisture) in its various forms (vapour, liquid and ice) are basically of two types: chemical and physical (mechanical). As a chemical agent, water participates in the principal processes that affect rocks (e.g. carbonate dissolution, hydrolysis of silicates, oxidation-reduction reactions, hydration, etc) In terms of mechanical deterioration, the freezing of water held in the pores building stones procedures an increase in volume (about nine times). Frost damage occurs only in those features of a building that are frequently frozen whilst very wet. Frost may provide the 'last straw' that dislodges pieces of stone already loosened by some other means but this is readily distinguishable from the spectacular cracking that occurs when frost is the sole cause of the damage. As with salt crystallisation damage, the susceptibility of a stone to frost damage is governed by its pore structure. This is partly because the pore structure governs the natural degree of saturation and partly because it governs the magnitude of the stresses that can be generated upon freezing. After repeated freeze-thaw cycles, this can cause remarkable physical damage to the stone.

Soluble salts

In the sort term, building stone tend to be affected by presence of aqueous solutions containing soluble salts of a diverse nature (principally sulphates, nitrates and chlorides of calcium, sodium, potassium and magnesium) These salts can be party of the original composition of the rock material (e.g. gypsumin marls or limestones); or introduced from soils or other construction materials (e.g. mortars) or produced by the interaction petrographic minerals with atmospheric minerals with atmospheric pollutants or marine aerosols. Soluble salts cause efflorescences or cryptoflorescences when they crystallise on or close to the surface deposit, more or less compacted. When salts crystallise within the pores of a stone, stresses may be generated that are sufficiently large to cause local fragmentation of stone. This process is the major cause of stone decay. The salts may get into the stone in a number of ways, one of the more important being the ultimate production of calcium sulphate by the reaction of limestones with sulphur dioxide dissolved in rainwater – this can lead to two types of decay. In the features of a limestone building that is frequently wetted by rain, the repeated crystallisation of the calcium sulphate dislodges particles of stone which are subsequently washed off, together with the calcium sulphate during very heavy rainfall and the surface of the stone therefore erodes gradually. In more sheltered parts the calcium sulphate remains in position to form a hard and often dirty skin. With certain types of stone this skin eventually blisters to reveal an underlying layer of crumbling debris. The calcium sulphate that is washed out of limestones may cause crystallisation damage to other building materials that can absorb the contaminated rain washings. Washing containing magnesium limestones may also cause damage. For this reason limestone should not be used in association with sandstone or brickwork in such a way that sulphates from the limestone may be picked up. Other common sources of salts include groundwater, sea spray and unsuitable cleaning materials. Crystallisation damage caused by freely soluble salts such as sodium chloride, sodium sulphate or sodium hydroxide normally consists of a powdering and crumbling of the entire surface of the contaminated stone. Some stones are virtually immune to crystallisation damage whereas others are liable to quite rapid decay. Resistance is strongly dependent on the internal structure of the stone and its overall resistance increases directly in proportion to the decrease in the fine pores. The removal of stone by wind-borne particles occurs only in exceptional circumstances, if at all, and most instances of decay attributed to wind erosion are probably due to the crystallisation of salts. Any increase in the rate of decay in areas that are severely exposed to wind is due to an accumulation of salts and a higher frequency of crystallisation cycles.

Atmospheric pollutants

It is well known that lime-based materials such as travertine are attacked by pollutants brought to the stone surface by air (in gaseous and/or aerosol form) or by water (acid rain). The most aggressive of these species are sulphur dioxide, nitrogen oxides and organic particulates, which originate mainly from the combustion of hydrocarbons (vehicular traffic, domestic heating, industrial activities). Before starting restoration, it is crucial to make a correct diagnosis of the deterioration state. Also in the case of a monument, a detailed knowledge of the state of the materials, at both superficial and bulk level, is extremely important in order to choose the most appropriate technologies for restoration.

The aggressiveness of water as an agent of chemical alteration can be enhanced by the presence the atmospheric pollutants. Among the pollutants affecting, directly or indirectly, the durability of building stone, are carbon and nitrogen oxides and sulphur compounds, many of which are anthropogenic origin (mainly derived from the combustion of fossil fuels). In the presence of moisture, these substances attack rock components, producing soluble salts, the harmful effects of which have already been mentioned. It is in urban and industrial areas, in which the highest levels of pollution have been reached in recent decades that the deterioration of rocks materials has been found to be most accelerated, though the effects of these substances can also extend into rural areas in the form of acid rain.

Other agents and mechanisms

In addition to those already described, building stones are exposed to other mechanisms of deterioration. Our understanding of the interaction between biological agents and stone materials has increased greatly in the last three decades. This is due to a systematic multidisciplinary approach to the study of stone deterioration.

Biodeterioration which refers to undesirable changes in a material caused by living organisms—is a complex phenomenon that occurs in conjunction with other causes of decay. The alteration of stone monuments and sculptures by living organisms usually is indicative of an advanced state of deterioration—but because the phenomenology of this decay is similar to other physical and chemical causes, it has not been possible to distinguish the extent of decay caused by biological agents from decay caused by physical and chemical processes. Although the effects of environmental factors are widely recognized, significant debate continues among conservators about biological processes' contribution to stone deterioration. It is obvious that higher plants cause significant destruction to monuments and their structural stability. Damage caused by micro-organisms, on the other hand, is not yet clearly defined or understood. Biodeterioration research has focused chiefly on bacteria, algae, fungi and lichens; mosses and liverworts have received comparatively less attention because their impact on stone has been considered primarily aesthetic. The action of bacteria on stone substrates is rather unclear. Large bacterial populations have been detected on weathered stone surfaces, whereas they are only minimally present on unweathered stone surfaces. It is, however, difficult to evaluate whether such observations indicate that bacteria are primarily responsible for stone decay or whether weathered surfaces merely provide a more suitable habitat for bacterial growth. Considerable ambiguities also persist in studies on stone deterioration by cyanobacteria and algae: The only thing that is clear is that these organisms cause discolouration of stone surfaces. Stone deterioration due to fungi largely depends on the production of corrosive metabolites that can solubilize minerals in a manner similar to other chemical processes. The role of acids produced by fungi isolated from stone monuments has been demonstrated in the laboratory. However, low frequency isolation cannot be directly correlated with metabolic activities as the fungi isolated in culture media may be dormant and not necessarily the ones functioning in the ecosystem. The contribution of lichens in stone degradation is fairly well established. They cause chemical damage through the production of biogenic acids and physical damage through the penetration of their rhizine/hyphae into stone fissures.

Most microorganisms involved in bio-decay of monuments produce organic acids, which have been discussed in the scientific literature as a permanent cause of biodeterioration. However, their suggested role has not been proven conclusively. There is an apparent lack of research to assess the susceptibility of a wide range of stone types to microbial deterioration. In instances where several types of microorganisms are present, it is difficult to assess to what extent each one is detrimental to the stone. Also, for all microorganisms the quantitative aspect has been the primary basis for evaluating their importance in the biodeterioration processes. But the level of the normal environmental biological populations above which these microorganisms could become pathogenic for stone monuments is yet to be established in the field. It is clear that further research is required to fully understand the extent and the role of these metabolites. Another important question is the interaction between microorganisms and air pollutants such as sulfur dioxide, nitrogen oxides and particulate matters, and their combined contributing role, if any, in the bio-decay of stone. Several accounts of biocidal treatments are available. Some have been based on cultures in the laboratory, but most have been based on field trials. There is a lack of published information on their relative effectiveness over an extended period. Periodic qualitative and quantitative monitoring has not been considered vital in assessing the efficacy of biocides on substrata. In practice, visual observations of the appearance of microorganisms on monuments have been the sole method for evaluating the long-term effectiveness of biocides. Biocides for treating cultural properties usually are selected for their apparent successful use elsewhere on different materials, their availability and their affordability.

Most of the evaluation tests have been based on trial-and-error in the field. Attention has not been given to identifying appropriate biocides based on their molecular structural-activity relationship properties. Product testing currently relies heavily on information provided by the manufacturers, and there is a great need for thorough independent study of compounds considered for use as biocides. Such research may eliminate inappropriate selection of biocides for testing or use. Most research on biocides has focused on eliminating algae, lichens, fungi, mosses, liverworts and higher plants. Despite the extensive work on the role of bacteria in stone decay, relatively little research has been conducted on antibacterial treatments for stone. Possible antibacterial treatments need further research. A good residual biocide that would deposit a long-term reservoir of the appropriate chemical in and on the stone substrate has not been identified. Research is required to identify such systems within the established criteria of biocides selection for combating the biodeterioration of stone monuments and sculpture. For example, in areas of heavy rainfall, the development of effective residual compounds such as copper- and zinc-based biocides could be very useful. This would limit the possibility of biocide loss, thereby prolonging the time between re-applications. No biocide has been found that is uniformly effective on all organisms and on all stone substrates. Further research is needed on biocidal treatments on different stone substrates within the framework of other conservation treatments in order to avoid interaction with conservation materials prior or subsequent to biocide application. The use of biocidal solutions may introduce chemicals into the substrate that can result in formation of soluble salts and initiate salt crystallization damage. Recent studies indicate that the materials commonly used for water-repellent treatments or stone consolidation may increase the potential for biological growth by providing nutrients for microorganisms. This possibility also needs to be considered in studying biocides.

Little effort has been made to investigate the merits of traditional techniques, such as using natural products for their biocidal properties. In tropical environments this may prove to be a more viable and cost-effective solution than the use of expensive chemicals and synthetic products that may be toxic to humans and hazardous to the environment. Many of the works published to date are largely empirical in nature and have yet to be adequately substantiated by long-term experimentation.

Biodeterioration research demands an interdisciplinary approach, and the outcome of the study must have field applications. This does not imply that long-term strategic and fundamental research should be discouraged, but that such work ultimately must contribute to the care and preservation of our stone-built cultural heritage.

The biological action of certain living organisms (bacteria, algae, fungi, lichens, etc), by means, above all, of the chemical substances produce (e.g. organic acids), sometimes assists in the physico-chemical deterioration of rocks materials. The presence of organisms in building stone does not always causes damage, however, apart from aesthetic considerations. Others agents can promote or facilitate deterioration include: Aeolian erosion (abrasion), thermal cycling and the release of internal stress, external loading and vibration and not to be forgotten, human activity.

8.4. Decay diagnosis techniques

8.4.1. Diagnosis techniques

Petrographic microscopy is a very powerful and versatile tool in evaluation of rock alteration and detection or mechanical weak surfaces (Figure 31). The main information provided using microscope are as follows:

Porous system: evolution and characteristics of the porous system, such as, dissolutions, migrations or joints evolution.

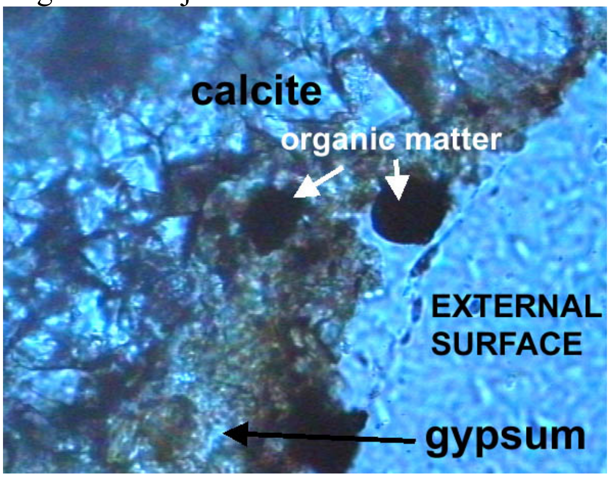


Figure 30. Gypsum growth near surface and organic matter precipitation on a travertine. Thin section. Palau Generalitat, Valencia, Spain. Transmitter light (after Lopez Buendia, 2002)

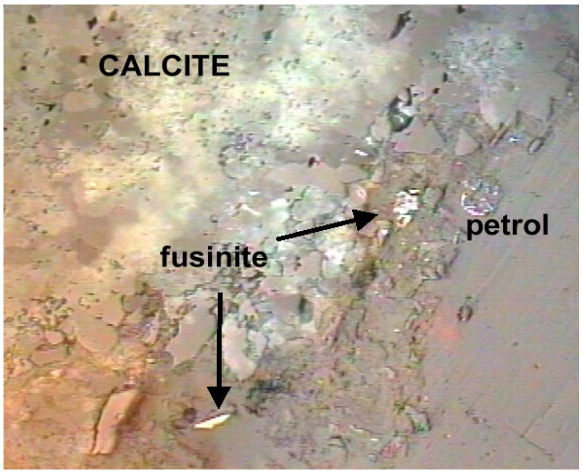


Figure 31 High intensity reflection of organic matter near suface. Fusinte maceral of fired organic matter and petrol detection. Polished thin section. Same sample than previous Reflected light POL parallel, with lateral filter. Palau Generalitat, Valencia, Spain

Alteration of components: recrystalisation (p.e. change of dolomite to calcite, pheldspar alteration to kaolinite, amphibolite to sericite, pyrite to iron oxides), intercrystal contact, grain-cement contact.

Secondary neo-formed phases: alteration phases, as salts (p.e. gypsum, epsomite, calcite, nitratine) and clays (p.e. kaolinite, sericite).

Pollutant precipitation (Figure 30): is the example of oil, charcoal, other fired organic matter, lichen than growth in situ. Petrographic microscope is the better tool to detect and evaluate the distribution of the organic matter as well as to determine its alteration influence.

8.4.2. Scanning electronic microscopy (SEM) Diagnosis techniques

SEM is very practical tool for small crystal identification (combined with EDX) and contact structures. With use of ESEM (environmental SEM) is possible to simulate alteration with observation in situ (Doehne, 1993). Full Emission SEM (FESEM) provides high definition images for rock alterations (Figures 32, 33, 34, 35).

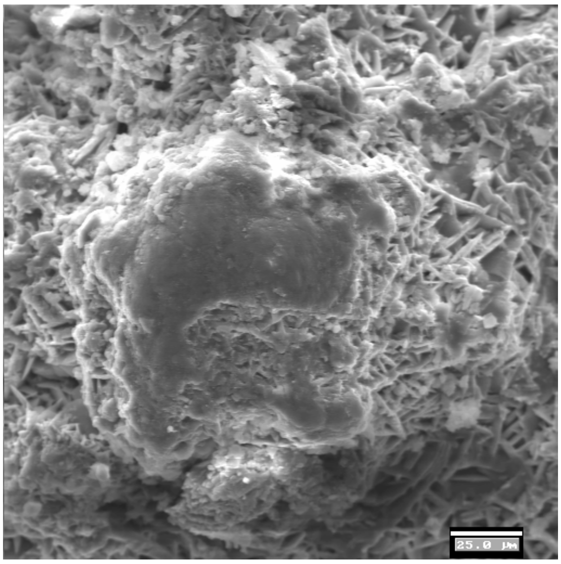


Figure 32. Organic matter by lichens on a black crust. It is formed over a travertine rock. Palau de la Generalitat, Valencia, Spain. FE-SEM (after Lopez-Buendia, 2002)

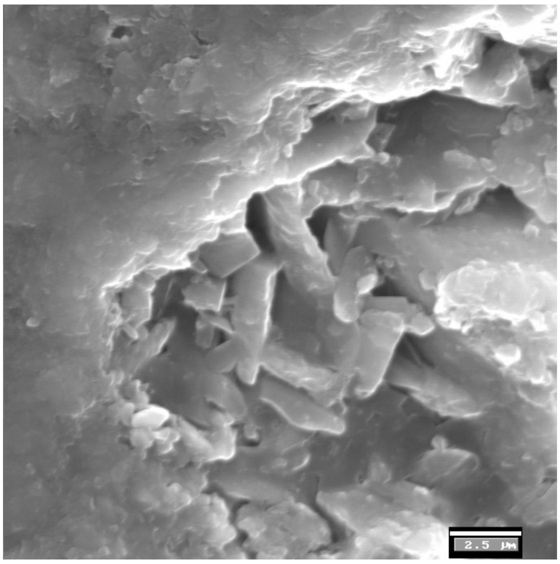


Figure 33. Detail of the previous figure showing contact within organic matter (left) and gypsum crystals (right)

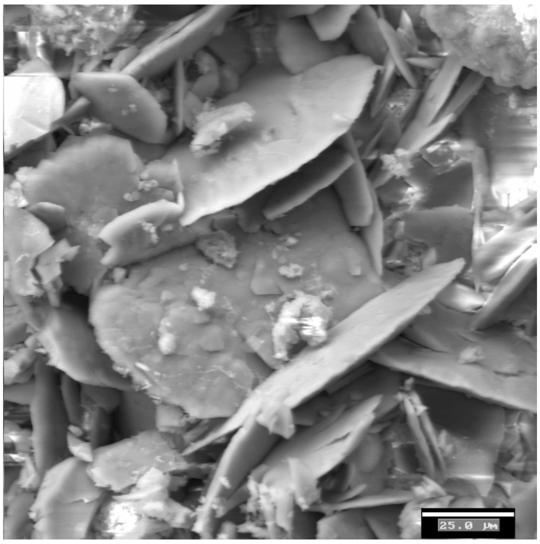


Figure 34. Gypsum growing in a multilayer gypsum-gypsum/calcite-calcite crust. PG, Valencia, Spain (after Lopez-Buendia, 2002)

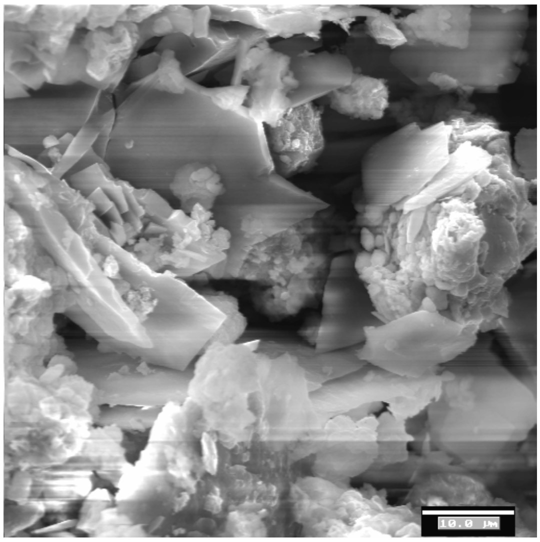


Figure 35. Calcite and gypsum inter-growing in a multilayer gypsum-gypsum/calcite-calcite crust. Same sample than previous one.

8.4.3. X-ray diffraction Diagnosis techniques

Method of powder diffraction in disoriented preparation and oriented aggregates is a basic tool for crystalline phases identification. It is very useful in bulk rock or in efflorescences. The technique need very small sample and provide precise information for crystalline phases.

8.4.4. Non-destructive techniques

The importance of the non-invasive techniques in the evaluation of rock alteration is obvious, mainly if the subject is the art heritage. Georadar (GPR), ultrasonic wavelength and electric current are very widely used techniques in building rocks. Among them the georadar is more commonly used for structural proposed than alteration itself. Electric methods can be used for deep alteration and also as humidimeter.

The ultrasonic wavelength is a powerful tool to detect the alteration. It can be used through three methods:

Through-Transmission system. It needs two transducers and good accessibility by two faces of the stone (Figure 36).

Pulse-Echo system. Only one transducer is needed, but it has the limitation of penetration and transitory effect.

Impact method. It is powerful system for global evaluation and can be also used for ultrasonic velocity.

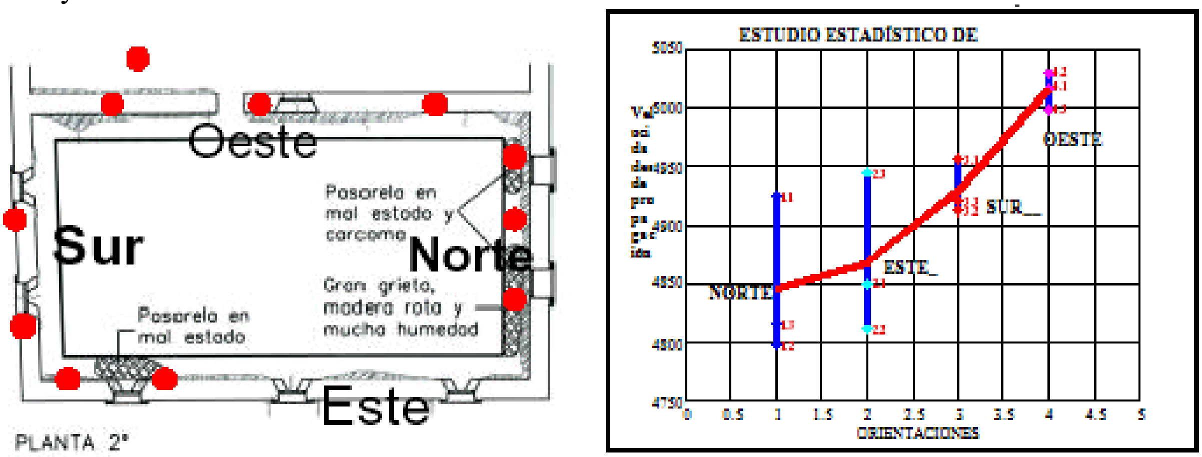


Figure 36. Variation of ultrasonic propagation velocity in three orientation of the building tower, using pulse-echo method. Wall is 75 cm thick. North façade has the lower velocity. East façade has also low velocities due to sea wind. South façade shows higher velocities with lower pollutant, humidity and wind influence. (after Fuente et al. 2002).

8.4.5. Hydric properties

Water migration behaviour is fundamental for rock alterability diagnosis, it is due to most of the changes are in relation with water intervention by direct reaction or as a media for dissolved gas and ions transport.

The more useful tests are: water absortion under vacuum, free water absortion, capilar suction, free water desortion, and water vapour capillarity.

8.4.6. Quasy-non destructive techniques.

Penetrometers are used tools when it want to studied the internal alteration. From the penetrometers, may be the more powerful and useful is the microdrilling.

Microdrilling give information of Drilling Resistance, which is related to mechanical properties of the rock and, subsequently, to alteration. Accuracy of this method is near 2-3 mm, and can be useful for sub-superficial alterations (Figure 37).

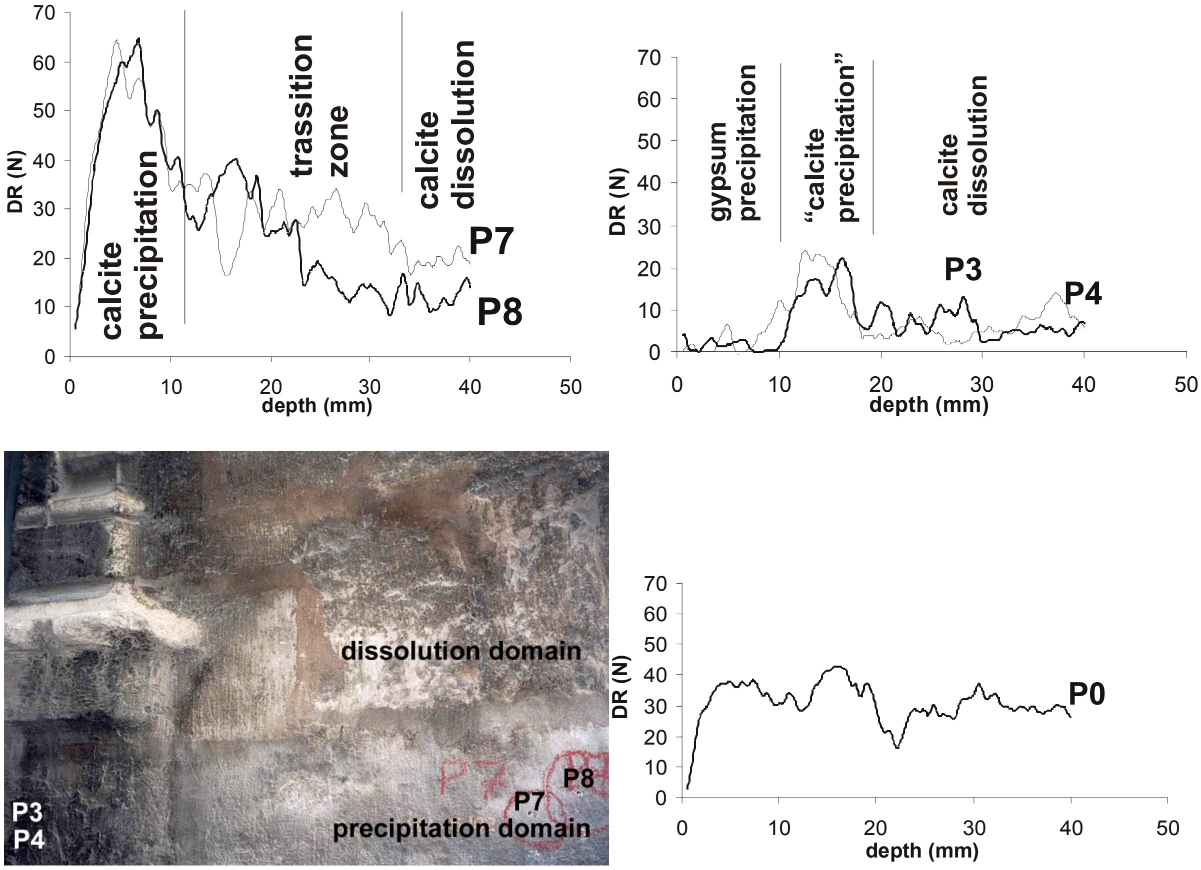


Figure 37. Calcite migration in a structural travertine (external). It is very frequent the calcite migration from internal dissolution to external precipitation, P7 and P8. When there are some gypsum mortar, gypsum have longer migration and is precipitated with preference in higher humidity, P3 and P4. P7 and P8, Drilling Resistance (DR) signature in calcitic surface. P2 and P3, DR signature in gypsum-organic matter-calcitic surface with second internal surface (1-2 cm depth) of calcite. P0, DR in a sound (non-altered) travertine. (after Lopez Buendia et al. 2002).

8.5. CONSERVATION

In the conservation of stones in buildings, it is convenient to focus upon two different aspects of the work: firstly the prevention of damage, in the which measures are taken more in the environment than on the stone itself; and secondly remedial action on the stone, in which cleaning, consolidation, protection, substitution and replacement are the possible steps to be undertaken, according to the type and degree the deterioration.

In practice, when the conservation work is undertaken, both preventive and remedial measures must be considered, as the future durability of the stone after carrying out conservation work is much better assured if the effects of external factors are minimised or controlled.

Reading the scientific work being carried out in the field of conservation of monumental stone, many investigations are currently underway, each studying various different aspects in depth. Many publications have analysed environmental factors and their role in the deterioration stone. The bibliography covering specific aspects of environment pollution is also quite extensive.

With regard to conservation measures, which involve remedial action on the roc itself, it must be recognised that stone, as a building material, forms only part of a structure, each block being fixed to its neighbours by a mortar or cement. There must, therefore, be an integrated approach to treating the stone, the mortar and the entire building of which they form part. To this end, an understanding of the petrophysical characteristic of the materials to be treated, of the type and degree of deterioration, of the nature and physique-chemical characteristics of the alteration products, of the fundamental role of soluble salts, and of the incidence of biodeterioration, etc.

In the same way, the characteristics of the building itself, that have influence the deterioration of blocks and mortars must be taken into account: problems related to the water table, the distribution of moisture in the walls of the building etc; structural faults, including cracks caused by uneven distribution loads, tie bars etc.; not forgetting the different types of quarry finish applied to block surfaces and the location of the blocks building. All of these aspects, which form part of the diagnostic phase conservation, are essential both in deciding which stages of conservation work should be applied (substitution, treatment or replacement), and which procedures, methods or products are most suitable for the treatment of the altered stone.

8.5.1. Stages of Intervention

Cleaning

Cleaning of stonework is normally undertaken in order to remove damaging crust, deposits and patinas. Prior to any cleaning procedure, and in order to select the most appropriate method, a number of factors must be considered in relation to the artistic value of the object, the nature of the stone and the type of alteration products to be removed. The different cleaning techniques available tends to the based upon the application of water, mechanical procedures, chemical solvents, organic solvents, special clays, heat, ultrasonic techniques, etc. The need to clean a building is commonly perceived as being critical for its well being. Such a physical act is driven by aesthetic considerations often without considering the after-effects or consequences properly. The decision is also frequently made on townscape or streetscape grounds regardless of the physical impact on the actual face of the structure.

Until relatively recently, cleaning methods generally lacked proper specification and site control. This has resulted in a wide variety of techniques being offered by contractors without due regard to the full consequences of their effect, and usually little or no detailed consideration was shown by manufacturers or suppliers to this need. In attempting to deal with all types of dirt and surface coatings in one treatment, contractors and specifies catered for worst-case scenarios, and over-treatment was the established norm.

In particular, insufficient consideration was given to the wide range of natural materials being dealt with and their relative susceptibility to deteriorate as a result. No building is homogeneous in its construction or detail. Materials such as sandstone, limestone, granite, brick and terracotta are liable to be bound by lime mortar. Some may be used in combination, and other factors such as variations in colour, texture, tooling and form are likely to be met. In many, the composition will vary, and different combinations can lead to the interaction of materials, one with the other. Decay may also be present and different patch repairs, with different substances at different times, may further complicate the issue.A basic difficulty is deciding where to stop. This can lead to a form of facadism, with only the principal elevation being treated. However, this approach has one advantageous side effect: any change that subsequently reveals itself can be compared against the untreated return faces of the same stones at the extremity of the cleaned area.

The type of soiling also needs to be taken into account. In the cleaning debate, soiling is often pre-supposed only to be an external agent, with particulate deposition and reaction resulting from either wet or dry conditions. Damaging crust-formation can be evident on the surface limestone, but the prospect of benign mineral movement occurring from within the body of sandstone is rarely considered.

Biological surface soiling is equally complex, with bacteria, algae, fungi and lichens each seeking out the appropriate colonisation conditions within which they will flourish. Influencing factors in their growth can include atmospheric and micro-climatic conditions, fluid movement and concentrations, surface roughness and physical changes.

Once the building has been cleaned, incidents of resoiling, iron mobilisation, efflorescence, vandalism and graffiti further complicate matters. Two fundamental methods of cleaning buildings have habitually been adopted, although a number of specialised techniques have become available in recent years:

- Physical methods: these include brushing and rubbing, washing and steaming, wet and dry abrasives, or surface redressing.
- Chemical methods: applied as liquids or poultices, these may employ the use of alkaline treatments, acidic treatments or organic solvents, singly or in combination.
- Special techniques may promote the use of impregnated sponge, laser technology, ultrasonic equipment, heat lances, gypsum inversion, bacteria, poultices or gels, and surfactants (degreasants or soaps).

Not all treatments are appropriate for all materials, and extreme care needs to be exercised when deciding which system to adopt. Due to the need to minimise the risk of damage, the 'do not clean option' should also be borne in mind.

The decision to clean an historic building is not one which should be made lightly, as cleaning can have significant physical and visual results. A period of detailed investigation must be undertaken to determine whether cleaning should be undertaken and, if so, the details of how this should be done. The nature and condition of all substrates must be understood, not forgetting pointing materials, as must the soiling to be removed. The latter may include atmospheric soiling, paint, limewash, metallic staining, anti-pigeon gel and graffiti. Each can require a different cleaning approach or at least modifications to the system selected for use elsewhere.

Every cleaning system can be used correctly or incorrectly. Poor cleaning should not be blamed on poor application alone, as it is often the result of incorrect selection of a process. Glossy trade literature is no guarantee of correct selection. The design of a cleaning regime for an historic building is often deceptively complex, requiring specialist professional input.

The purpose of cleaning is to remove soiling, often a source of long-term deterioration to masonry, while causing little or no disruption of the masonry beneath. This can be difficult to achieve due to the intimate relationship between the stone and its soiling, as the soiling can be embedded deeply in between the surface particles.

Several published sources now exist which outline the basic constituents of various historic masonry materials and the susceptibilities of these to selective cleaning procedures. Previous experience must also come into play in assessing surface conditions and characteristics particular to the job at hand. The basic principles of any cleaning process must be determined if it is to be considered for use. Works should be undertaken by skilled supervisors and operatives from specialist masonry firms experienced in the cleaning of historic masonry.

Determining the actual testing methodology, and the validity of trial area results, can be an elaborate process if it is to be carried out effectively and meaningfully. Topics that should be considered include colour measurements, depth profiling, surface roughness tests, and the use of scanning electron microscopy, determining the petrology (the geological structure of the stone) and pH values, porosity and permeability measurements, before and after test cleaning. Care needs to be exercised when contemplating the consequences of washing chemicals into underlying masonry during rinse-off stages, and the question of how to stop 'wash-in' occurring on porous stone surfaces when 'washing off' chemicals should also be addressed.

Reporting and recording the consequences of tests should lead to a full analysis of results before writing a relevant specification and obtaining statutory consents (if required). Risks may also be reduced by carefully selecting an experienced and suitable contractor; by determining the training and experience of site operatives; by ensuring effective site controls and health and safety precautions; and by the maintenance of adequate site progress records.

Stone cleaning is a complex issue. In the past it has been undertaken without sufficient consideration being given to the consequences. As a result, an incalculable amount of permanent damage has been caused to the country's building stock. How well this point is accepted greatly depends upon the perceived value of carrying out cleaning in the first place. For those committed to broader planning and social benefits, it is possible that no amount of evidence will shake the belief that cleaning is for the overall benefit of a building and its surroundings.

Unfortunately, the health of a building is not determined by an appearance that might be viewed from a distance, or across the street, but by what is happening on the actual surface itself. The appropriate course of action must be driven by establishing what can be accepted at this level, bearing in mind the long-term affects on the appearance of the building and its surroundings, not just the short-term benefits. The adoption of a damage-limitation approach should also influence the final choice of mechanism or technique.

With a greater awareness of the issues now to hand, there should be no excuse for inarticulate decision-making or specifying. There can be no standard answer offered as to what the most relevant technique might be. All involved must share in the responsibility of getting it right.

The dirt on the stone material appears as a persistent layer and of more or less regular thickness where the products of distinct types are mixed without distinction. Carbonell de Massy distinguishes between the following products:

Smoke and dust

Particles formed by ash, solid oils that are not burnt and proceeding from the erosion of solid materials.

Spots

Florescence, areas of colour loss, spots due to dissolution of metallic structure elements, to sprays and paints, etc. Substances of biological origin: vegetation and micro fauna.

Crusts and remains of previous treatments

Before the intervention, one has to consider the aspects that will determine the choice of method. These are: The historical-artistic value or interest of the monument and the state of conservation. Factors relative to the rocks: its physical-chemical nature, texture, technical and petro-physical properties and environmental behaviour in the area where it is located. Factors relative to the substance to be eliminated: nature, type, extension, and thickness. Speed of cleaning action, so that the workers can control its effects.

The method used must not generate products damaging to the stone and the worker, neither there should be surface modifications that facilitate its deterioration.

There is no universal cleaning product which exists, for each type of material specific products should be used, causing the minimum desegregation of petreo-material and dissolution of cementing agent (Parrot). We will now go to the main methods of cleaning, we will focus on those mechanisms that are the most well known and frequently used.

Mechanical techniques separate the dirt of the petreo-material to be cleaned employing the mechanical energy that is generated when projecting abrasives. It is very important that the separation takes place right on the interface dirt - surface of the stone.

Sand jet

This method has lost prestige over time because it was used before in an uncontrolled manner and the abrasive particles had angled edges. The mechanical action of the method is a function of:

1. The abrasive particle
   - ✓ Type: pumice stone, aluminium oxide, glass and sand.
   - ✓ Strength: minimum 5 in the Mohs scale.
   - ✓ Form: spheres, hollow or solid
   - ✓ Size: the thinner it is, better penetration and precision.
2. The abrasive jet.
   - ✓ Pressure and density
   - ✓ Application time
   - ✓ Distance between mouth of the jet and the surface to be cleaned.

Micro-jet of sand

Method very similar to the previous one but the particles are of less strength and their size is less than 60 microns, they are normally of glass and aluminium oxides. They are very effective for removing thick and strong incrustations, thin crusts and black crusts that cover stones with polychromes. The main advantage is that the jet pressure and the quantity of abrasive projected can be regulated, thus the cleaning can be regulated and can be used on all types of rocks. An inconvenience is that it is slow, a lot of dust is taken out which has to be collected and the apparatus destined for this end is expensive, and the cost of sand is also high.

Air abrasive cleaning systems are usually considered when soiling is not water-soluble and when, for reasons of site logistics or material incompatibility, chemical processes are inappropriate or less preferable.

All air abrasive techniques operate by directing particles of abrasive onto the soiled masonry in a stream of compressed air. Cleaning is accomplished by impingement of the particles that dislodge or pulverise the surface layer of the masonry. This may be the layer of soiling or the stonework or brickwork to which it is attached. Most systems also involve the use of water, either additional to the air/abrasive stream or combined as slurry with the abrasive. The main effect of the introduction of water is to reduce dust (both dry and wet abrasive systems clean in a similar manner), although the mist produced is still a health hazard.

Air abrasive cleaning techniques are most successful on surfaces of even profile and consistent surface texture and hardness. An air abrasive stream cannot on its own differentiate between the removal of soiling and the removal of masonry. Nor can it distinguish portions of masonry, which are closer to the nozzle from those further away, or areas of masonry that are softer. Damage to the masonry can only be avoided through the skill and ability of the operator to make the necessary adjustments in technique.

Air abrasive cleaning is usually most successful on plain stone surfaces of even hardness. Careful use can enable the technique to be employed on moulded and some carved stone surfaces. However it is difficult to successfully clean brickwork by abrasive means without any damage, due to the many variations in surface texture and hardness that are often present and due to the intolerance of many bricks to its impact. The removal of hard, traditional paints can rarely be achieved successfully from any masonry surface using air abrasives.

In the normal use of abrasive cleaning, two factors are of utmost importance: the velocity and the concentration of the particles that impact on the surfaces. The pressure and volume of the airflow and the concentration of abrasive feed into the line control these parameters. It is therefore not adequate to specify pressure alone. Important parameters will also include the size of the abrasive particle, its shape and its hardness. Commonly available abrasives for facade cleaning include aluminium silicate, calcium silicate, olivine and calcium carbonate. More specialist materials are also available, particularly for pencil abrasive equipment used by conservators. Nozzle shape, nozzle size, rate of water flow and working distance must also be established.

It is usually best to determine the many parameters relating to abrasive cleaning on site when all soiling types, the degree of soiling and masonry conditions can be properly assessed. Specific advice such as recommended pressures and abrasive types cannot be given here as they are only a few of the many variables which must be determined, as already described. However, the following general principles can be applied:

i. Smaller particles of the same abrasive type can be less damaging than larger ones, used in the same manner.
ii. Harder abrasives can be more damaging than softer abrasives of the same size, used in the same manner.
iii. A higher concentration of abrasive particles can be more damaging than a lower concentration, all other factors being equal.
iv. Higher air pressure and volume can be more damaging than lower air pressure and volume, all other factors being equal.
v. A closer working distance between the end of the nozzle and the masonry can be more damaging than a greater one, all other factors being equal.
vi. Depending on how they are used, some small scale abrasive systems can be as or more damaging than larger scale systems.

vii. Differences in technique will be required for plain and carved surfaces, sound and deteriorated conditions.

General recommendations cannot be made in relation to air abrasive cleaning, any more than with any other cleaning approach. Pre-contract on-site trials are always recommended for the cleaning of historic masonry. An experienced professional who can observe and assess the effects of each procedure and produce a detailed specification for the works should oversee these.

Others

Here other simple methods are included, which can be:

- Manual: sandpaper, pumice stone, knife, bronze and phosphorous brushes, glass paper, etc.
- Electric: these are small rotating machines equipped with different points and perfectly controlled.

Pneumatic tools

The efficiency of the method depends on the skill of the worker, and being a slow method it is used for pieces of small dimensions.

Specials

These are techniques, which are still being experimented, and in spite of their effectiveness having been proved, they are not yet easily available. Among the most important ones are, the microwaves, the ultrasound, and the laser, the last one being a technique the use of which is on the rise.

Laser

Cleaning is a critical part of the conservation process. It serves not only to improve the aesthetic appeal of an object or building but also to reveal its true condition so that appropriate action can be taken to ensure that it survives for many future generations to enjoy.

During recent years there has been increasing concern over some of the more conventional methods of cleaning used on sculpture and sculptural decoration on historic buildings. Careless and inappropriate use of techniques, such as air-abrasive and steam cleaning, can lead to severe damage of the underlying stone surface. The loss of surface detail by over thorough cleaning can reduce the visual appeal of a surface and in extreme cases can even lead to its accelerated decay. Even if cleaning is carried out very carefully, techniques such as air-abrasive cleaning will result in some loss of material from a surface, particularly from a decayed crumbling surface, simply because abrasive particles cannot discriminate between the soiling and the stone surface. The removal of black encrustations from limestone sculpture is usually accompanied by removal of the patina, which develops, on the surface over a period of time and within which the original surface relief is preserved. Chemical-based cleaning techniques also have associated problems: chemicals often leave residues within the stone which can cause problems later on and once they have been applied their reaction cannot be suitably controlled. In Glasgow some sandstone buildings, which were chemically cleaned a few years ago, are turning green at an alarming rate since ideal conditions for algae growth have been created on the surface. The development of laser-based techniques during the past few years has been a significant advance in making conservation methods less intrusive and more controllable. The fundamental difference between cleaning with laser radiation and conventional methods is that particles of light, or photons, can discriminate between the soiling and substrate. This allows the conservator to control the level to which the surface is cleaned.

Laser is characterised by its constant intensity, the radiation not being dispersed, the waves coinciding in phase and that it is a monochromatic radiation. Since in each pulse the energy that is liberated is very low and the duration of light rays is very short, the material does not become hot; moreover, the wavelength is such that it propagates on the stone without altering it.

It has resulted as being very effective for pulverising black crusts produced from environmental contamination, liberating them when mechanical micro-resonance is produced on the surface of the stone. In spite of being a method that does no damage to the stone and which can also be used over not consolidated supports, it needs to be used with great care and precaution.

The laser is a unique source of light, providing energy in the form of a very intense, monochromatic (a single colour or wavelength), well-collimated beam (a typical laser beam spreads out only a few millimetres after travelling several metres). When a laser beam interacts with a surface, part of the energy is reflected and the remainder is absorbed (assuming no transmission). The fraction of energy absorbed depends on the wavelength of the laser radiation and on the physical and chemical properties of the surface. A laser beam can have no effect on a surface unless it is at least partially absorbed.

The most common laser used in conservation at the moment is the Q-switched Nd:YAG laser which provides short pulses (typically 5-10 ns long) of near infrared radiation at a wavelength of 1.064 mm (or 1.064 x 10-6 m). These are effectively very short pulses of heat. The short pulse length is important since it prevents heat from being conducted beneath the soiling into the stone surface. This type of laser is commonly used since most soiling layers are much more strongly absorbing than the underlying substrate at 1.064 mm. This means that, provided cleaning is carried out within safe parameters, once the dirt has been removed, further pulses will have no effect on the surface as insufficient energy is absorbed to cause any damage - in other words the process is self-limiting. The Nd:YAG laser is also extremely reliable, easy to maintain, relatively compact and robust.

Commercial laser cleaning systems have become available during the last three years and are now being used by conservation studios across Europe. In a typical system the laser head, power and cooling supplies are housed in a single portable unit, which weighs about 125 kg and runs off a 13A/240V mains supply. In this case the laser beam is directed by means of a 7-jointed articulated arm with the beam emerging through a pen-like hand piece within which a lens is used to produce a diverging beam. The conservator controls the cleaning effect through adjustments to the energy in each pulse, the number of pulses fired per second (repetition rate) and the distance between the tool and the surface (which controls the intensity or spread of the beam). The maximum pulse energy and repetition rate varies between systems and a few systems use an optical fibre rather than an articulated arm to deliver the beam. Most commercial systems are suitable for work either in a studio or out onsite.

The most important cleaning parameter is the energy density, or fluence, of the laser beam that is defined as the energy per unit area incident on the surface (energy per pulse/beam size at the surface) and is usually measured in joules per square centimetre (J/cm2). When working the fluence should be high enough to remove the dirt layers but low enough to ensure that the substrate surface is not damaged. At the Nd:YAG wavelength there is a safe 'working window' within which this can be achieved for a wide range of materials. This is the 'self-limiting' regime of laser cleaning. If the fluence must be raised above the damage threshold of the substrate in order to remove the soiling then the process will not be self-limiting and, as is the way with conventional cleaning methods, the conservator must attempt to stop the process as soon as the soiling has been removed to prevent any damage.

Laser cleaning occurs by a combination of mechanisms, the relative importance of each depending on the fluence used and the properties of the soiling. Since most types of soiling absorb strongly at 1.064 mm, cleaning can usually be carried out at relatively low fluence (<1 J/cm^2) to minimise any risk of damage to the substrate. Strong absorption of energy leads to rapid heating and subsequent expansion of a dirt particle. Since the pulse length is so short the expansion happens so quickly that the resultant forces generated are sufficient to eject the particle from the surface. This is a very selective process. If the fluence is increased slightly then some material will be heated to a sufficiently high temperature to cause vaporisation. At higher fluences still (above approximately 1.5 J/cm^2; values depend on the properties of the soiling) the removal mechanisms become more complex and involve the formation of plasma just above the surface and generation of a shock wave. This mechanism is less selective and can result in damage to the underlying substrate. Cleaning should therefore be carried out at the lowest practical fluence so that the more selective mechanisms operate.

Water can sometimes be used to enhance the cleaning effect. By brushing or spraying a thin coating of water onto the dirt surface immediately prior to irradiation, stubborn deposits of dirt can be removed without having to increase the fluence to unacceptably high levels. Dirt particles become coated with a thin film of water that is also able to penetrate into cracks and pores within the dirt layer. Absorption of the laser beam by the dirt layer occurs as normal and rapid heating at the dirt/water interface leads to explosive vaporisation of the water molecules, which exerts forces on and within the dirt layer sufficient to eject further material from the surface. The addition of water usually increases the cleaning rate significantly.

The main advantages of laser cleaning are:

Selectivity

Provided cleaning is carried out within suitable parameters it is possible to remove layers of dirt without removing any original material from the surface of the object. Such control allows the conservator to select exactly what is removed from a surface and also allows him or her to go back over an area which has already been cleaned to remove remnants of dirt without over-cleaning. The technique is sensitive enough to preserve the surface relief; original tool markings can be uncovered and delicate patinas left intact.

Non-contact

Since energy is delivered in the form of light there is no mechanical contact with the surface. This allows extremely fragile surfaces to be worked on.

Localised action

The laser cleans only where directed. A single laser can supply a beam with a diameter variable between a fraction of a millimetre and one centimetre, allowing the same tool to be used for both extremely precise and relatively large-scale work.

Immediate control and feedback

The cleaning action is instantly halted once the laser is switched off so the conservator can stop the process whenever he or she decides. The condition of the surface can be continuously monitored by the conservator during cleaning, allowing decisions to be made at the earliest possible stage.

Environmental

Laser cleaning generates very small quantities of waste material (of the order 100 g/m^2 for a uniform black soiling approximately 0.1 mm thick on outdoor limestone). The only waste generated is the dirt ejected from the surface which is straightforward to collect and dispose of using efficient extraction systems. There is no use of hazardous chemicals or solvents and the only protective clothing necessary is safety spectacles and a face mask. Laser cleaning is a clean and quiet technique which causes minimum disruption.

Versatility and reliability

Laser radiation at 1.06 μm has successfully been used to remove dirt and other coatings from a wide range of materials including: marble, limestones, sandstones, terracotta, alabaster, plaster, aluminium, bone, ivory and vellum. In some cases the availability of radiation at other wavelengths can increase the flexibility of the tool, for example in the removal of some types of organic growth. As lasers have very few moving parts, they are also extremely reliable. The particular laser has been designed specifically for work on sculpture and sculptural detail on buildings. More powerful laser systems capable of cleaning approximately ten times faster are available and would be more suitable for larger scale cleaning.

Laser cleaning does not work on everything. The cleaning of polychrome sculpture poses problems since different pigments absorb different amounts of radiation, certain types being very sensitive. For example, a single low-energy pulse will be sufficient to turn vermilion from red to black. In cases where there is evidence of pigment on a stone surface cleaning is usually carried out in such a way that the area is not exposed to laser radiation, unless it is known to be stable at the fluence being used.

Although laser cleaning of sculpture is usually much quicker than cleaning by the more sensitive conventional techniques, the large scale laser-cleaning of buildings cannot, at the moment, compete in terms of speed with techniques such as grit-blasting. It does however leave the stone surface intact. The development of laser systems is so rapid that it might not be too long before large-scale laser cleaning systems become available.

Chemical

Tensioactive products, alkaline cleaners, acid cleaners and organic solutions.

Water based

Water jet at low and high pressure, water in the form of vapour, cloudy water and water applied with poultice.

Consolidation-protection

After the cleaning, the action of the agents of alteration continues to modify the porous system of the rocks and its capacity of water absorption. The product employed must avoid the degrading action of water on the rock, creating an impermeable barrier to water but permeable to water vapour.

Different authors indicate that the treatments have to be applied when the rock is dry, they should penetrate right up to the rock that is sane, covering walls of pores and fissures, should be reversible and adhere to the substrate, they should not generate harmful sub-products such as salts, modify substantially the porous system of the original material and neither its permeability to water vapour, so as to permit the respiration of the rock. One should also take into account the chromatic incidence (they are usually transparent so as not to modify the colour and natural shine of the stone), the expiry date, toxicity, resistance to acids and alkaline and ultraviolet radiation, ease of handling or the economic cost.

Since the ideal product does not exist, a majority of the times it is necessary to adopt a compromise solution that does least damage to the rock. The behaviour and efficiency of treatment depends on the porosity of the rock, of the tests to be done and the product itself.

Consolidation consists of the application of a material, which improved the cohesion between the mineral components and, in turn, increases the mechanical resistance of the rock. At the same time, the adhesion of the most deteriorated exterior part of the rock to the less altered interior is improved. The most immediate result of consolidation is a change in the porosity of the stone by the entry into empty pore spaces of the consolidant. How the consolidant fills the pore spaces, creating the new porosity and new porometric distribution of the treated stone, are poorly understood. Their understanding, however, is of great importance in determining the suitability of treatment, since the results determine the uptake and transfer of moisture through the interior of the stone treatment system.

Among their most important properties could be emphasize the followings: consolidant value, influence of treatment stone alterability, penetration depth, changes in porosity, compatibility with stone, capability of moist transfer and effect on stone appearance.

Protection of building stone confers to the surface of the rock, exposed to the action-weathering agents, hydro-repellent properties by the application of chemical substances, which act as screen between the rock and the environment. By minimising the action of water, the effects of alteration phenomena associated with water ingress, such as dissolution, transport and crystallisation of salts, freeze-thaw phenomena, the action of atmospheric pollutants, etc, are also reduced.

The more usual protective products are chemically diverse: polysiloxanes, alkyl-alkoxy-silanes, fluorate polymers, fluoric-acrylic compounds, acrylic siliconic compounds, polyurethanes, microcrystalline wax, etc.

The consolidants, hidrorepellents and protectors are classified in three groups of can be distinguished based on its chemical nature: inorganic compounds, organosilicic compounds and organic compounds.

The inorganic consolidants are very similar to stone. Among inorganic consolidants are lime, bicarbonate of lime, barium hydroxide and potassium aluminate. These products have not application in the last decade because the following characteristics: low penetration depth, low elasticity, low mechanical resistance, and limited durability. Beside the inorganic substances can produce changes of colour, appearance of patinas, of soluble salts and of crystallisation of sales giving rise the degree of deterioration the rock.

The organosilicic consolidants are characterised by outstanding water repellence, with no significant impairment of water vapour permeability. They also show outstanding durability. The latter property results from the fact that silicones are extremely resistance to environment effects (such UV radiation, heat, chemically aggressive substances and microbes), and that silicone resin forms a stable, covalent bond with the construction materials. They must be able to penetrate into the pore system and they must not degrade under the alkaline conditions.

The silanes, siloxanes and silicone resins are three products groups which vary mainly according to their molecular weight and their capability and effectiveness on different natural stones. They all are the following rang of properties:

- They react chemically with stone. This results in extremely good bonding and adhesion to the substrate.
- They do not discolour the materials.
- They have good UV and weathering resistance.
- They can reduce the water absorption, water vapour and gas permeability of the rocks.
- They have a high affinity to the rocks, particularly silicates. This also explains their good effectiveness and their durability.

The compounds of organic nature include various resins (or polymer): acrylic, epoxy, polyurethane, polyester, etc.

The organic compounds are the consolidants mostly used because these compounds give impressive improvement the mechanical resistance of the rock. The mixture prepolymer-accelerator is placed on the stone surface where the curing process produces a thermoset polymer with high hardness to generate an appropriate reinforcement.

Mainly, the important problems of consolidation with organic polymers are to get a good penetration, which depends of its viscosity, of its superficial energy. Furthermore, other important disadvantage of organic compounds is the UV and chemical resistance, and the high toxicity.

When a solution resin is placed in contact with the stone, there is a tendency for smaller solvent molecules to flow into a porous substrate more easily and more deeply than large oligomeric resin molecules. This inevitably leaves higher resin concentrations near the surface. The degree of separation between solvent and solute is determined by the number of characteristics beyond molecular size, such a differences in polarity of the solvent and polymer and high vapour pressure of the solvent.

On the other hand, the use of the epoxy resins for stone consolidation are limited by the discolouration, because the presence of multiple amines groups and phenoxymethylene functionality in cured bisphenol A derived resins provides ample opportunity of chromophoric structures to form upon exposure to oxygen and sunlight.

Before the application of any treatment product to a building, experiments must be carried out in the laboratory and, if possible, in the building itself, or in restricted part of its, in order to obtain an understanding of the future behaviour of the stone-treatment system. The effectiveness of particular treatment methods depends upon the mode of application of the products employed, and the initial preparation of the stone, removing soluble salts, patinas, etc. An indication of the effectiveness of treatment methods can be obtained by studying variations in measured physical properties (e.g. capillary suction, absorption and desorption water, permeability to water vapour swelling, etc) before and after the application of treatment product.

Finally, the evolution of conservation treatments on the monument itself during the period following their application must be understood, by observation and measurement “in situ” of certain parameters related essentially to the transfer of moisture trough the interior of the stone.

References

1. http://www.eni.it/english/notizie/mediateca/special/s_pietro/pietra.html
2. Webster RGM (ed) Stone cleaning and the nature, soiling and decay mechanisms of stone, (1992). *Proceedings of the International Conference*, Edinburgh, Donhead, Shaftesbury
3. *Stone Cleaning in Scotland* (5 vols), Historic Scotland, Edinburgh 1992
4. Ashurst Nichola (1994). *Cleaning Historic Buildings* (2 vols), Donhead, Shaftesbury
5. Stone Cleaning: A Guide for Practitioners, Historic Scotland, Edinburgh 1994
6. Research Commission investigation: Cleaning of Granite Buildings (Report and Literature Review, Masonry Conservation Research Group, The Robert Gordon University), Historic Scotland, Edinburgh 1995
7. Research Commission investigation: Biological Growths, Biocide Treatment, Soiling and Decay of Sandstone Buildings and Monuments in Scotland (Report and Literature Review, Masonry Conservation Research Group, The Robert Gordon University). Historic Scotland, Edinburgh 1995
8. Technical Advice Note 9: Stone Cleaning Granite Buildings. Historic Scotland, Edinburgh 1997
9. Technical Advice Note 10: Biological Growths on Sandstone Buildings: Control and Treatment. Historic Scotland, Edinburgh 1997
10. Andrew C et al, (1994). Stone Cleaning: A Guide for Practitioners Masonry Conservation Research Group, The Robert Gordon University, Aberdeen, The Robert Gordon University and Historic Scotland
11. Ashurst N., (1994). *Cleaning Historic Buildings*, Volumes 1 and 2 Donhead, London
12. British Standards Institution BS 6270: Code of practice for cleaning and surface repair of buildings, Part 1 BSI, London, (1982). At the time of writing, this is being updated significantly by the BSI
13. Society for the Protection of Ancient Buildings (SPAB), Technical Pamphlet 4: Cleaning Brick and Stone, (1994), SPAB, London
14. Weaver, M.E., Matero F.G., (1993). Conserving Buildings: A Guide to Techniques and Materials John Wiley, New York
15. Webster R.G.M., Stone Cleaning and the Nature, Soiling and Decay Mechanisms of Stone Donhead, London, 1992
16. http://www.buildingconservation.com/articles/masonry/abrasive.html
17. Asmus JF, Seracini M., Zetler MJ., (1976). Surface morphology of laser-cleaned stone, *Lithoclastia*, 1, pp. 23-45

18. Verges-Belmin V, Pichot C., Orial G., (1993). Elimination des croutes noires sur marbre et craie; a quel niveau arreter le nettoyage? Conservation of Stone and other Materials, Thiel, MJ (ed), *Proceedings of the International RILEM/UNESCO Congress*, pp. 534-541

19. Cooper MI, Emmony DC, Larson JH, (1995). Characterisation of laser cleaning of limestone, *Optics and Laser Technology*, 27 (1), pp. 69-73

20. Cooper MI, Larson JH, (1996). The use of laser cleaning to preserve patina on marble sculpture, *The Conservator*, 20

21. Wilson J., Hawkes JFB (1983). Optoelectronics: An Introduction, *Prentice-Hall International*, pp254-261

22. Tam AC, Leung WP, Zapka W., Ziemlich W., (1992). Laser-cleaning techniques for removal of surface particulates, *Journal of Applied Physics*, 71 (7) pp. 3515-3523

23. http://www.buildingconservation.com/articles/laser/laser.htm

24. Lithos magazine

9

Examples of Innovative Products

ERICA LABORATORY

This chapter transfers the experience gained from two Italian research projects relating to the development of innovative stone products.

9.1. MANUFACTURING TECHNOLOGIES FOR "THIN MARBLE" PRODUCTS

The research work plan of this project involved the following main aspects relevant to the manufacturing process of "thin marble" products (e.g. 5- 6 mm thickness of the stone slabs):

- Technologies actually used to manufacture "thin marble" products.
- Technical characteristics of the various types of products actually in use.
- Theoretical economic analysis for the various types of products actually in use.
- Analysis of the physical, mechanical and technological characteristics of various types of supports used for the stone thin slabs.
- Bonding methodologies between the stone slab and the supporting structure.
- Experimental tests.
- Technologies actually used to manufacture "thin marble" products.

9.1.1. Thin marble panels

The technologies actually used to make the thin marble panels are mainly involving the bonding of thin stone slabs over other materials, like expanded plastic, zinc coated steel sheets, fibreglass and other composites, aluminium sheets, in honeycomb or in sandwich with plastics.

The best advantage of these products is certainly their reduced weight with similar physical, mechanical and esthetical characteristics; in fact this property can become mandatory for some applications as on board of boats, aeroplanes and lifts although accepting higher production costs. The same assumes a significant value also for claddings of the vertical facades by reducing costs and handling problems for the installation on buildings. The general approach for the cost vs benefit evaluation related to the use of the “thin marble” is due to the actual trend of optimising the choice and combination of the construction products in order to reach high performance materials. One of the primary results of this type of products is due to the low consumption of stone, being a collective non renewable source, thus limiting environmental and landscape damages and improving the utilisation of natural stones having peculiar ornamental and coloured characteristics. The special composite techniques allow manufacturing large dimension slabs by using re-composition technology on marbles, with low soundness but very precious, which should be normally very difficult to cut.

Other advantages are deriving from the increased mechanical features (e.g. shock resistance, compression and flexure strength) of the products, so decreasing the risk of fractures during handling and installation. Furthermore eventual failures of the cladding panels do not cause detachment of the stone slab from support avoiding the fall down of stone fragments especially in seismic areas.

The principal obstacle to the diffusion of “thin marble” products is the high manufacturing cost induced by the low engineering of their cutting process and bonding techniques. The actual applications are therefore limited to small industrial productions performed with traditional machinery only getting a very low efficiency technology.

In conclusion, the “thin marble” products can represent an open field of research addressed to find technical solutions for the scope of increasing both economical and quality competitiveness in respect to the stone materials currently marketed for construction.

Beyond the small production cases the stone based composite sector has been developed through the research and technology set up by few manufacturers, e.g. TECNOMAIERA in Turin (IT), TF-Tecnologie per il Futuro in Brindisi (IT) and STONE PANELS INC. in Carrolton (Texas-USA).

9.1.2. TECNOMAIERA

TECNOMAIERA has separated its products in two different lines:

1. Materials, including various types of basic compounds with variable thickness and forms:

- RS1 layered panel composed of a thin stone slab reinforced on one side by a steel sheet and a fiber-glass net in a matrix of epoxy resin impregnated under vacuum
- RS3 layered panel composed of two thin slabs, being the external faces, and a phenol resin sheet, being the central support, reinforced by a composite constituted by two steel sheets in a matrix of epoxy resin impregnated under vacuum

- RS4 layered panel similar to RS1 but without the fiber-glass net.
- RS7 layered panel composed of a thin stone slab reinforced on one side by a steel inox net in a matrix of epoxy resin impregnated under vacuum.
- ISO layered panel composed of a thin stone slab reinforced on one side by a fiber-glass textile in epoxy resin matrix bonded to an aluminium honeycomb panel reinforced both sides with a fiber-glass composite in epoxy matrix.
- FIBERMAR GL layered slab composed of a large slab (raw block section) of thin stone reinforced on one side with fiber-glass, representing the base of FIBERMAR ISO and FIBERMAR QUARTZ products.
- FIBERMAR ISO layered panel composed of a slab of thin stone FIBERMAR GL bonded to a polyurethane or mica expanded support and a steel sheet
- FIBERMAR QUARTZ layered panel composed of a thin stone slab FIBERMAR GL bonded to a glass, being the external surface, for covering the building facades.

2. Solutions, including pre-formed elements for specific covering needs:
   - MAX standard finished panel, with large dimensions (60x280 cm), obtained from a semi-machined FIBERMAR ISO for covering walls without intermediate joints in the horizontal direction; the fixing is made by anchoring devices on the back steel sheet.
   - SAM standard finished panel, with dimensions (60x60 cm), obtained from a semi-machined FIBERMAR GL for covering smooth plane surfaces, horizontal and vertical; the fixing is done by a direct bonding on the laying surfaces.
   - FLO standard finished panel, with dimensions (60x60 cm), obtained from a semi-machined FIBERMAR ISO with a support of calcium silicate added to cellulose fibres for floating floorings.
   - PAT components system for the preformed covering of walls and floorings of bathrooms, based on panels similar to the MAX types, but without standard width; these panels are complete with holes and fittings for piping, circuits and assembling of various services.
   - TOM system of modular components for construction of office service desks having the front and top surfaces made with stone coverings based on two FIBERMAR ISO panels supported by an independent steel frame.

9.1.3. Tecnologie per il Futuro (TF)

The manufacturing strategy of the TF (TECNOLOGIE PER IL FUTURO) enterprise is based on technologically advanced structural components, made of combinations of traditional and natural (marble, granite, aluminium, wood and glass) with composite materials. Regarding the stone coverings, the production involves three fundamental lines:

- TF PANEL HP layered panel in various sizes, composed of a thin slab (5 mm. thickness) in marble, granite or travertine, bonded to a composite aluminium honeycomb panel reinforced both sides by a textile composite consisting of glass wool in epoxy resin matrix. There are three standard categories:
  - TF PANEL HP 18 – honeycomb ½”, total thickness 18 mm.
  - TF PANEL HP 25 – honeycomb ¾”, total thickness 25 mm.

- TF PANEL HP 31 – honeycomb 1" , total thickness 31 mm.

- TF PANEL S layered panel in various sizes (up to 300x150 mm), composed of a thin slab (5 mm. thickness) in marble, granite or travertine, bonded to a composite plastic honeycomb panel reinforced both sides by a textile composite consisting of glass wool in epoxy resin matrix. There are four standard categories:
  - TF PANEL S 22 –total thickness 22 mm.
  - TF PANEL S 27 –total thickness 27 mm.
  - TF PANEL S 30 –total thickness 30 mm.
  - TF PANEL S 35 –total thickness 35 mm.

This product has lower mechanical characteristics and costs than the HP types.

- TF PANEL UF layered panel composed of a thin slab (5 mm. thickness) in marble, granite or travertine, bonded to a composite consisting micro-spheres of cave glass compacted between two glass wool textiles in thermal-curing resin matrix. The product has the best mechanical characteristics, with only 8 mm. total thickness and a specific mass of 16 Kg/sqm, for standard sizes 60 x 60, 120 x 60 and 240 x 60 cm.

9.1.4. Stone Panels INC

It was the first enterprise to make research on the composite stone panels and nowadays represents the primary world producer. SPI ULTRA-LITE is the unique panel which the enterprise is basing their production on. It is composed of a thin slab (5 mm. thickness) of marble or granite bonded with epoxy resins to a panel consisting of an aluminium honeycomb reinforced both sides with a composite of fibre-glass textile in epoxy resin matrix.
The main application of this product has been the covering of external facades of buildings, among which are worth to be recalled the 40 buildings of Savings of America (in marble and travertine) and the reconstruction of Merry Hill Center of Birmingham (UK) of 60.000 sqm. of surface.

9.2. TECHNICAL CHARACTERISTICS OF VARIOUS TYPES OF PRODUCTS IN USE

Analysis of the production technologies actually in use

The technological aspects featuring the manufacturing of the composite panels with thin stone slabs reinforced mainly involve the following phases:

- Thin cut of the slab of the stone material at reduced thickness
- Bondage of the thin slab with the reinforcing materials

Thin cut of the slab of the stone material at reduced thickness

The cutting systems currently used are basically of two types:

- the direct cutting from the block, as done by TECNOMAIERA, using the traditional cutters operating on the quarried blocks;
- the splitting of the traditional slabs, as performed by STONE PANELS INC. and TF (Tecnologie per il futuro), using the standard slabs with 2 cm. thickness.

Bondage of the thin slab with the reinforcing materials

The bonding operation between the thin slabs and the reinforcing supports are realised with two different techniques depending on the type of reinforcement chosen. The first class of products requires the impregnation of a face of the thin slab with a fibrous structure in a resin matrix to make a proper composite. The used resins are generally epoxy and the bondage is obtained through a simple laying or under vacuum.

This type of process is adopted by TECNOMAIERA for their products RS type and FIBERMAR GL to get semi machined basic crafts to be further bonded with reinforced panels during the final installation.

The second class of products is consisting of the bondage of the thin slab already reinforced, like TECNOMAIERA type, or non reinforced, like STONE PANELS and TF types, bonded with independent supporting panels. Also in this case the used bonding technique requires the impregnation with epoxy resins under vacuum conditions.

9.3. ANALYSIS OF THE MAIN TYPES OF APPLICATION

Floorings

The industrially produced thin slab composites can be used for new floorings or for their restoration.

Especially in restoration there is the advantage to lay down, just by gluing, these kind of light roofing panels without any structural strengthening of the roof.

One of the most interesting application of the composite panels is certainly the laying down of the so called “floating floorings” in which the walking surface is superimposed from the building base structure creating an useful inter-space allowing the passage of cabling, piping and other circuits to be installed.

External coverings

The thin slab composites are joining the good resistance to the atmospheric agents of many stone materials with their advantages of handling and assembling (lower weight and suitable fixing devices). Due to the reduced thickness it is important to check the following aspects:

- environmental climatic conditions for operation
- laboratory tests to prove the mechanical behaviour and environmental resistance

The most important application is represented from the ventilated facades for which the weight reduction of panels allows the use of lighter metal structures for support.

One target of the research has regarded the composition of thin stone slabs with glass panels, being the outer surface of the covering, as to make a protective layer for the stone decoration. This innovation introduced by TECNOMAIERA is not in current production.

Internal coverings

Also for the internal coverings the composite stone panels present their advantages of handling and assembling; moreover they allow the availability of bigger size panels (60 x 280 cm.), having very light weight, which can be installed in unique solution for the vertical height of the wall creating interesting effects especially for the bathrooms.

To such extent TECNOMAIERA started a typical production of this kind of pre-formed panels for covering and housing of services and hydro-sanitary plants.

9.4. ECONOMIC ANALYSIS FOR VARIOUS TYPES OF PRODUCTS ACTUALLY IN USE

The main cost indexes involved in the comparison between the traditional techniques and the thin marble covering have been considered in the present economic analysis, both regarding the direct and the indirect charges.

Direct Costs

Stone material cost: The lower cost of the stone material assembled in the thin composite panels is clearly due to the reduced thickness (and volume) respect to the current use. The cost reduction is ranging from minimum 2 up to 3 and 4 times when the design thickness of the conventional slab should be of 4 cm. The material cost is, however, very significant for the economic analysis especially in function of the best quality of stones used in the covering panels.

Stone material cutting cost. The major incidence of the cutting of thin slabs versus the traditional panels is due to the splitting of the slabs performed with the currently available cutting technologies (e.g. gang-saw, block cutter) for getting thin sheets 5-8 mm. thick. The cutting operation is carried out as follows in the actual production of “thin marble”:

- through repetition. This involves a transverse displacement of the block, during the cutting operation by means of a multi-blade block cutter, as it is performed by TECNOMAIERA. In this case there is an additional cost due to epoxy resin filling in between the subsequent cutting processes
- slab by slab, after the application of the two reinforcing panels, by means of machines using diamond tools, as performed by STONE PANEL and TF companies. In this case the cost can be higher due to the use of precision tool machinery with high risk of scrapes as well

For the experimentation and set up of machinery, dedicated to this kind of production, it is needed to evaluate also splitting technologies, slab by slab, using:

- diamond disks, for panels having height lower than 60-80 cm.
- diamond blade machines in closed loop, capable to split two slabs simultaneously on two opposite sides with the same downwards motion

Cost of the reinforcement to the stone material: This cost is particularly important in the composite thin panels since it is connected with the quality of used support and the associated bonding procedures. In the actual productions the materials used for reinforcement can vary from the simple fibre-glass to the most sophisticate composite or cellular materials, with bonding techniques involving only manual laying till the impregnation by resin under vacuum.

The relevant comparison against the traditional application must be always done based on the same characteristics, type and use of the covering elements.

Costs for the precision cutting and polishing: Generally they are the same both for the traditional and thin marble panels, however there could be a cost reduction for this operation in favour of the thin panels based on the bigger sizes achievable with these latter.

Handling and transport costs: These costs are reduced by 20 – 40 % for the thin panels with respect to the traditional massive slabs application.

Indirect Costs

Assembling and installation costs: The use of thin panels allows a reduction of assembling and installation of complex coverings like ventilated facades, bathrooms and services:

- thanks to their ease in handling and lighter weight for big sizes
- thanks to the possibility of pre-assembling of complex groups or whole rooms

An additional reduction is possible by laying the thin panels on the previous flooring or wall avoiding the dismounting costs of the old structures.

Costs of the supporting frames in the ventilated facades: The supporting frames in the ventilated facades can be reduced thanks to the use of the composite thin panels also requiring anchoring devices less strong than the traditional slabs to be fixed.

Analysis of the physical, mechanical and technological characteristics of various types of supports used for the stone thin slabs

9.5. Analysis of the Physical, Mechanical and Technological Characteristics of Supports

The usable materials for reinforcement of the thin stone slabs are mostly produced for multi-layer structures application (sandwich) and can be included within the following types: composite materials, metallic materials, expanded polymers, honeycomb panels and other commercial products.

Composite materials

This composites are the combination of two or more materials, different and insoluble, in order to realise a product with proper mechanical characteristics. The particular assembling of a homogeneous matrix with a disperse fibrous material to increase stiffness and resistance of the base matrix is called “Fibrous composite”, while the composites strengthened with plastic elements are named “Reinforced plastics”. The reinforcing fibres can be homogeneous or different in the “Hybrid composites”. In particular the homogeneous reinforced plastics are the following types:

- Glass Fiber Reinforced Plastic, GFRP
- Carbon Fiber Reinforced Plastic, CFRP
- Kevlar Fiber Reinforced Plastic, KFRP

Special structures of fibres for reinforced plastic are listed below:

- the “nets” (Mats), composed of continuous fibres, random oriented and bonded together
- the “textiles” (Fabrics), planar light structures formed by orthogonal intersecting wires
- the “reinforces” (Woven Rovings), heavy textiles formed by groups of rovings of fibre-glass

The composite materials used in the sandwich structures are made in "layers" (Plies) consisting of a sheet of mat, fabric, woven roving or unidirectional fibres bonded together in a matrix; the sandwich structure composed by bonding more plies together is called "Laminate". The use of composite materials in sandwich structure bonded with thin stone slabs is certainly encouraged from the good relationship between the mechanical characteristics and the weight typical of most of these products.

Mechanics of the composite materials: A basic characteristic of the composites is the specific density of the laminate which is a function of the specific density of the matrix, of the reinforcement fibres ad the quantity of each component used. The main mechanical properties of the various types of composite materials (both for Glass mat and Woven Rovings - polyester composites) are represented by the Tensile rupture Load and the relative Elastic Modulus, the Compression rupture Load and the relevant Elastic Modulus, the Flexural resistance and the related Flexural Modulus, the Poisson Modulus.

Unidirectional composites: The mechanical properties of the unidirectional composites, featuring a structure with reinforcing fibres parallel to a reference direction, present a non isotropic behaviour for the longitudinal and transverse orientations.

Balanced laminates of unidirectional composites: These types of laminates are composed of more plies of unidirectional composites bonded together. The evaluation of their elastic properties can be done with the combination of the characteristics of the single unidirectional plies.

Metallic materials

The metallic sheets used for composing the sandwich structures are including steel and aluminium light alloys, requiring special surface treatments (zinc and phosphate coatings for steel, anodising for aluminium alloys) in order to provide the necessary corrosion resistance to the atmospheric agents. Often stainless steel is used.

Expanded polymers

Expanded polymers, in form of foam, can be used for making the composite panels with thin marble, by filling the "core" spaces between the rigid surface panels.

The main function is to provide thermal and sound insulation, which is fundamental for the covering application in the buildings.

Some other special composite materials have been further investigated like the following:

- honeycomb laminates
- honeycomb panels

and some commercial products like these are: Alucobond, Ligustica prepreg, Mitlight

A proper experimental testing campaign, based on the most representative Standard tests like the Flexural Strength ASTM C 880, has been conducted on samples of said composite materials in order to evaluate the difference in behaviour under conditioning in water and after thermal cycling in Temperature and Relative Humidity.

The samples have been composed using the different epoxy resins available on the market and produced by primary manufacturers (3M/SCOTCH and AKEMI GmbH) like AKEPOX 2000-2010-2020-2030 and 2040.

Moreover some acrylic adhesives (thermal-curing) with high mechanical characteristics and peel strength, like MULTI-BOND 329 and 330 produced by LOCTITE CORPORATION in Ireland.

A fundamental problem to overcome in the industrial use of the two different families of chemical products is anyway the research of new non-toxic resins as to assure the correct an healthy working conditions in the manufacturing process and a safe application of the composite panels in the future building construction.

9.6. COUPLING BETWEEN STONE MATERIALS AND METAL FIXINGS

This transfer action, which covers the preliminary phase of experimentation, is relative to the development of innovative techniques for fixing of metal anchors by means of structural adhesives, properly formulated for cladding stone panels in the ventilated facades of buildings. Gluing resins have been tested in order to develop innovative-glued joints for the anchoring system of stone panels used in cladding of the ventilated facades.

To the purpose of carrying out an experimental activity conforming the current practice and meeting the actual needs of application in the civil constructions the analysis of the updated state of the art has been performed which allowed defining the technical and operative specifications of the anchoring system. On the above basis a design activity has been made to figure out a schematic of the joint suitable to simulate the joint samples to be submitted to the mechanical resistance tests which are fundamental for their behavior in the time. The formulation of the nature and the architecture of the structural adhesives has been therefore defined together with the relevant bonding elements, polymeric based, to be used during the test campaign conducted on two basic materials, e.g. marble and granite. These stones present different physical, petrographic, chemical and mechanical characteristics beyond being non-homogeneous due to their natural variability.

Finally the optimisation of the gluing components (adhesives and bonds) has been done regarding the mating between the stone and the anchor surfaces and especially concerning the adhesion of the stainless steel (through the oxidation treatment) by controlling the variation of the mechanical tensile resistance (Pull-out) in function of the environmental installation conditions (freezing, thermal shock, humidity and atmospheric acidity due to pollution).

The preliminary results of this stage of the research have proved the feasibility of design and implementation of an innovative joint for the anchorage of stone cladding in facade based on the effective adhesion achieved by the means of structural adhesives and bonding resins properly formulated to this purpose.

The mechanical resistance of the new type of joint is fully comparable with that obtained in the mechanical type of joint currently used for the application in the facades cladding anchoring system.

It remains yet to improve the long-life features of the adhesives with polymeric base so far experimented together with the impregnating properties of the consolidating agents on the local points for assembling the metal fixings in the stone panels. This work will allow to optimise the reliability of performances under critical environmental conditions due to the installation in extremely severe climates (freezing, high humidity, sensible atmospheric pollution, etc.).

Therefore it is confirmed, at the end of the present stage of development and experimentation, the need to continue the research performing more complex tests on extended sampling for statistical evaluation, also using special fixtures suitable for measuring other mechanical characteristics of the joint like the resistance to shear of the glued couplings.

For the above reasons there will be the opportunity of developing a deeper research program in order to verify completely the conformance to the technical and performance specifications defined for the installation of the new generation type of glued joints.

This research program could be included within a Project having a greater allocation of resources more suitable to the experimental activities required for the themes of the structural joints on the basis of Regional, national R&D initiatives or sustained by the European Community.

9.6.1. Resins used for experimentation on the anchors for stones

In the preliminary phase to the research organization, the experiences relative to the use of the structural adhesives with polymeric base relative to the stone sector and, more in general, in the construction engineering representing a wide field of application

It is useful to examine some knowledge results and concrete applications done as to place the research inside a general reference framework with the aim to give a bigger experimental value to the project: the implementation of mechanical joints by using the synthetic adhesives for the installation of stone claddings on the exterior of buildings.

Many times the attribute structural has been used joined with the substative adhesive since the former is selecting a specific category of adhesives. In fact, the meaning of structural in this case can be highlighted in the following definition: "Attribute of the adhesive according to its resistance rate intended as capability of withstanding static and dynamic forces without significant deformations for unlimited time under normal operational conditions"

The polymers used to produce the structural adhesives are of several kinds and can be among the following main types:

- Acrylic
- Epoxipoliammines
- Epoxipoliammides
- Epoxyphenolic
- Epoxypolisulfuric
- Epoxypoliurethanic
- Metacrylates
- Poliammides
- Polyiurethanic

In this wide range it has been chosen to exclude from the research investigation, both for the antecedent and the actual phase, the polymers and therefore the adhesives not usable at ambient temperature, as they are not reactive at low temperatures. From the above list it is evident that the epoxy component is a major characteristic inside the polymers used for the production of adhesives. The epoxy resins are certainly the polymers providing the best adhesion forces towards a wide variety of materials, especially the "porous" ones like the stones.

Consequently, after proper formulation and preparation, n. 2 resins consolidating the suface on the stone materials (marble and granite), identified as Type 20 and 30, have been tested together with n. 4 structural adhesives, identified as Bond #600, #613, #618 and #700.

9.6.2. Final Conclusions

Before reporting the final conclusions based on the results obtained during the research, it is necessary to underline that the extension of the investigation should require experiments in many more samples, both for quantity and typology, in order to reach a reliability rate and confidence level adequate to each stone material since it is particularly subject to high variability of its own technical characteristics (physical-chemical, mechanical, petrographic, etc)

Consequently, the task performed in these initial phases of the research has allowed to verify an experimental analysis on the behavior of the polymeric elements (bonds and adhesives) representing the basic components of the innovative joints under testing for stones, achieving the two following objectives:

1) Determination and verification of the structural resistance of the polymeric adhesives used for gluing the metal anchors in the cladding of ventilated facades.
2) Experimentation on the efficiency of impregnation by the means of synthetic polymeric bonds with the scope to consolidate the skin layer of the stone materials (marble and granite) as a pre-treatment on the surface to get a stronger grip of the adhesive resin to be applied for the joint assembling.

As far as the objective 1 is concerned, it can be stated that out of the 4 different types tested, at least one adhesive (Type I Bond # 600) has shown a better behaviour with respect to all the others both for marble and granite since it did not fail after the accelerated conditioning, nor after the long natural ageing. Moreover this compound has presented a tensile resistance characteristic fully comparable with those measured in the actual joints of mechanical type currently used in the facades cladding.

Based on the positive behaviour recorded on this adhesive it has been therefore possible to determine the project parameters, which should characterize a good structural adhesive and can be summarized into the following main features:

- Low surface tension
- Good reactivity at low temperature
- High glass transition
- Shrinkage values negligible, almost zero
- Mechanical resistance adequate to the stone material used
- Low elastic module
- No-stress under thermal shock
- Low creep value

It has been possible to verify that the new joint system composed of “stone panel-adhesive compound-stainless anchor” is largely meeting the requirements for its applicability in the anchorage field of the facade claddings, also showing further interesting margin of safety in these applications. In particular, having measured a good sampling of mechanical resistance values, a preliminary data-base was collected which is useful to design this type of stone joints glued according to some criteria an parameters defined through the present research.

As far as the objective 2 is concerned, relative to the investigation of the behaviour of two bonding compounds with polymeric base, the consolidating agent Type 20 only has shown a good conformance to the application requirements planned, though it has not improved significantly the adhesion strength provided by the structural adhesive as instead it would be expected for its extensive use on a large scale.

However, a positive effect is the proved optimum compatibility between the adhesive Compound # 600, giving successful results, and the Bond Type 20 over the samples where these two have been joined together to assemble the joints. In particular the relevant samples showed a good resistance to the long ageing and to the accelerated freezing condition.

The other objectives of the research were aiming to the following scopes:

- definition of tests and methods for experimentation of the performances of the newly designed glued joints
- tests and definition of the procedures for preparing the samples of joints to be submitted to the tests
- confirm, through experiments, the correct choice of using the adhesives with polymeric base for the anchorage of the stone cladding panels.

An auxiliary objective of the actual research, but for this reason not less important, was certainly to confirm the efficiency of the gluing adhesion for the stainless steel anchor. As already reported, none of the samples under testing has presented separation of the structural adhesive from the metal disk representing the fixing anchor. The structural adhesive on the metal disk and also the type Bond # 600 have shown to wet the steel material adequately even at low temperature, which is representing a very critical condition in the real installation on the site.

The activity so far developed has set the basis for further eventual experiments necessary to continue the research under a wider programme extended to the different stone materials actually used, by optimising the formulation properties of the tested polymers. The overall purpose is to answer the fundamental objective, which is the complete design of an innovative anchoring system, based on glued joints, to be largely used in the civil construction.