EVALUATION OF THE TECHNICAL PROPERTIES OF PORCELAIN TILE AND GRANITE

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ABSTRACT

In the year 2000, the production of porcelain tile in Brazil was approximately 0.9% of total ceramic tile production, i.e., 4 million m², a very low figure compared with the production of Italy in same year (approximately 268.5 million m²).[1] In Brazil, only four companies have produced porcelain tile, but there is a tendency for growth in the next few years. In the ceramic tile market, the main products competing with porcelain tile are natural stones (marbles and granites). In 2000, Brazilian production of marbles and granites was estimated at 3.92 million tons, of which 75% was granite and 25% marble production.[2] As marbles generally present low hardness and mechanical strength for use in flooring, only granites were chosen for this study. The main objective of the work was to carry out a technical comparison between the two types of coverings: porcelain tile and granite, with the intention of establishing the technical advantages and disadvantages of each, and proposing improvements for greater competitiveness of the ceramic product against its main competitor. Samples of national and imported porcelain tiles, and five types of Brazilian granite were studied. The types of porcelain tile evaluated were polished and natural products with plain colours and "salt and pepper" decorations.

1. INTRODUCTION

After the development of fast firing (single fire), which characterised the end of the 70s and beginning of the 80s, the second great revolution in the ceramic sector was the conception of porcelain tile, a product that differs from other types of ceramic tiles owing to its highly technological production process, with fast firing cycles at temperatures around 1200 to 1250°C. Due to the high level of quality of its raw materials, high degree of milling, high grade fluxes and high required compaction force, the manufacturing process yields products with low porosity (less than 0.5%) and high mechanical strength, chemical and frost resistance. Porcelain tile can be classified in terms of: natural, polished and glazed.[3]

World production of porcelain tile has increased steadily in the last few years. Due to the development of porcelain tile decoration technologies (double-charge pressing, application of soluble salts, etc), it is possible to obtain products with a very similar "design" to natural stones, mainly involving certain marbles and granites. Unglazed porcelain tile competes directly with stone in the market, but the price is generally lower. To date, no technical studies have been found on the technical behaviour of stones compared with porcelain tile, with a view to highlighting the technical characteristics of each, thus providing a tool to promote porcelain tile sales.

The objective of this work was to investigate the chemical, physical and mechanical properties of several types of granites and compare these with the same properties of porcelain tile. This study has allowed identifying the technical differences between the ceramic material and natural stones, and evaluating the technical advantages and disadvantages of each. It has also enabled diagnosing which technical characteristics could be improved in porcelain tiles with a view to heightening its competitiveness in the market.

2. EXPERIMENTAL PROCEDURE

2.1 MATERIALS USED

The commercial porcelain tile products used in the study, together with their origins, names and technical characteristics, are presented in Table 1. The products were bought in a large construction materials store. The selected products were "tinta unita" (plain colour) and "salt and pepper."

The choice of granite types was made based on their availability in the Brazilian market and having a price similar to porcelain tile. The granites and their names are given in Table 2. They were acquired at a large marble producer.

Type	Code	Size (cm^2)	Thickness (cm)
Polished porcelain tile tinta unita	NPBRAN	30 x 30	<7.5
Polished porcelain tile salt and pepper	NPGRAF	30 x 30	<7.5
Natural porcelain tile salt and pepper	NNGRAF	30 x 30	<7.5
Polished porcelain tile tinta unita	IPPAR	30 x 30	<7.5
Polished porcelain tile salt and pepper	IPBAR	30 x 30	<7.5
Natural porcelain tile salt and pepper	INBAR	30 x 30	<7.5
Polished porcelain tile tinta unita	EPNEV	40 x 40*	>7.5
Polished porcelain tile salt and pepper	EPTEN	40 x 40*	>7.5
Natural porcelain tile salt and pepper	ENTRAT	40 x 40*	>7.5

* No Spanish products were found in the Brazilian market with nominal sizes of 30 x 30 cm, so that larger tiles were used

Table 1: Studied porcelain tiles, their names and codes, sizes and thickness.

Commercial Names	Code	Size (cm^2)	Thickness (cm)
Granite Branco Cotton Polished	GBRAN	30 x 30	1,0
Granite Gris Andorinha Polished	GCINZ	30 x 30	1,0
Granite Capão Bonito Polished	GCAP	30 x 30	1,0
Granite Café Labrador Polished	GCAFÉ	30 x 30	1,0
Granite Preto São Gabriel Polished	GPRET	30 x 30	1,0

Table 2: Brazilian granites selected for this study with their names and codes, sizes and thickness.

In Brazil granites are sold in so-called "plumavit" packings without any information regarding size, main technical characteristics or way of installation.

The packings of the standard types of porcelain tile contain essential technical information as guidance on correct product specification and installation.

2.2 EVALUATION OF CHEMICAL COMPOSITION AND PHASES PRESENT

Chemical analysis of the twelve types of porcelain tile studied was carried out by X-ray fluorescence (XRF). To evaluate the crystalline phases present in the ceramic tiles, X-ray diffraction (XRD) tests were carried out on the powdered samples, using a SIEMENS D 5000 instrument.

The petrographic analyses of the granites were based on qualitative and quantitative mineralogical characterisation and on general aspects of texture and structure, observing relations of contacts between crystals, degree of alteration of the minerals and state of microcracks. For stone with fine to medium grain, mineralogical quantification was determined by summation of the minerals in thin sheets, using a Swift automatic digital instrument coupled to a stereoscopic microscope. For the stones with coarser grain, microscopic quantification was supplemented by summation of the minerals using coloured macroscopic cross sections for etching with hydrofluoric acid, followed by treatment with sodium cobalt nitrite, allowing microscopically distinguishing between potassium feldspar, quartz and plagioclase.

2.3 WATER ABSORPTION

To determine the water absorption of the products studied, the test method was used involving the Archimedes principle, in which completely dry tiles, already weighed, were submerged in water and boiled for 2 hours. The tiles were then reweighed and water absorption was calculated:

$$Wa = \frac{m_2 - m_1}{m_1} \times 100$$

where:

Wa= water absorption (%), m_1 = dry weight (g) and m_2 = saturated weight (g).

2.4 EVALUATION OF MOHS HARDNESS

The evaluation of Mohs hardness of the porcelain tile and granite samples was carried out according to Brazilian Standard NBR 13818[4] - Annex V (ISO 10545), making scratches by hand with minerals of known hardness (gypsum, calcite, fluorite, apatite, orthoclase, quartz, topaz, corundum) on the surface of the products.

2.5 DETERMINATION OF STAIN RESISTANCE

The stain resistance of the porcelain tile and granites was evaluated by verification of their cleanability after application of staining agents to the surface of the pieces, according to the test described in Brazilian Standard NBR 13818 - Annex G (ISO 10545).

The products were rated in cleaning classes of 1 to 5 according to the scale:

a) class 1 - Impossibility of removing the stain;

b) classes 2, 3 and 4 - Possibility of stain removal, depending on the applied agent and cleaning product used;

c) class 5 – This corresponds to the greatest stain cleanability.

2.6 EVALUATION OF MECHANICAL STRENGTH

The bending strength modulus (MRF) was determined by the 3-point mechanical bending strength test, using a Gabbrielli - model CR4 + E1, apparatus according to the procedure described in Brazilian Standard NBR 13818 - Annex C (ISO 10545). After the mechanical strength test, Weibull Statistics was applied to the results, to establish the modulus of reproducibility of the products being studied.

The Weibull modulus was calculated from the equation:

$$\mathrm{Lnln}\,(1/S) = \ln V - m\ln\sigma_o + m\ln \mathrm{MRF}$$

where: S is the probability of survival, V is volume; σ_o is the equation fitting parameter and MRF is the applied force.

2.7 DETERMINATION OF ABRASION RESISTANCE

The determination of the resistance to deep abrasion was carried out on a CAP – Gabrielli abrasion tester, as set out in Brazilian Standard NBR 13818 - I Annex E (ISO 10545). The abrasive material used was sieve 80 electrofused alumina.

The determination of abrasion resistance using the Amsler Method, the method used by the natural stone sector, was found by measuring the loss of thickness of stone test specimens. In accordance with Brazilian standard NBR 12042, the test specimens have a rectangular form with dimensions of 7.0X5.0X2.5 cm, and are subjected to abrasion in an Amsler Machine. In the apparatus, the samples travel 1000m in contact with sand abrasive. Wear is measured as the difference in thickness of the test specimens before and after the test. Abrasion resistance is related to grain size, hardness and state of aggregation of the minerals in the stones.

2.8 EVALUATION OF THE DYNAMIC COEFFICIENT OF FRICTION

The coefficient of friction was measured using a TORTUS - Gabrielli measuring system, in accordance with the procedure described in Brazilian standard NBR 13818 - Annex N (ISO 10545).

2.9 DETERMINATION OF RESISTANCE TO CHEMICAL ATTACK

For the determination of the resistance to chemical attack of the studied porcelain tiles and granites, the procedure described in Brazilian Standard NBR 13818 - Annex H (ISO 10545) was used.

The agents used in the chemical attack were:

- Household chemical products - ammonium chloride, 100 g/l;
- Products for treating swimming pool water - 20 mg/l sodium hypochlorite solution, made using technical grade sodium hypochlorite, with approximately 13% active chlorine;

- *Low concentration acids*

a) hydrochloric acid solution at 3% (V/V), by volume, prepared from concentrated hydrochloric acid {density equal to $(1.19 \pm 0.01) g/cm^3$};

b) citric acid solution, 100 g/l.

- *High concentration acids*

a) hydrochloric acid solution at 18% (V/V), by volume, prepared from concentrated hydrochloric acid {density equal to $(1.19 \pm 0.01) g/cm^3$};

b) lactic acid solution, 5% (V/V).

- Low concentration alkalis - 30 g/l potassium hydroxide solution
- High concentration alkalis - 100 g/l. potassium hydroxide solution

The codes used in the classification were as follows:

a) U (unglazed);

c) H (high concentration);

d) L (low concentration) ;

e) A/B/C - these are classes of chemical resistance.

2.10 DETERMINATION OF THE COEFFICIENT OF LINEAR THERMAL EXPANSION

Samples of porcelain tile and granites were cut measuring 1X1X5cm and tested in a NETZSCH 402E dilatometer at a heating rate of 10°C/minute.

3. RESULTS AND DISCUSSION

3.1 EVALUATION OF THE CHEMICAL COMPOSITION OF THE PHASES PRESENT

Table 3 sets out the chemical analysis data of all the porcelain tile samples studied.

Compounds	Percentage								
	NPGRAF	NNGRAF	NPBRAN	IPPAR	IPBAR	INBAR	ENTRAT	EPTEN	EPNEV
SiO_2	71.44	71.96	69.34	71.55	72.96	72.25	69.12	69.46	67.74
Al_2O_3	17.99	17.67	18.44	17.27	17.32	17.95	19.98	19.43	21.10
Fe_2O_3	1.27	1.57	0.68	0.37	0.50	0.54	0.74	0.77	0.44
CaO	0.25	0.24	0.20	0.55	0.77	1.14	0.43	0.37	0.74
Na_2O	3.29	3.10	2.30	5.10	4.09	5.10	4.99	4.95	5.63
K_2O	3.16	2.84	3.53	1.87	2.37	1.23	1.27	1.33	0.64
MnO	<0.01	<0.01	0.01	0.02	0.01	< 0.01	0.02	0.02	<0.01
TiO_2	0.50	0.54	0.43	0.13	0.35	0.45	0.69	0.69	0.48
MgO	0.78	0.86	0.32	0.27	0.35	0.39	0.16	0.23	0.10
P_2O_5	0.20	0.15	0.19	0.33	0.19	0.17	0.25	0.31	0.21
Cr_2O_3	0.37	0.54	0.01	0.03	0.09	0.14	0.14	0.16	0.01
ZrO_2	0.51	0.38	4.24	2.20	0.68	0.34	2.06	2.02	2.66
SrO	0.02	0.02	0.02	0.02	0.03	0.05	0.02	0.02	0.02
L.O.I.	0.25	0.13	0.28	0.30	0.29	0.25	0.10	0.26	0.22

Table 3: Chemical analysis data of the porcelain tile samples studied.

Analysing Table 3 shows that:

- lthe quantities of SiO_2 and Al_2O_3 of the products NPGRAF, NNGRAF, NPBRAN, IPPAR, IPBAR and INBAR are similar;

- the products ENTRAT, EPTEN and EPNEV presented a greater quantity of Al_2O_3 and smaller percentage of SiO_2 when compared with the Brazilian and Italian products;

- the lighter the colour of the product mass (NPBRAN, IPPAR and EPNEV), the larger is the quantity of Al_2O_3 and ZrO_2. Of the three light-coloured products, the product NPBRAN presented the largest percentage of ZrO_2 (4.24%) compared with product IPPAR (2.20%) and EPNEV(2.66%);

- except for products NPGRAF, NNGRAF and NPBRAN, the others presented larger quantities of Na_2O and lower percentages of K_2O compared with those previously mentioned. This fact could indicate that these products were made with a larger content of Na_2O flux, and the products NPGRAF, NNGRAF and NPBRAN with sodium potassium flux contents;

- the products IPBAR, INBAR and IPPAR exhibited larger quantities of CaO than the other products;

- the products NPGRAF and NNGRAF exhibited larger quantities of Fe_2O_3 compared with the other studied products, which probably contributed to their darker colour.

Table 4 sets out the crystalline phases present in the studied ceramic products.

Sample	Phases present
NPGRAF	Quartz, Mullite
NNGRAF	Quartz, Mullite
NPBRAN	Quartz, Mullite
IPPAR	Quartz, albite, mullite
IPBAR	Quartz, mullite and small quantity of albite
INBAR	Quartz, mullite, and small quantity of albite
ENTRAT	Quartz, mullite
EPTEN	Quartz, mullite and small quantity of albite
EPNEV	Quartz, mullite and small quantity of albite

Table 4: Crystalline phases present in the studied ceramic products

The crystalline phases present in the porcelain tiles, as shown by the XRD results, basically consist of quartz and mullite. Except for products NPGRAF, NPBRAN and NNGRAF, the presence of a small quantity of albite was found in the others, confirming the chemical analysis results, which indicated the probable use of sodium feldspar (albite) in a larger quantity in making these products.

Table 5 sets out the results of the petrographic analysis of the granites. Granite GCAP is a red-coloured stone (due to the presence of potassium feldspar), with a solid structure and medium-to-large non-uniform granular texture. The grain size varies from approximately 3 to 20 mm, where the largest crystals are microcline (potassium feldspar). The quartz occurs forming aggregates with irregular forms that can reach sizes exceeding 20 mm. The degree of microcracking is moderate, with intergranular microcracks predominating.

Granite GCINZ is a grey stone with a light colour, solid structure and uniform granular texture from medium to medium/fine, with grain sizes varying from 0,5 to 5 mm, and crystals predominating with dimensions of 1 to 2 mm. The degree of microcracking is moderate, predominantly intragranule microcracks being found.

Granite GBRAN is characterised as a white stone, with a solid structure and porphyritic texture with a matrix of medium/fine grains. The phenocrysts are represented by quartz crystals that can reach approximately 10 mm. The stone presents a discreet degree of microcracking.

Sample GCAFE is a coffee-coloured stone, with a laminated structure and non-uniform granular texture with medium/coarse grains with crystals varying from 0.5 mm to 10 mm, 7 mm grain sizes predominating. The degree of microcracking is high, but almost exclusively of an intragranule character, and having low communication with each other.

Granite GPRET is dark grey, with a solid structure and discreetly non-uniform granular texture, medium to medium/fine, of a generally homogeneous appearance, in which plagioclase crystals are to be noted measuring 3x 55 mm. The stone exhibits an intense degree of microcracking.

Samples		GCAP	GCINZ	GBRAN	GCAFE	GPRET
Quartz		30.0	30.0	28.0	-	1.0
Plagioclase		17.0	25.0	45.0 (albite)	Tr	60.0
Microcline		45.0	31.0	20.0	75.0	-
Biotite		4.0	12.0	-	5.0	10.0
Aegerine – augite (clinopx.)		-	-	-	15.0	-
Augite (Clinopyrox.)		-	-	-	-	7.0
Hypersthene (orthopyrox.)		-	-	-	-	18.0
Mica		-	-	7.0	-	-
Opaque		Tr	1.5	-	2.5	3.5
Titanite		-	0.5	-	1.5	Tr
Apatite		Tr	Tr	Tr	1.0	0.5
Topaz		-	-	Tr	-	-
Zircon		Tr	Tr	Tr	Tr	Tr
Sericite		Tr	Tr	Tr	Tr	Tr
Chlorite		Tr	Tr	-	Tr	Tr
Epidote		Tr	Tr	Tr	Tr	Tr
Carbonate		Tr	Tr	Tr	Tr	Tr
Clay minerals		Tr	Tr	Tr	Tr	Tr
Grain size (mm)	Variation	3 to 20	0.5 to 5	-	0.5 to 10	0.5 to 5.5
	Predomin.	10	1 to 2	-	7	2
Porphyritic (mm)	Matrix			0.5 to 2		
	Phenocryst			5 to 10		
Classification		Syeno/Monzogranite	Monzogranite	Microcline – albite granite	Syenite	Gabronorite
Structure		Solid	Solid	Solid	Laminated	Solid
Texture		Non-uniform granular medium to large	Uniform granular medium to medium/fine	Porphyritic	Non-uniform granular medium/large	Non-uniform granular medium/fine
Nº Microcracks /mm^2		0.47 (moderate)	1.25 (moderate)	0.1 (low)	2.8 (high)	3.6 (high)
Contact (%)	Conc./convex	80.4	71.5	78	53.4	70.8
	Flat	19.6	28.5	22	46.6	29.2
Degree of alteration		Moderate	Incipient to moderate	Incipient	Incipient	Incipient

Table 5: Synopsis of the results of the petrographic analysis of the granites studied.

3.2 EVALUATION OF WATER ABSORPTION

Table 6 sets out the water absorption results of all the porcelain tile and granite samples in the study.

Analysis of Table 6 shows that all the porcelain tile samples presented water absorption values below the limit set by Brazilian standard NBR 13818 - ISO 13006 (less than 0.5% water absorption).

The water absorption values of the granites, except GPRET, are higher than those of the porcelain tile samples, but below 0.5%. The degree and type (inter or intra granular) microcracks, microstructural heterogeneity and grain size influence the water absorption value of the granites.

Porcelain tile		Granite	
Sample	**Water absorption (%)**	**Sample**	**Water absorption (%)**
NPBRAN	0.11 ± 0.02	GCAFE	0.33 ± 0.11
NPGRAF	0.06 ± 0.01	GPRET	0.15 ± 0.07
NNGRAF	0.10 ± 0.02	GBRAN	0.29 ± 0.01
IPPAR	0.06 ± 0.04	GCINZ	0.42 ± 0.01
IPBAR	0.13 ± 0.02	GCAP	0.21±0.01
INBAR	0.08 ± 0.01		
EPNEV	0.10 ± 0.01		
EPTEN	0.09 ± 0.01		
ENTRAT	0.09 ± 0.01		

Table 6: Water absorption values with the respective STD deviations of the studied porcelain tile and granite samples.

3.4 EVALUATION OF MOHS HARDNESS

Table 7 gives the Mohs hardness data of the porcelain tile and granite samples. Table 7 shows that the polished porcelain tile products exhibit Mohs hardness 3. Although porcelain tile is characterised by having high mechanical strength and abrasion resistance, this product presents lower Mohs hardness after the polishing stage, which can indicate a greater tendency to scratch in use. Surface polishing, besides contributing to opening closed porosity contained in the products, makes it more susceptible to scratching. The natural products already presented Mohs hardness 6, with great difficulties for visualising the scratches.

Porcelain tile		Granite	
Sample	**Mohs hardness**	**Sample**	**Mohs hardness**
NPGRAF	3	GCAFE	5
NNGRAF	6	GPRET	5
NPBRAN	3	GBRAN	3
IPPAR	3	GCINZ	6
IPBAR	3	GCAP	3
INBAR	5		
ENTRAT	6		
EPTEN	3		
EPNEV	3		

Table 7: Mohs hardness of the studied porcelain tile and granites.

Granite GCINZ presented the greatest Mohs hardness (hardness 6). Granites GCAFE and GPRET exhibited Mohs hardness 5, and granites GBRAN and GCAP Mohs hardness 3, similarly to the samples of polished porcelain tile. Except the granites GBRAN and GCAP, the others exhibited higher Mohs hardness than the samples of polished porcelain tile. The fact that granite has a microstructure made up of quartz and feldspar crystals of different sizes and colours, and already has a certain degree of microcracking, makes the scratches less visible.

3.4 EVALUATION OF STAIN RESISTANCE

Table 8 presents the results of the stain resistance test on the studied porcelain tile samples.

Table 8 shows that practically all the polished products presented a tendency to stain when in contact with the penetrating agents, iron oxide in fine oil and chromium oxide in light oil, presenting cleaning class 1 (impossibility of stain removal). This behaviour is related to the polishing process, during which closed porosity appears at the surface, as Figure 1 shows. Another characteristic observed was that the products with a lighter colour showed the stain in a more pronounced way. Product NPGRAF exhibited cleaning class 3 with the staining agents, but this could be related to the difficulty of visualising the stains due to the dark colour of the ceramic tiles. The appearance of the stains in sample NPBRAN is homogeneous, unlike samples IPPAR and EPNEV that presented concentrated stains.

With regard to the susceptibility of the products on exposure to an oxidising agent (iodine in alcohol solution), the samples of polished porcelain tile NPGRAF AND NPBRAN presented cleaning class 3, the polished products IPPAR, and IPBAR presented class 3 to 4, and the polished products EPNEV and EPTEN presented class 4 to 5.

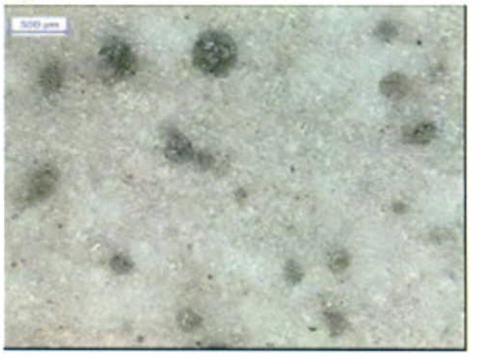
With regard to the film-forming agents (olive oil), the polished products NPGRAF, NPBRAN, IPPAR and IPBAR presented cleaning class 4 to 5, but the polished products EPTEN and EPNEV presented a much lower cleaning class (class 1), which could restrict the use of these products in industrial and domestic environments. The great susceptibility of these polished products to staining by film-forming agents can be attributed to the presence of large-size pores appearing at the surface of the products after polishing.

Sample	Cleaning class			
	Iron oxide	Chromium oxide	Iodine	Olive oil
NPGRAF	3 (saponaceous)	3 (saponaceous)	3 (saponaceous)	4 (detergent)
NNGRAF	5 (hot water)	5 (hot water)	5 (hot water)	5 (hot water)
NPBRAN	1	2 (HCl – 3% by volume)	3 (saponaceous)	4 (detergent)
IPPAR	1	1	3 (saponaceous)	4 (detergent)
IPBAR	1	1	4 (detergent)	4 (detergent)
INBAR	5 (hot water)	5 (hot water)	5 (hot water)	5 (hot water)
EPTEN	1	1	4 (detergent)	1
EPNEV	1	1	5 (hot water)	1
ENTRAT	5 (hot water)	5 (hot water)	5 (hot water)	5 (hot water)

Table 8: Cleaning class of the porcelain tile samples in terms of types of staining agents.

Cleaning classes: 1-impossibility of removing the stain, 2-stain removable with 3% HCl by volume, 3-stain removable with strong cleaning product (abrasive), 4-stain removable with weak cleaning product (detergent) and 5-maximum ease of stain removal (hot water).

NPBRAN



IPBAR

Figure 1: Image analysis of the polished porcelain tile surface, verifying the presence of porosity.

The samples of natural porcelain tile presented cleaning class 5 (maximum cleanability) for all the types of staining agents. This again confirms that surface polishing negatively affects porcelain tile stain resistance.

Table 9 presents the results of the stain resistance test on the two studied granites. Even though they have low water absorption, granites generally have inter or intragranular microcracks (Figure 2), which contribute to surface stain formation of the stones on coming into contact with staining agents. Simple contact with water already produces an alteration in the colour of the granites. However, the presence of crystals of various sizes and bright colours helps hide stain visibility a little.

Sample	Cleaning class			
	Iron oxide	Chromium oxide	Iodine	Olive oil
GCAFE	1	3	5	4
GPRET	4	4	5	5
GBRAN	1	1	5	1
GCINZ	2	2	2	2
GCAP	1	1	5	1

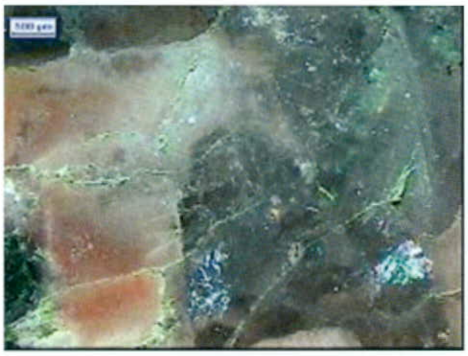
Table 9: Cleaning class of the granites in terms of types of staining agents.

Table 9 shows that granite GPRET presents a larger number of microcracks per mm^2, followed by granites GCAFE, GCINZ, GCAP and GBRAN, respectively. Although having a greater degree of microcracking, the dark colour of sample GPRET made it difficult to visualise the presence of the stains on the tile surface, which is why it presented cleaning classes 4 to 5.

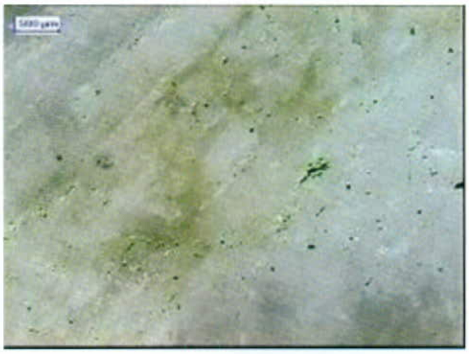
Analysing Table 9 confirms that the polished granites with a light colour presented a tendency to stain when in contact with the penetrating agents, iron oxide in fine oil and chromium oxide in fine oil, exhibiting cleaning classes from 1 to 2 (impossibility of stain removal or removal with 3% HCl solution). In granites GCAP and GCAFE, the staining agents ended up penetrating right through the thickness of the samples, appearing on the opposite surface.

With regard to the susceptibility of the products on exposure to the action of an oxidising agent (iodine in alcohol solution), the granites, except for GCINZ, presented cleaning class 5, i.e., maximum ease of stain removal.

As regards the film-forming agents (olive oil), the white granites exhibited cleaning class 1, i.e. impossibility of stain removal, which can restrict the use of the products in industrial and domestic environments. It is important to note that the solution of hydrochloric acid, used in the last cleaning stage, attacked the granites producing chromatic alterations of the stone surface.



GCAP



GBRAN

Figure 2: Image analysis of the granites showing the cracks into which the staining agents penetrate.

3.5 DETERMINATION OF MECHANICAL STRENGTH

Table 10 lists the breaking load and bending strength modulus for each studied porcelain tile. It is important to note that, except for products EPTEN, EPNEV and ENTRAT, all the other porcelain tile samples were less than 7.5 mm thick.

In accordance with Brazilian Standard NBR 13818, porcelain tile shall present a bending strength exceeding 35 MPa, with a minimum individual value of 32 MPa, and breaking load exceeding 1300N (for products with thickness $\geq$ 7.5 mm) and 700N (for thickness $\leq$ 7.5 mm). Table 10 shows that all the products meet the requirements of the standard and that the Brazilian products exceed the values set in the standard by up to about 80%. The Weibull modulus of the porcelain tile samples varied with the STD deviations. The products that exhibited the smallest STD deviations (NPGRAF, NNGRAF, NPBRAN, NNBIAN, ENTRAT and IPBAR) had the highest Weibull moduli. The higher the Weibull modulus, the greater is the reproducibility of the mechanical strength property of the product.

On correlating the modulus of rupture and total porosity of the porcelain tile samples, it was observed that there is no direct relationship between the two properties, because the products with the smallest total porosity values do not always present the greatest mechanical strength. Therefore, it is probably the largest flaw present in the test specimens (for example the largest pore) that influenced the mechanical behaviour of the products and not the quantity of pores present.

Sample	CR (N)	CR_{min} (N)	MRF (MPa)	MRF_{min} (MPa)	m
EPTEN	2220.9±113.9	1962.8	43.3±2.6	39.2	17.9
ENTRAT	2636.9±122.9	2402.0	45.9±2.0	42.1	24.5
EPNEV	2017.8±155.6	1773.5	38.3±3.3	32.8	12.7
INBAR	1435.4±83.4	1159.9	47.9±3.2	38.1	15.7
IPBAR	1893.89±93.1	1716.7	49.1±2.4	45.3	22.2
IPPAR	1923.9±127.9	1745.5	47.9±2.9	43.5	17.5
NPGRAF	1934.2±57.1	1807.9	51.4±1.5	47.7	37.1
NNGRAF	2197.9±103.5	2011.5	54.6±2.5	51.3	24.3
NPBRAN	1792.7±85.5	1612.5	50.2±2.3	45.0	23.7
NPPER	2017.3±97.3	1795.8	61.6±3.4	54.55	19.94
NPBIAN	2198.5±151.9	1705.08	64.8±4.8	49.20	13.83
NNBIAN	2595.5±120.2	2355.6	64.9±3.3	56.9	22.08

Table 10: Values of breaking load (CR), minimum individual breaking load (CR_{min}), bending strength modulus (MRF), minimum individual bending strength modulus (MRF_{min}) and Weibull modulus of the studied porcelain tile samples.

Table 11 presents the results of the breaking load and bending strength modulus for each granite in study. It is important to note that all the granites were over 7,5 mm thick.

Sample	CR (N)	CR_{min} (N)	MRF (MPa)	MRF_{min} (MPa)	m
GCAFE	771.5±237.0	465.5	11.4±2.3	7.5	5.4
GPRET	1546.2±253.8	1156.8	22.8±4.1	16.2	5.9
GBRAN	1434.1±104.2	995.9	21.6±1.5	14.9	11.9
GCINZ	1347.8±380.4	502.7	16.1±2.6	11.8	6.7
GCAP	637.3±137.9	378.2	11.3±2.2	7.4	5.4

Table 11: Values of breaking load (CR), minimum individual breaking load (CR_{min}), bending strength modulus (MRF), minimum individual bending strength modulus (MRF_{min}) and Weibull modulus of the studied granites.

Table 11 shows that the mechanical strength of the natural stones is relatively low when compared with the synthetic product porcelain tile, i.e., they did not present even exhibit the minimum individual value of 32 MPa required by the Standard for porcelain tile. The smaller the grain size and the better the bonding between the granules, the greater is granite mechanical strength.

The granites also presented lower Weibull moduli than the porcelain tile products, which was expected, because granites are natural stones with great microstructural heterogeneity, which limits the reproducibility of mechanical strength.

Granite GPRET had the largest mechanical strength value. Though exhibiting widespread microcracking, grain size is small and the connections between crystals are very good. Granite GBRAN has a porphyritic grain structure, with bundles of similar size grains and some large grains. Even with large size grains, its degree of microcracking is low, which contributes to its good mechanical strength. Granites GCAP and GCAFE presented coarse grain size and mean-to-high degree of cracking, therefore exhibiting low mechanical strength. Finally, granite GCINZ presented medium grain size and a moderate degree of microcracking, yielding a mechanical strength value midway between GBRAN and GCAP/GCAFE.

3.6 EVALUATION OF ABRASION RESISTANCE

Table 12 gives the results for resistance to deep abrasion of the porcelain tile and granite samples.

Brazilian Standard NBR 13818 (ISO 13006) establishes that porcelain tile needs to exhibit material volume removal by deep abrasion smaller than or equal to 175 mm^3. Table 12 shows that all the studied products meet the requirements of the Brazilian Standard.

Porcelain tile			Granite		
Sample	**C_{CAV} (mm)**	**V (mm^3)**	**Sample**	**C_{CAV} (mm)**	**V (mm^3)**
NPGRAF	20.6 ± 0.3	73.1 ± 4.0	**GCINZ**	22.0 ± 0.2	89.0 ± 3.0
NNGRAF	20.6 ± 0.2	72.5 ± 2.1	**GBRAN**	19.7 ± 0.2	63.9 ± 3.8
NPBRAN	20.2 ± 0.2	69.0 ± 2.1	**GPRET**	23.7 ± 0.4	111.1 ± 5.9
IPPAR	20.5 ± 0.4	72.6 ± 4.6	**GCAP**	19.6 ± 0.5	63.5 ± 5.8
IPBAR	20.6 ± 0.2	73.0 ± 1.4	**GCAFE**	23.6 ± 0.5	109.7 ± 6.3
INBAR	20.3 ± 0.4	69.6 ± 4.5			
EPNEV	20.5 ± 0.2	72.0 ± 1.8			
EPTEN	20.3 ± 0.2	70.5 ± 1.4			
ENTRAT	20.8 ± 0.1	75.1 ± 1.3			

Table 12: Mean values of cavity size (CCAV) and volume of material removed (V) during the deep abrasion test on the studied samples of porcelain tile and granite.

With regard to the granites, all presented resistance to deep abrasion below 175mm^3. The larger the quartz content and larger the quartz crystal size present, the greater is granite resistance to abrasion. The granites GBRAN, GCAP and GCINZ presented a high quartz content and the coarsest grain size, and therefore the best deep abrasion resistance values. Granites GPRET and GCAFE practically contained no quartz in their compositions, and therefore had the smallest abrasion resistance of the products. The abrasion resistance of the two granites GBRAN and GCAP was slightly higher than that of the porcelain tile samples.

To compare the techniques for wear evaluation used in the ceramic tile (deep abrasion) and natural stone sector (Amsler abrasion), tests were carried out with all the samples (porcelain tile and granites) involved in the study, using both techniques. Table 13 lists the results of the Amsler wear test.

Table 13 shows very similar abrasion data to those found by the deep abrasion test. The porcelain tile samples exhibited similar wear, the most noteworthy being that found with samples NPPER, NPBIAN and NNBIAN, which presented the smallest abrasion wear, even better than all the granites. These products also presented the highest mechanical strength values.

Granite abrasion resistance behaviour was identical to that found by the deep abrasion method. Granites GPRET and GCAFE again presented the lowest abrasion resistance, and granites GBRAN and GCAP the best results.

This fact demonstrated that the two abrasion measurement techniques are efficient and equivalent for measuring the behaviour of the two types of products: porcelain tile and granites.

Porcelain tile			Granite		
Sample	Wear at 500m (mm)	Wear at 1000m (mm)	Sample	Wear at 500m (mm)	Wear at 1000m (mm)
NPGRAF	0.27 ± 0.00	0.57 ± 0.03	**GCINZ**	0.44 ± 0.04	0.87 ± 0.03
NNGRAF	Not tested	Not tested	**GBRAN**	0.23 ± 0.02	0.50 ± 0.04
NPBRAN	0.26 ± 0.02	0.55 ± 0.04	**GPRET**	0.68 ± 0.05	1.38 ± 0.039
IPPAR	0.31 ± 0.00	0.64 ± 0.01	**GCAP**	0.24 ± 0.02	0.50 ± 0.01
IPBAR	0.28 ± 0.02	0.61 ± 0.01	**GCAFE**	0.58 ± 0.06	1.12 ± 0.03
INBAR	Not tested	Not tested			
EPNEV	0.33 ± 0.01	0.65 ± 0.02			
EPTEN	0.27 ± 0.01	0.58 ± 0.00			
ENTRAT	Not tested	Not tested			
NPPER	0.24 ± 0.00	0.49 ± 0.02			
NPBIAN	0.22 ± 0.02	0.44 ± 0.02			
NNBIAN	0.19 ± 0.03	0.43 ± 0.01			

Table 13: Abrasion wear results using the Amsler method.

3.7 EVALUATION OF THE COEFFICIENT OF FRICTION

Table 14 presents the mean values for the coefficient of friction on wet and dry porcelain tile and granite sample surfaces.

Porcelain tile			Granite		
Sample	Coefficient of friction (Mean Value)		Sample	Coefficient of friction (Mean Value)	
	Dry surface	Wet surface		Dry surface	Wet surface
NPGRAF	0.63 ± 0.20	0.43 ± 0.19	**GCINZ**	0.58 ± 0.15	0.44 ± 0.20
NNGRAF	0.76 ± 0.16	0.47 ± 0.16	**GBRAN**	0.64 ± 0.23	0.43 ± 0.16
NPBRAN	0.73 ± 0.16	0.47 ± 0.20	**GPRET**	0.61 ± 0.17	0.53 ± 0.26
IPPAR	0.72 ± 0.18	0.38 ± 0.15	**GCAP**	0.49 ± 0.12	0.39 ± 0.15
IPBAR	0.68 ± 0.18	0.37 ± 0.10	**GCAFE**	0.62 ± 0.15	0.43 ± 0.18
INBAR	0.70 ± 0.16	0.60 ± 0.10			
EPNEV	0.50 ± 0.16	0.48 ± 0.15			
EPTEN	0.50 ± 0.14	0.44 ± 0.18			
ENTRAT	0.71 ± 0.17	0.45 ± 0.13			

Table 14: Coefficient of friction values on wet and dry porcelain tile and granite sample surfaces.

The coefficient of friction is related to the roughness of the product surface, type of shoe sole and agent present at the surface (water, oil, dirt). Table 14 shows that except porcelain tiles EPNEV and EPTEN, the other products presented similar coefficient of friction values on a dry surface. On wet surfaces of polished porcelain tiles IPPAR and IPBAR, coefficient of friction values below 0.4 were found, i.e., in accordance with Brazilian Standard NBR 13818 (ISO 13006) these values are indicated for normal conditions of use not requiring slip resistance. The other products exhibited wet coefficient of friction values exceeding 0.4, i.e., in accordance with Brazilian Standard NBR 13818 (ISO 13006) these products can be used in environments where a certain slip resistance is required.

The coefficient of friction values of the granites indicate that, except granite type GCAP, the other products presented similar dry coefficient of friction values. Granite type GCAP presented a wet coefficient of friction below 0.4, i.e., according to Brazilian standard NBR 13818 (ISO 13006) it is indicated for normal conditions of use. The other granites exhibited wet coefficient of friction values above 0.4, similar to the porcelain tile samples, indicating their suitability for use in environments requiring a certain slip resistance.

However, in environments where it is necessary to have high slip resistance, such as wet ramps and regions around swimming pools, the ideal approach is to use products with a wet coefficient of friction exceeding 0.7. Therefore, in these cases, neither porcelain tiles nor granites are advisable products for these situations.

3.8 DETERMINATION OF CHEMICAL RESISTANCE

Table 15 presents the results of the chemical resistance tests of the porcelain tile samples. Table 15 shows that the porcelain tile samples have a high resistance to household cleaning products and products for swimming pools, and high resistance to high and low concentration acid attack, but do not resist attack by basic solutions, which alter the gloss of the sample surfaces.

Sample	Household and swimming pool products		Acids				Bases	
			Low concentration		High concentration		Low concentration	High concentration
	NH_4Cl (100g/L)	Sodium hypochlorite (20mg/L)	HCl (3%)	Citric acid (100g/L)	HCl (18%)	Lactic acid (5% v/v)	KOH (30g/L)	KOH (100g/L)
NPBRAN	UA	UA	ULA	ULA	UHA	UHA	ULC	UHC
NPGRAF	UA	UA	ULA	ULA	UHA	UHA	ULC	UHC
NNGRAF	UA	UA	ULA	ULA	UHA	UHA	ULC	UHC
IPPAR	UA	UA	ULA	ULA	UHA	UHA	ULC	UHC
IPBAR	UA	UA	ULC	ULC	UHC	UHC	ULC	ULC
INBAR	UA	UA	ULC	ULA	UHC	UHA	ULA	UHA
EPTEN	UA	UA	ULA	ULA	UHA	UHA	ULC	UHC
ENTRAT	UA	UA	ULA	ULA	ULA	ULA	ULA	UHA
EPNEV	UA	UA	ULC	ULC	UHC	UHC	ULC	UHC

Class UA, ULA and UHA refer to non-visual effects; Class ULC and UHC refer to visual effects at the surface.

Table 15: Results of the chemical resistance tests of the porcelain tile samples.

Brazilian standard NBR 13818 (ISO 13006) requires that ceramic tiles exhibit resistance class ≥ UB on chemical attack by household cleaning products and products for treating swimming pools. With regard to chemical resistance with low or high concentration acids and bases, Standard NBR 13818 requires the product manufacturer to declare the respective resistance class on the packing. In accordance with Table 15, all the products meet the demands of the standard. Porcelain tile generally presents good resistance to acid attack, but low resistance to base attack, which can be explained by having a chemical composition rich in silica, similar to "glass". Products INBAR and IPBAR presented different behaviour compared with the other products, with a low resistance class for chemical attack by bases. Product EPNEV presented low chemical resistance to bases and acids.

Table 16 shows the results of the chemical resistance tests of the granites. The granites, unlike porcelain tile, are more susceptible to acid attack. The attack produced discoloration of the stone surface. Granite GCAFE presented class UC on exposure to NH_4Cl, therefore not meeting the requirement of NBR 13818.

Sample	Household and swimming pool products		Acids				Bases	
			Low concentration		High concentration		Low concentration	High concentration
	NH_4Cl (100g/L)	Sodium hypochlorite (20mg/L)	HCl (3%)	Citric acid (100g/L)	HCl (18%)	Lactic acid (5% v/v)	KOH (30g/L)	KOH (100g/L)
GCINZ	UA	UA	ULC	ULC	UHC	UHC	ULA	UHA
GBRAN	UA	UA	ULA	ULA	UHC	UHC	ULC	UHC
GPRET	UA	UA	ULC	ULC	UHC	UHC	ULA	UHA
GCAP	UA	UB	ULC	ULC	UHC	UHC	ULA	UHB
GCAFE	UC	UA	ULC	ULC	UHC	UHC	ULA	UHC

Class UA, ULA and UHA refer to non-visual effects; Class ULC and UHC refer to visual effects at the surface.

Table 16: Results of the chemical resistance tests of the studied granites.

3.9 DETERMINATION OF THE COEFFICIENT OF LINEAR THERMAL EXPANSION AND BULK DENSITY

Table 17 presents the coefficients of linear thermal expansion of the studied samples of porcelain tile and granites. The porcelain tiles presented lower coefficients of thermal expansion than the granites. This characteristic favours the use of porcelain tile in external environments, with thermal stresses, e.g. such as building facades. With the intense heat of the sun, temperatures can reach 90°C or more.

Granites can present different coefficients of expansion depending on the direction of the cut made in the stone. For example, if the stone has oriented graining, the expansion is larger in the direction of the orientation. This fact demands great care by the planners on projecting the size of the expansion joints.

Porcelain tile		Granite	
Sample	$\alpha_{25\text{-}325°C}^{-1}$ ($X10^{-7}$ °C^{-1})	Sample	$\alpha_{25\text{-}325°C}^{-1}$ ($X10^{-7}$ °C^{-1})
NPBRAN	77.6	**GCAFE**	140.8
NPGRAF	80.9	**GPRET**	107.3
NNGRAF	83.0	**GBRAN**	136.8
IPPAR	82.4	**GCINZ**	136.6
IPBAR	82.4	**GCAP**	122.5
INBAR	77.8		
EPNEV	73.3		
EPTEN	78.4		
ENTRAT	77.7		

Table 17: Coefficients of linear thermal expansion of samples of porcelain tile and granites (temperature of 25 to 325°C).

Another characteristic that differentiates granite and porcelain tile and therefore needs to be highlighted is the bulk density of each material (Table 18). Besides presenting a greater density, the granites are generally sold with greater thickness (1.5cm) than porcelain tiles (0.8cm), which means a larger final weight for the building to be clad. For example, a granite tile of 30X30X1.5 cm weighs approximately 3.5kg, while a common porcelain tile of 30X30X0.8 cm weighs approximately 1.7 kg, i.e., half the weight of the granite tile.

Porcelain tile		Granite	
Sample	**Bulk density (g/cm^3)**	**Sample**	**Bulk density (g/cm^3)**
NPBRAN	2.43	**GCAFE**	2.77
NPGRAF	2.35	**GPRET**	3.00
NNGRAF	2.38	**GBRAN**	2.61
IPPAR	2.36	**GCINZ**	2.65
IPBAR	2.36	**GCAP**	2.63
INBAR	2.36		
EPNEV	2.38		
EPTEN	2.41		
ENTRAT	2.41		

Table 18: Bulk density values of the samples of porcelain tile and granites.

3.9 BEAUTY AND AESTHETICS

As mentioned previously, the ceramic industry is constantly optimising porcelain tile decoration technology. Today products similar to many stones are found in the market, e.g. such as travertine marble. In Brazil nature has been very generous with the variety of available granites. About 130 types of granites and 11 types of marbles have been classified at the Web site www.marble.com.br. Italy has an even greater available variety of marbles, involving approximately 190 types of marbles and 36 types of granites classified at www.marble.com.br..

To provide some idea of the beauty of Brazilian granites, some products are shown in Figure 3.

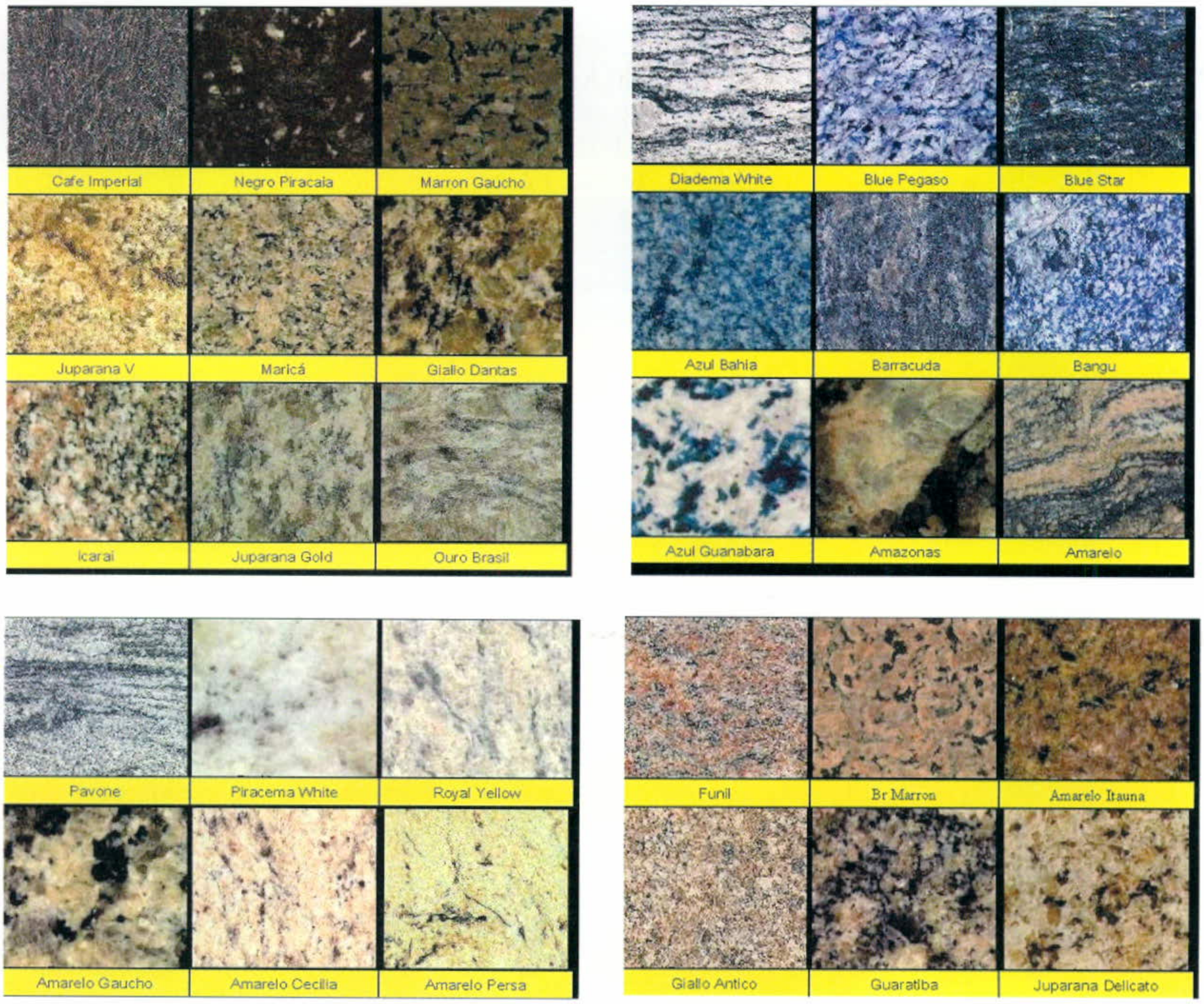


Figure 3: Examples of the beauty of Brazilian granites (www.marble.com.br).

4. CONCLUSIONS

Technically, porcelain tile exhibits similar or superior properties to the granites. Mechanical strength is greater, abrasion resistance is similar, chemical stability is very good and it is lighter than the granites. The technical points that should be improved in porcelain tile in order to increase its competitiveness against granites are: stain and scratch resistance. Granites also stain, but as they are natural materials this behaviour cannot be altered. With regard to scratching, as crystals of varying nature, size and hardness are present in the granites, the visualisation of the lines is less, making this a significant advantage compared with porcelain tile.

With regard to aesthetics, stones have an incomparable beauty made by nature. The ceramic industry needs to develop more decoration techniques, seeking the perfect beauty of natural stones.

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