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Natural stone from the Azores archipelago: Relationship between lithology and physical-mechanical behaviour

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ABSTRACT: Since the early days of the settlement in the Azores archipelago, in the 15th century, natural stone has been used in the construction of residences, religious monuments and public buildings, because of its local abundance. The purpose of this study was the characterization of the main commercial types of natural stone of the archipelago of Azores, in terms of their petrographic, mineralogical, chemical and physico-mechanical properties. This characterization allowed the appraisal of their suitability for the different types of applications. In a preliminary stage, the study comprised seven varieties of natural stones exploited in severals quarries and processing plants of São Miguel Island and Santa Maria Island—two of the nine islands that form the Azores archipelago. Petrographic studies and chemical analysis were performed in all the selected varieties as well as the following physical-mechanical tests (carried out according to European Standards): uniaxial compressive strength, flexural strength under concentrated load, apparent density, water absorption at atmospheric pressure, open porosity (or apparent porosity), linear thermal expansion coefficient, abrasion resistance (with Capon machine) and rupture energy (commonly known as impact resistance). Finally, relationships were established between the main physical-mechanical properties of the natural stones under study, and their main lithological and textural characteristics.

1 INTRODUCTION

On a national range, natural stone is a resource whose current importance, in economical terms, has been accompanied by growing scientific and technological knowledge (Moura, 1991, Costa *et al.*, 1995).

On a regional scale, regarding Azores archipelago, extracting, manufacturing and trading natural stone industries on São Miguel Island, and to a lesser extent on Santa Maria Island, have great social, cultural and economical interest for their communities, whose demand for local raw materials has grown in recent years.

The study of the main physical, chemical and technological properties of natural stone is designed to optimize the use of this resource in the construction industry, putting in perspective the establishment of quality criteria, both in the resource exploitation and in the resource use.

Since the beginning of the Azores archipelago settlement in the 15th century, lavic and pyroclastic volcanic stones, both common in this archipelago, are important mineral resources used for the construction of houses, monuments and public works, among other applications.

On this work seven rock types of natural stone were studied. The selection criteria were based upon its representativeness, and also on the fact of being widely used, both in quality and in quantity on the islands of São Miguel (5) and Santa Maria (2). In Azores arquipelago there is a trade and popular nomenclature used to characterize natural stone which comprises hardness, cohesion, mechanical strength, carving and cutting mode: dimensional stone, farming or "lavoura" stone and sawed or lumber stone.

2 GEOLOGICAL SETTING AND LOCATION OF NATURAL STONE QUARRIES

The Azores archipelago is composed of nine islands and several islets that are located in the North Atlantic Ocean between latitudes 37° and 40°N and longitudes 25° and 31° W, spread over 610 km long in a direction WNW-ESE. Due to its geographic distribution, the archipelago is organized into three groups: the Western Group which includes the islands of Flores and Corvo, the Central Group is composed of the islands of Terceira, Graciosa, São Jorge, Pico and Faial, and the Eastern Group which includes the islands of São Miguel and Santa Maria, and the islets of Formigas.

Azores is located in an area where three major tectonic plates converge—the Eurasian, African and North American—and where other minor tectonic structures occur. These are arranged along a set of tectonic alignments of general orientation WNW-ESSE (França *et al.*, 2003). This general trend is usually also found, in the shape of most of the islands.

The dynamics of its tectonic Framework (Figure 1) is the element responsible for the petrological and geochemical characteristics of lavas ejected by regional volcanic apparatus (França *et al.*, 2003).

Regional volcanism determines that stones from Azores are primarily basaltic, although there are also acidic stones, with less representation (França, *et al.*, 2003). While Santa Maria, São Jorge and Pico islands are mainly formed by basalts and alkali basalts, the other islands have a variety of lithologies, from alkali basalt to trachyte, through the hawaiite and mugearite (França, *et al.*, 2003).

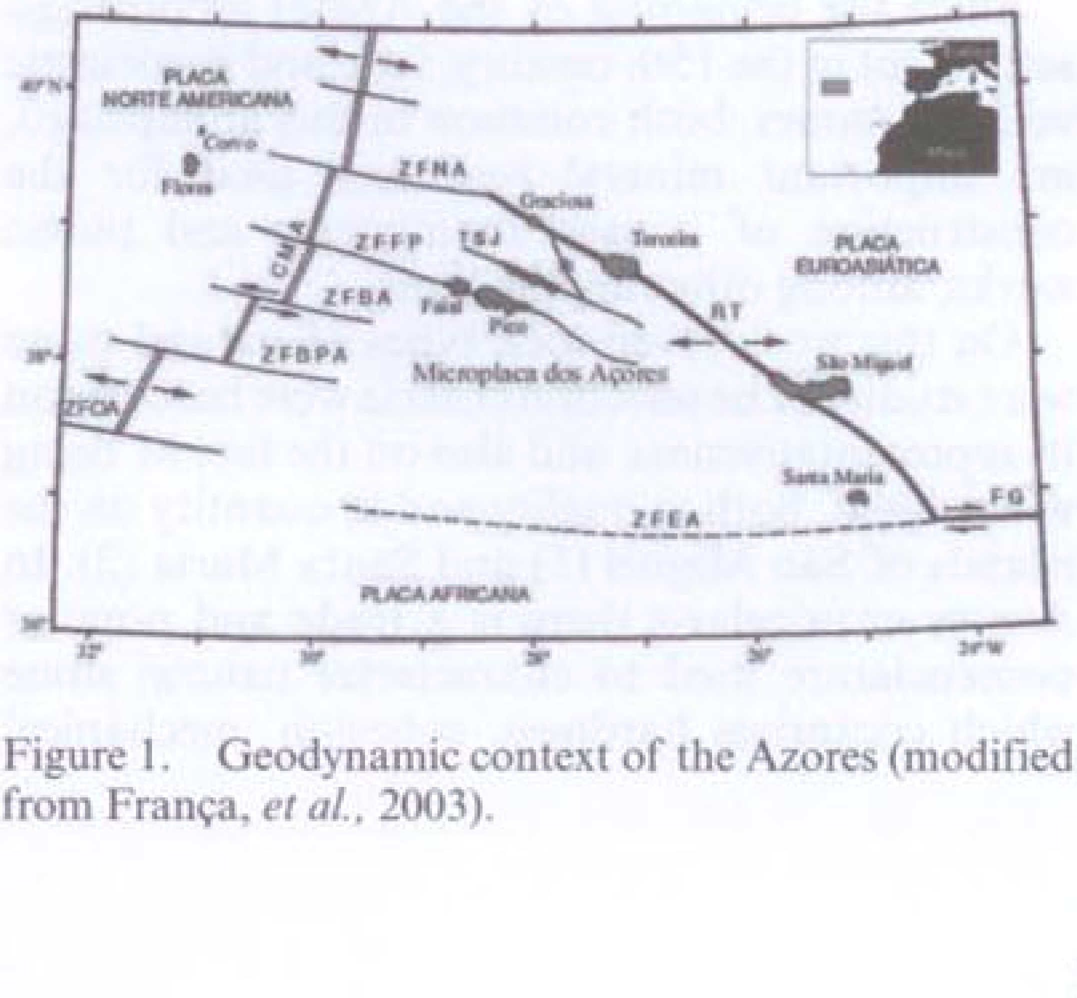

Figure 1. Geodynamic context of the Azores (modified from França, *et al.*, 2003).

Most of the geological formations that occur in the Azores archipelago from which extrusive rocks are used as natural stone, are distributed by two very different sets:

a. The first set comprises compact and/or porous and vacuolar lavic rocks represented by basaltic flows (s.l.) and trachytic flows (s.l.).
b. The second set comprises pyroclastic rocks resulting from explosive activity. In fact, there is a wide variety of materials, from huge blocks to very fine ash, through intermediate terms as "bagacina", "gravel", "lapilli" and "areão" (coarse sand) exhibiting vesicular and spongy structure, among which bombs frequently can be found. However, these pyroclasts exhibit some consolidation (welded materials), and in some cases they look like heterometric breccia and in other cases they look like tuff (Gomes & Silva, 1997).

The quarries of natural stone in the island of São Miguel are more numerous than those in the island of Santa Maria.

In the island of São Miguel, given the demand for natural stone of diverse lithology, natural stone from distinctive volcanic complexes, such as: Complexo Vulcânico dos Picos (1), Complexo Vulcânico do Fogo (2), Complexo Vulcânico das Furnas (1) and Complexo Vulcânico da Povoação (1), has been studied.

With the exception of the Complexo Vulcânico dos Picos of fissural nature, all the others being studied comprise central volcanic structures (Figure 2).

In the case of the island of Santa Maria, the two studied natural stones are included in the Complexo Vulcânico dos Anjos which occupies most of the west sector of the island and consists of basaltic lava flows of metric thickness, sometimes alternating with thin layers of pyroclasts. Veins are frequently seen cutting the basaltic flows.

Table 1 contains the references, the sources, the technical-commercial names, and the exploiting

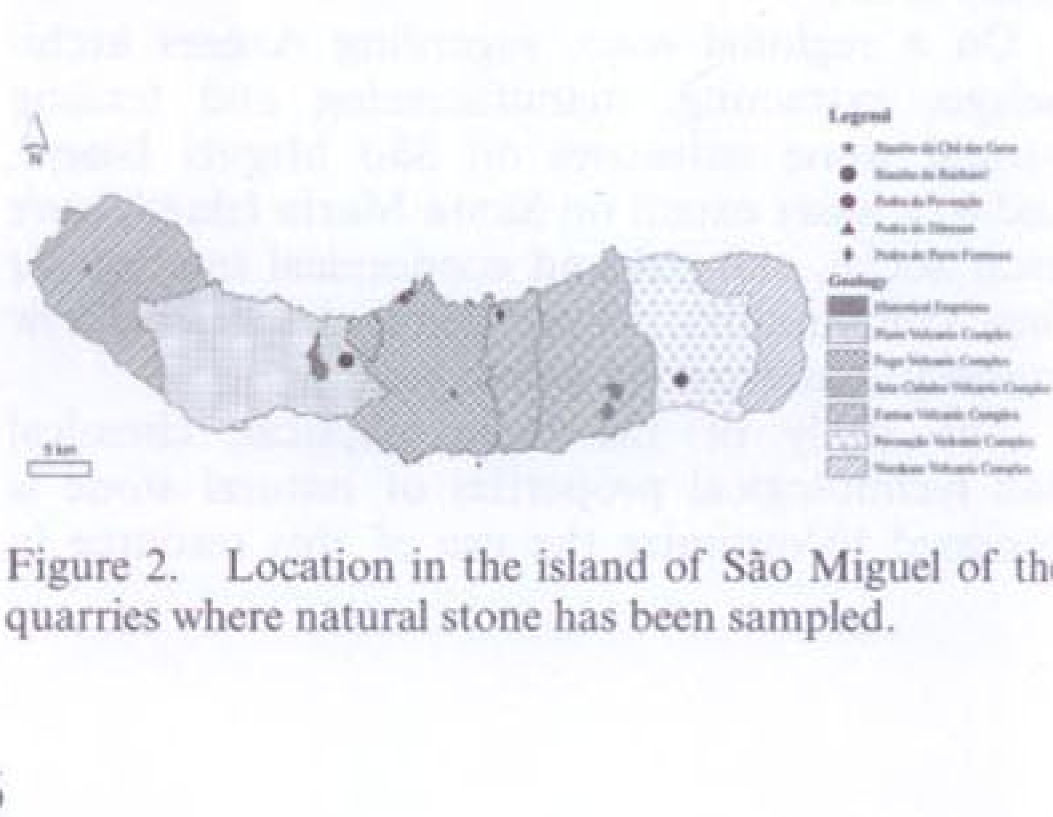

Figure 2. Location in the island of São Miguel of the quarries where natural stone has been sampled.

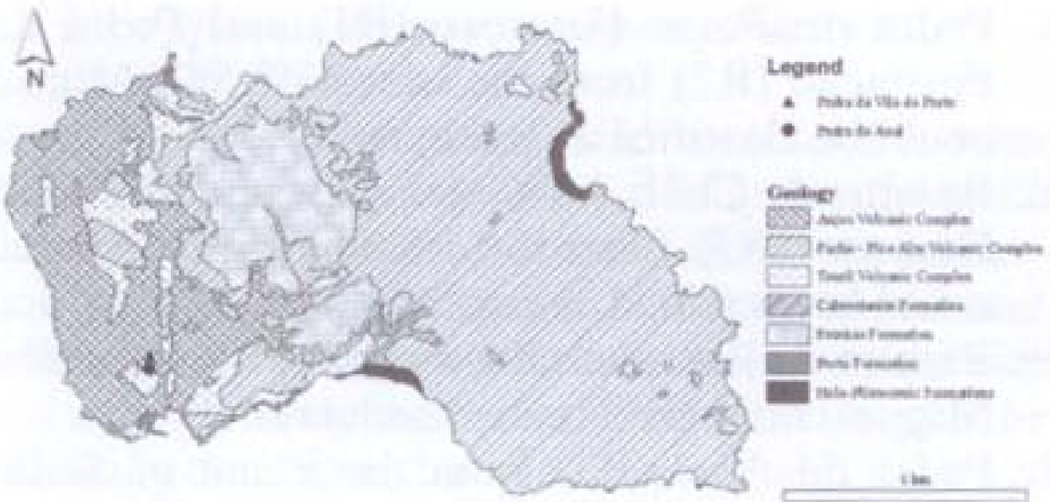

Figure 3. Location, in the island of Santa Maria, of the quarries where natural stone has been sampled.

Table 1. References, sources, trade names and exploiting enterprises.

S. Miguel Island	
R1-Pedra do Porto Formoso	Herdeiros Agostinho F. Medeiros, Lda
R2-Pedra da Povoação	Herdeiros Agostinho F. Medeiros, Lda
R3-Basalto da Chã das Gatas	Herdeiros Agostinho F. Medeiros, Lda
R4-Basalto do Bacharel	Herdeiros Agostinho F. Medeiros, Lda
R5-Pedra do Dâmaso	José Dâmaso e Filhas, Lda
Sta. Maria Island	
R6-Pedra da Vila do Porto	Mário Batista
R7-Pedra do Anal	Mário Batista

enterprises involved in the extraction of the seven types of natural stone being studied.

3 GENERAL AND MACROSCOPIC CHARACTERIZATION OF THE NATURAL STONE FROM THE AZORES

The ornamental value of an igneous rock depends on its colour and textural homogeneity. These characteristics determine to a large extent the rock ornamental and commercial value.

The colour exhibited by a natural stone, to a large extent, is associated with the colour of the dominant minerals, with the granularity of the same minerals, and with minerals alteration degree.

The lava rocks show gray shades, darker or lighter, being predominantly represented by basalt, basanite, trachybasalt, trachyandesite and trachyte.

The pyroclastic flows, associated with very explosive eruptions of acid magma, show black to brown shades, and are predominantly represented by ignimbrite. O the other hand the pyroclastic rocks show a wide range of shades, the most common ones being: brown, black, red, and gray, and are predominantly represented by lapilli tuff and breccia tuff.

Rock texture depends on the following factors: the number and how the larger minerals are distributed within a more or less abundant matrix constituted of smaller minerals; the small fissures; the alteration degree of minerals; and the number and size of pores and vacuoles.

In general, the effusive rocks show aphanitic or microcrystalline texture (Gomes & Silva, 1997), and the pyroclastic rocks show porous to very porous, vesicular to very vesicular, and rarely amygdalar and breccioid texture.

4 PETROGRAPHIC, MINERALOGICAL AND CHEMICAL CHARACTERIZATION

4.1 *Analytical methods*

The petrographic, mineralogical, and chemical characterization of the studied natural stones was carried out at the Departamento de Geociências da Universidade de Aveiro, and at the LNEG (Laboratório Nacional de Energia e Geologia).

The petrographic analysis was carried out using an optical microscope and polarized transmitted light and the observation of thin sections of the studied natural stones. Petrographic analysis provided information very useful for the interpretation of the physical-mechanical behavior of the natural stone, and for the identification of certain features or defects that could penalize natural stone quality.

The mineralogical analysis was carried out using X-Ray Diffraction (XRD) whenever due to minerals alteration they could not be identified by petrographic analysis.

The chemical analysis was carried out using X-Ray Fluorescence (XRF).

4.2 *Petrographic and mineralogical analysis*

Some types of the studied natural stones show great similarities, both in petrographic and in mineralogical terms:

i. Pedra do Porto Formoso (R1) and Pedra da Povoação (R2) from the island of São Miguel are characterized by their light gray and brownish black colours and by their small pores due to the release of gas; they show porphyritic texture, and fenocrysts of leucite, K-feldspar, Na-Ca feldspar, pyroxene and olivine have been identified; both rocks could be classified as leucite-basanites.
ii. Pedra do Chão das Gatas (R3) and Pedra do Dâmaso (R5), both from the island of São Miguel, correspond to extrusive mafic igneous

rocks showing ligth gray colour; they show porphyritic texture and numerous pores; within the phenocrysts, K-feldspar, Na-Ca feldspar and pyroxene have been identified; both rocks could be classified as trachytes.

iii. The so-called Basalto do Bacharel (R4), in the island of São Miguel, is an extrusive volcanic rock of dark gray colour and pores of medium size; it shows porphyritic texture, and within their phenocrysts Na-Ca feldspar, pyroxene and olivine have been identified; this rock could be classified as basalt.

iv. Pedra da Vila do Porto (6) and Pedra do Anal (R7), both from the island of Santa Maria, are pyroclastic rocks of reddish brown and greenish gray colour, respectively; they show porous and vesicular texture, and the clasts have dimensions within the range 2–64 mm; Na-Ca feldspar, Ca-Mg pyroxene, olivine and analcite were the main minerals which have been identified; they were classified as picrite basalts.

4.3 *Chemical analysis*

Table 2 shows the results of the chemical analyses carried out on the studied natural stones.

The most comprehensive classification of volcanic materials being used as ornamental natural stone in the archipelago of the Azores had been established using the Francis´classification (1993) that is based on the relationship ($Na_2O + K_2O$) content *versus* (SiO_2) content, expressed weight %.

The representation of the data shown in Table 2 allowed the classification into seven typologies of the studied natural stones:

Table 2. Results obtained FRX the studied volcanic stone samples.

	References of the natural stones						
% Oxides	R1	R2	R3	R4	R5	R6	R7
SiO_2	60.11	61.41	55.92	45.26	56.10	44.75	45.08
TiO_2	1.01	1.03	1.81	3.78	1.83	3.18	3.14
Al_2O_3	18.24	17.92	17.66	14.34	17.68	16.99	16.75
Fe_2O_3 T	4.48	3.99	6.32	12,87	6.34	12.74	12.56
MnO	0.17	0.15	0.12	0.18	0.12	0.26	0.19
MgO	0.96	0.84	2.35	7.61	2.34	3.62	3.99
CaO	2.57	1.94	4.68	9.14	4.69	7.26	7.92
Na_2O	6.91	6.03	5.38	4.20	5.16	4.98	5.52
K_2O	4.93	6.36	5.25	1.92	5.25	0.99	0.75
P_2O_5	0.21	0.14	0.35	0.64	0.35	0.63	0.59
P.R.	0.40	0.20	0.17	0.05	0.14	4.60	3.50

i. Pedra do Porto Formoso (R1) and Pedra da Povoação (R2) from the island of São Miguel could be classified as trachytes.

ii. Basalto do Chão das Gatas (R3) and Pedra do Dâmaso (R5) from the island of São Miguel could be classified as trachybasalts.

iii. Basalto do Bacharel (R4) from the island of São Miguel could be classified as hawaiite.

iv. Pedra do Anal (R7) from the island of Santa Maria and Pedra da Vila do Porto (R6) from the island of São Miguel could be classified as picrite basalt.

Also, taking into account the data contained in Table 3 and the chemical classification of Le Bas *et al.*, (1986), the studied ornamental natural stones from the Azores archipelago, in terms of SiO_2 content, range from basic (45% > SiO_2 <52%) to intermediate (52% > SiO_2 < 63%).

5 PHYSICAL AND MECHANICAL TESTS

The properties that were determined on studied volcanic stone samples are listed bellow, as well as the European Standards (EN) used to perform the tests. Properties were grouped according to their purpose and a short procedure description was also included.

5.1 *Identification properties*

5.1.1 *Uniaxial compressive strength (EN 1926)*

Six cubic specimens were laid and centred on the plate of an ELE International ADR 200 compressive testing machine. It was applied a uniformly distributed and continuously increased load until specimen failure occurred. Compressive strength was calculated as the ratio between the failure load and the surface area submitted to compression.

5.1.2 *Flexural strength under concentrated load (EN 12372)*

Ten parallelepiped specimens were placed on two supporting rollers of an ELE International Tritest 50 Digital flexural testing machine. The distance between these rollers (span) was calculated according to the specimen thickness and previously adjusted. A force was applied by a third roller placed on the middle of the specimen. The load was progressively increased until failure occurred. Flexural strength was calculated by the following equation 1 below:

$$\text{Flexural strength} = \frac{3 \times \text{failure load} \times \text{span}}{2 \times \text{width} \times \text{thickness}^2} \qquad (1)$$

5.1.3 *Apparent density and open porosity (EN 1936)*

Six cubic specimens were dried to constant mass and placed in a vessel to absorb distilled water while submitted to a standard vacuum. After an immersion period of time, also standard, saturated and immersed weightings were made. Apparent density and open porosity were calculated according to the following equations 2 and 3, respectively:

$$\frac{\text{dried mass}}{\text{saturated mass} - \text{immersed mass}} \times \text{water density} \tag{2}$$

$$\frac{\text{saturated mass} - \text{dried mass}}{\text{saturated mass} - \text{immersed mass}} \times 100 \tag{3}$$

5.1.4 *Water absorption at atmospheric pressure (EN 13755)*

For this test, six cubic specimens were also used. The test method is quite similar to the one used to determine apparent density and open porosity. The main differences were that vacuum was not used, the immersion was staged into 3 steps and specimens were left immersed in water until constant mass was reached. Water absorption was calculated by the ratio between the mass of absorbed water and the mass of the specimen.

5.2 *Performance after application properties*

5.2.1 *Rupture energy (EN 14158)*

Six specimen slabs were used to perform the test. After placing and levelling the slab on a silica sand bed of standard grain size, a steel ball of both standard mass and diameter was dropped on the upper face centre of the tested slab. On the first test, the ball was dropped from an initial height of 10 cm and the height was continuously increased, 5 cm each time, until the specimen broke. On the following five tests the procedure was the same, except for the initial height of the ball dropping: 15 cm bellow the result obtained on the first test. *Rupture energy* was calculated as the ball work when dropped from the height which produced specimen failure, according to the following equation 4:

$$\text{Work} = \text{Ball mass} \times g \times \text{dropping height} \tag{4}$$

where g is the value of gravity acceleration.

5.3 *Durability properties*

5.3.1 *Abrasion resistance (EN 14157)*

The faces exposed in use of six specimen slabs were abraded by means of a Capon wearing machine (Tecnilab 440C). In this machine type, abrasion is obtained by using both a rotating abrasion wheel (with standard dimensions and made of a standard steel) and a standard abrasive powder (white fused alumina). A Certified Reference Material (CRM)—"Marbre du Boulonnais"—was used to calibrate the testing machine, but also to correct test results. The test was carried out under standard conditions and at the end a groove was obtained in the tested face. The abrasion resistance value is the chord dimension measured on the middle of the groove

Table 3. Results of CS and FS for the studied volcanic natural stones.

Volcanic stones	CS MPa	FS MPa
S. Miguel Island		
Pedra do Porto Formoso	81	13.6
Pedra da Povoação	6	1.4
Basalto da Chã das Gatas	32	7.8
Basalto do Bacharel	53	9.5
Pedra do Dâmaso	86	7.7
Sta. Maria Island		
Pedra da Vila do Porto	7	3.1
Pedra do Anal	8	4.7

Table 4. AD, OP and WA results obtained for the studied volcanic natural stones.

Volcanic stones	AD (kg/m^3)	OP (%)	WA (%)
S. Miguel Island			
Pedra do Porto Formoso	2220	9.4	4.7
Pedra da Povoação	1430	34.6	27.4
Basalto da Chã das Gatas	1930	6.5	3.7
Basalto do Bacharel	2160	7.0	3.7
Pedra do Dâmaso	2190	5.2	2.9
Sta. Maria Island			
Pedra da Vila do Porto	1430	26.0	21.1
Pedra do Anal	1630	24.5	16.1

Table 5. Results obtained for IR and AR for the studied volcanic natural stones.

Volcanic stones	IR Joules	AR mm
S. Miguel Island		
Pedra do Porto Formoso	4	23.0
Pedra da Povoação	2	42.5
Basalto da Chã das Gatas	4	22.0
Basalto do Bacharel	6	20.0
Pedra do Dâmaso	4	20.0
Sta. Maria Island		
Pedra da Vila do Porto	3	26.0
Pedra do Anal	4	25.5

after correction according to the value obtained for CRM.

5.4 *Physical and mechanical properties*

The average results of *uniaxial compressive strength* (CS) and *flexural strength under concentrated load* (FS) obtained for the studied volcanic natural stones are listed in Table 3.

The average results obtained for *apparent density* (AD), *open porosity* (OP) and *water absorption at atmospheric pressure* (WA) are listed in Table 4.

Rupture energy, also known as impact resistance (IR) and abrasion resistance (AR) average results obtained for the studied volcanic stone samples are listed in Table 5.

6 DISCUSSION OF THE RESULTS OF THE PHYSICAL-MECHANICAL TESTS

Analyzing the results obtained for *compressive strength* on the studied volcanic natural stones, three of them from S. Miguel Island (Pedra do Porto Formoso, Basalto do Bacharel and Pedra do Dâmaso) present values above 40 MPa. Any values below the referred to value usually are considered low. Stones *Flexural strength* commonly has identical behaviour to the *compressive strength*. Stones that present low values of compressive strength also present low values of flexural strength and vice-versa. On the studied volcanic natural stones, the only exception to this statement is Pedra do Dâmaso that presents the highest value of *compressive strength* (86 MPa), but does not has the highest value for *flexural strength* that belongs to Pedra do Porto Formoso (13.6 MPa). All *flexural strength* values under 4 MPa usually are considered low; only two stones present values below this limit (Pedra da Povoação and Pedra da Vila do Porto).

The results obtained for the physical properties (presented in Table 2) are compatible with the types of natural stone being tested. Their open porosity is high, and consequently their *apparent density* is low. Concerning *open porosity*, values above 10% are considered very high and three of the studied volcanic natural stones exceed this limit (Pedra da Povoação and the two stones from Sta. Maria Island). These three stones are also the only ones which present *water absorption* values above 6%, value above which water absorption is considered high. As expected, physical properties have great influence on the mechanical behavior. That is why stones having higher apparent density and both lower open porosity and water absorption generally present higher values of compressive and flexural strength.

Analyzing the results of the test *resistance to impact*, only Pedra da Povoação presents a value of 2 Joules, which is considered very low, and Pedra da Vila do Porto is the only one that presents a value which is considered low (3 Joules).

In terms of *resistance to abrasion*, Pedra da Povoação presents the highest value (42.5 mm), and is the only stone that should not be used for paving. The two volcanic natural stones from Santa Maria Island should only be used for paving on low traffic conditions (for private applications). The remaining volcanic natural stones can be used for collective applications. Pedra do Porto Formoso and Basalto do Chão das Gatas only could be used for moderate traffic conditions. On the other hand, Basalto do Bacharel and Pedra do Dâmaso could be used for both moderate and strong traffic conditions.

7 CONCLUSIONS

The research being carried out on volcanic natural stones of different typology from the Azores archipelago clearly has shown how much the physical-mechanical properties are dependent upon rock lithology and texture. Such has been also found on similar studies carried out by Gomes & Silva (1997), Silva *et al.*, 2002, and Silva & Gomes (2004), on volcanic natural stones from the Madeira archipelago.

Compiling the information obtained for the physical and mechanical properties of the studied volcanic natural stones from the Azores, it can be concluded that all stones are more suited for internal applications, due to the fact that the required water absorption value for external applications is usually $\leq 0.5\%$.

Pedra da Povoação from S. Miguel Island is not suitable for paving, not only because of its high abrasion resistance value (42.5 mm), but also because of its low impact resistance (2 Joules). In fact, for most of the applications, the selection of this stone and also of the two stones from Sta. Maria Island has to be deeply considered to avoid unsuccessful results.

In Portugal and in many European countries there are not national specifications which regulate property values that stones should satisfy to be used as construction materials. As a consequence, the selection of an adequate stone for a specific application depends mainly upon the prescriber expertise.

This study, in addition to the characterization of several volcanic natural stones exploited in the Azores archipelago, also put forward some considerations about stone applications.

Until the eighties the exploitation and processing of natural stone was performed using manual processes and the stone was used almost exclusively in religious, civil and military architecture. Since then new extractive methods have been introduced that allowed to increase production, to improve the quality and to increase the variety of products to be used in civil construction, public works and funerary art. In general, the applications given over time to the natural stone of the Azores are in accordance with the results obtained in the physical-mechanical tests being carried out.

The lithological varieties corresponding to the so-called "pedra de lavoura" and "welded pyroclasts" impede any type of polishing due to several factors: the low hardness of many of their minerals, the existence of glass in some stones, the porosity exhibited by others, and the alteration degree as well as the weak cohesion between minerals shown in some others.

Despite the existing textural (porosity, size of the volcanic fragments, and xenoliths) and compositional differences shown by the studied lithologies, the obtained results are very similar. Such findings are important to assure both quality and certification of the manufactured products and the consumer confidence. However, it is recommended the consultation of the harmonized standards corresponding to the different products to be manufactured, as well as the periodic control of raw materials, of products dimension and of the processing equipments.

The waste from the processing of natural stone in the Azores is almost totally utilizable. In what concerns the so-called "pedra de lavoura" (hawaiite, trachybasalt and trachyte) the waste is utilized, either in the production of pre-fabricated, or sold as the so-called "lajetas" applied to face walls and pavements, whereas the waste from the "welded pyroclasts" (tuff and lapilli tuff) after being ground is utilized both as soil for greenhouses, and as inert material in the manufacture of bricks for civil construction.

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