Bull Eng Geol Environ (2011) 70:625–631
DOI 10.1007/s10064-010-0345-4

ORIGINAL PAPER

Factors affecting slab surface roughness of siliceous dimension stones

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Received: 4 May 2010 / Accepted: 1 October 2010 / Published online: 16 November 2010

Abstract The sawing of granite blocks using multi-blade gangsaws and an abrasive mixture is one of the most complex operations in the rock transformation industry. The surface quality of the finished slabs is the main determinant of the volume of material to be removed in subsequent polishing operations, thus affecting the product's final cost. Measurements carried out on five types of siliceous dimension stone slabs showed differences in sawing speed and industrial process costs. The roughness values obtained, together with the test results for the uniaxial compressive strength, Amsler wear, sawability, coefficient of dynamic friction and petrographic analysis, showed that the rock texture has the most important influence on the production cost of polished slabs.

Keywords Block sawing · Granites · Texture · Surface roughness · Dimension stones

Résumé Le sciage de blocs de granite utilisant une scie à châssis et un mélange abrasif est l'une des opérations les plus complexes dans l'industrie de transformation des roches. La qualité de surface des plaques obtenues est le paramètre essentiel dont résulte le volume de matériau à enlever dans les opérations suivantes de polissage, affectant ainsi le coût final du produit. Les mesures réalisées sur cinq types de plaques de roches siliceuses ont montré des différences dans les vitesses de sciage et les coûts des process industriels. Les valeurs de rugosité obtenues, avec les résultats de tests de résistance à la compression simple, de résistance à l'usure Amsler, de sciabilité, de coefficient de friction dynamique et des analyses pétrographiques, ont montré que la texture de la roche a l'influence la plus importante sur le coût de production des plaques polies.

Mots clés Sciage de bloc · Granites · Texture · Rugosité de surface · Pierres dimensionnelles

Introduction

Large diameter circular diamond saws, multiwire sawing machines, and multiblade gangsaws which use steel shots as the abrasive element have been widely used in stone slab processing plants.

The cutting of granite using diamond tools has been widely studied, because of both the enormous economic resources and research capabilities of diamond producers and the considerable difference in the hardness of diamond and rocks. Rock sawability depends on the machine's characteristics (Brook 2002; Mancini et al. 2003; Ersoy and Atici 2004), the depth of cut, the cutting rate and tool wear (Suárez-Del-Rio et al. 1998; Xu 1999; Konstanty 2002; Eyuboglu et al. 2003; Wei et al. 2003; Huang and Xu 2004), and the rock properties (Howart and Rowlands 1987; Rodríguez-Rey et al. 1998; Amaral et al. 1999; Ozcelik et al. 2004; Agus et al. 2005; Sánchez-Delgado et al. 2005).

The sawing of granite blocks using multi-blade gangsaws is the most well known and inexpensive means of obtaining rock slabs. Brazil has the world's second largest rock sawing industrial park, with approximately 1,300 gangsaws in operation. However, an in depth understanding of this complex operation has not yet been attained and various factors need to be considered:

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(a) the material used in sawing is of a similar hardness to that of the sawn material;
(b) the large number of parameters involved;
(c) the lack of a well established sawing theory and
(d) the implied empiricism in evaluating the slab quality in the sawing industry.

Indeed, many of the technological advances in sawing equipment have been accompanied by a mere handful of studies on the intrinsic properties of the rock that influence the sawing process (Spínola 1998; Citran 2000; Ribeiro et al. 2007).

The objective of this research work is to investigate the relationship between slab surface quality (roughness) and coefficient of dynamic friction with the principal technological properties related to the sawability of siliceous dimension stones, e.g. uniaxial compressive strength, abrasive wear strength, Knoop hardness, and deep abrasion strength.

Types of rocks

Five types of Brazilian dimension stones were chosen for the present study—*Preto Indiano* (migmatite), *Café Imperial* (syenite), *Verde Labrador* (charnockite), *Vermelho Brasília* (sienogranite), and *Vermelho Capão Bonito* (syenogranite). The selection was based on the following criteria: differences in sawability ("hardness"), high commercial acceptance, and the feasibility of following up the entire industrial processing of these rocks.

Preto Indiano

The Preto Indiano is a folded migmatite, with different foliation spacings between the mesocratic and leucocratic levels. The mesosome is dark gray in color, tonalitic in composition and consists of andesine/oligoclase (41.0 vol.%), quartz (22.0 vol.%), biotite (23.0 vol.%) and subordinate microcline (4.5 vol.%), as well as sillimanite (5.0 vol.%) and muscovite (3.0 vol.%), and locally minor garnet (1.0 vol.%) and cordierite (0.3 vol.%). The accessory and secondary minerals (0.2 vol.%) are opaques, zircon, carbonates, sericite, and clay minerals. The microstructure varies from granoblastic to granolepidoblastic in texture with a medium grain size, predominantly between 1.5 and 4.0 mm. The leucosome is of a whitish color with a monzogranitic/granodioritic composition essentially made up of andesine/oligoclase (40.0 vol.%), quartz (32.0 vol.%), microcline (25.0 vol.%), and biotite (3.0 vol.%). The leucosome microstructure is hypidiomorphic-granular with a medium (2.0–4.0 mm) to coarse (5.0–10.0 mm) grain size.

Café Imperial

The Café Imperial is a brownish colored syenite with clear fluid flow foliation and long plane orthoclase crystals in juxtaposition. It presents a hypidiomorphic equigranular texture and a grain size varying from 5 to 10 mm, with a substantial quantity of fine to very fine grains. Its essential minerals are orthoclase (3.5 vol.%), aegirine-augite (15.6 vol.%), apatite (2.5 vol.%), and biotite (1.9 vol.%) and the accessory minerals are (3.5 vol.%) titanite and opaques. Secondary minerals (clay minerals, sericite and iron oxide-hydroxide) occur as trace only.

Verde Labrador

The Verde Labrador is a charnockite (hypersthene syenogranite) containing garnet. The coloration is dark green and the grain size is in the 2–25 mm range (predominantly around 10 mm). The rock is isotropic and the microsctrucure hypidiomorphic inequigranular. The main minerals are quartz (14.0 vol.%), microcline (39.0 vol.%), oligoclase (19.0 vol.%), biotite (5.0 vol.%), hypersthene (5.0 vol.%), hornblende (5.0 vol.%) and garnet (5.0 vol.%), with accessory (5.0 vol.%)—opaques, allanite, apatite and zircon and secondary minerals (<3.0 vol.%)—sheet silicates, carbonate, and iron hydroxides.

Vermelho Brasília

The Vermelho Brasília is a reddish equigranular syenogranite with a hypidiomorphic microstructure and coarse grain size (3–50 mm), predominantly between 5 and 30 mm. Its essential minerals are quartz (32.0 vol.%), microcline (41.0 vol.%), oligoclase (16.0 vol.%), and biotite (5.0 vol.%); with accessory (2.0 vol.%) opaques, apatite, zircon and garnet, and secondary minerals (<4.0 vol.%)-sericite, muscovite, epidote, chlorite, carbonates, clay minerals, and iron hydroxides.

Vermelho Capão Bonito

The Vermelho Capão Bonito is a reddish inequigranular syenogranite. It has a hypidiomorphic-granular texture and a coarse grain size in the 2–30 mm range, predominantly between 5 and 10 mm. Its essential minerals are quartz (34.5 vol.%), microcline (40.5 vol.%), oligoclase (15.5 vol.%), and biotite (6.0 vol.%); with accessory (1.5 vol.%) opaques, apatite, titanite and zircon, and secondary minerals (<2.0 vol.%) sericite, muscovite, epidote, chlorite, carbonates, and clay minerals.

The good mineral imbrication gives the Vermelho Brasília and Vermelho Capão Bonito syenogranite a high cohesion.

Considering the degree of microcracking and mineral alteration of the five rocks studied, some similarity exists between Preto Indiano migmatite, Vermelho Brasília and Vermelho Capão Bonito syenogranites (Figs. 1, 2, 3). For these three rocks, the degree of microcracking is low. The intergrain and intragrain microcrack length is also small, with microcracking more frequent in the large crystals, mainly feldspar and quartz. The observed mineral alteration is weak to moderate and is characterized by visible plagioclase argillation. On the other hand, in the case of the Verde Labrador charnockite and Café Imperial syenite the intragrain microcracks filled with sheet silicates are interconnected (Figs. 4, 5) while the degree of microcracking and mineral alteration is moderate to intense.

The rocks were sawed under identical operational conditions using the same sawing machine (Fig. 6) equipped with an automatic system for supplying metal shots, such that the sawing speed (cm/h) and average consumption of metal shots (kg/m^2) could be obtained.

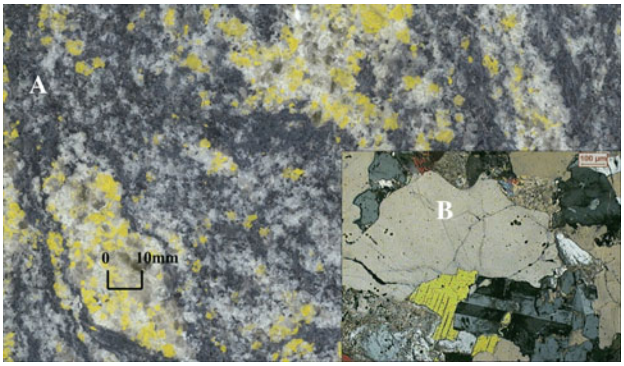

Fig. 1 **a** Macroscopic appearance of the tile after the feldspar selective staining test and **b** photomicrograph of Preto Indiano migmatite: leucosome with saussuritized plagioclase crystals and quartz with intragranular microcracks

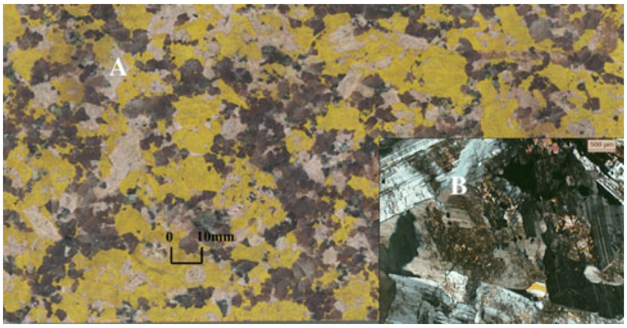

Fig. 2 **a** Macroscopic appearance of the tile after the feldspar selective staining test and **b** photomicrograph of Vermelho Brasília sienogranite. Note the saussuritization on the plagioclase crystals with subsequent formation of muscovite crystals

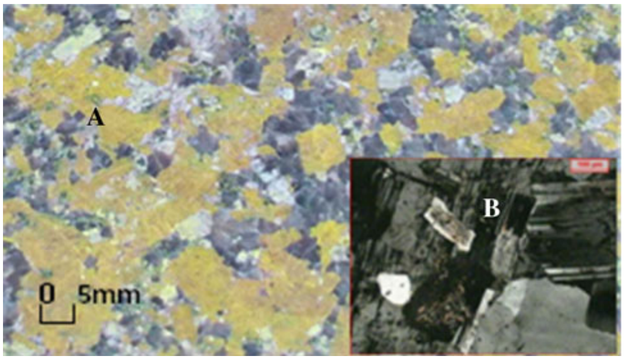

Fig. 3 **a** Macroscopic appearance of the tile after the feldspar selective staining test and **b** photomicrograph of Vermelho Capão Bonito syenogranite

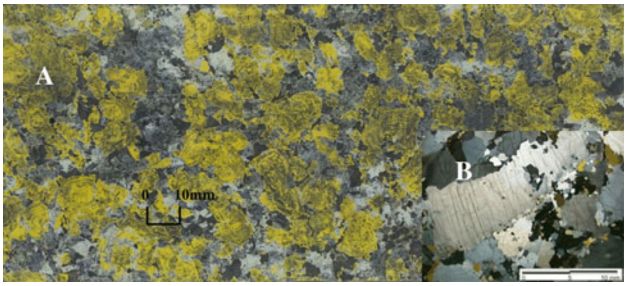

Fig. 4 **a** Macroscopic appearance of the tile after the feldspar selective staining test and **b** photomicrograph of Verde Labrador charnockite. Note the intense intergranular microcracking

Fig. 5 **a** Macroscopic appearance and **b** photomicrograph of Café Imperial syenite

Rock characterization

Petrographic analyses of thin sections (c. 30 μm) were carried out based on the EN 12407 (CEN 2000) code guidelines. The sections were cut in three orthogonal directions, one parallel to the sawn surface, and analyzed by macroscopic observation and the optical polarizing microscope. Due to the relatively large grain size of the studied rocks, the modal percentage was determined by integrating the mineral count obtained directly from the polished slabs using a selective feldspar staining technique based on the methodology of Moraes and Rodrigues (1978).

Fig. 6 Distribution system of the abrasive mixture in the sawing of siliceous dimension stones

The uniaxial compressive strength was determined according to the NBR 12767 (ABNT 1992a) Code guidelines on specimens perpendicular to the sawing direction. Five tests were undertaken for each rock type.

Some experiments were conducted to test the dimension stone under study for wear. Six specimens of each rock type were subjected to abrasive runs (1,000 m) in an Amsler machine and the reduction in thickness (in mm) was measured (following NBR 12042, ABNT 1992b). To simulate the gangsaw (rock, metal shot, blade), the Amsler machine had three parts (rock, abrasive, steel disk); the impact of the blade was simulated by the metal shots. Low reduction of thickness (in mm) indicates higher wear strength.

The Knoop hardness was determined following the Quitete and Rodrigues (1998) method. For each type of rock, three test specimens (7 × 7 × 3 cm) were cut from commercial tiles and the hardness determined by applying 40 repetitions of a 1.96 N load on the surface of each test specimen. The diagonal length of the indentation, in micrometers, was then measured using a Vernier scale.

The deep abrasion test, originally developed for ceramic tiles, measures the degree of surface wear using a Capon machine. For each type of rock, three test specimens (10 × 10 × 2 cm) were cut from commercial tiles. Following EN 14157 (CEN 2004), the deep abrasion resistance is expressed in terms of the volume of material removed (mm^3), calculated as the length of the cavity formed during abrasion "C_{cav}" using the following expression:

$$V = \left(\frac{\pi \times \alpha}{180} - \text{sine}\alpha\right) \times \left(\frac{h \times d^2}{8}\right) \tag{1}$$

where

$$\frac{\text{sine}\alpha}{2} = \frac{C_{\text{cav}}}{d} \tag{2}$$

where V the volume of material removed (mm^3); d the diameter of the rotating disk = 200 mm ± 0.2; h the thickness of disk = 10 mm ± 0.1; α the angle formed by the arc (groove) left by the disc, and C_{cav} length of the cavity (mm).

Characterization and measurement of the superficial irregularities of slabs

When dealing with the sawing of dimension stones, the frequency of irregularities on the slab surface is usually related to both the characteristics of the rock and the operational conditions under which the rock is being sawn.

Irregularities (surface texture) can be classified in two categories according to the wave length: large and small scale. The roughness is shown to have a spacing/height ratio between 5 and 100. In practice, this interval indicates macrometric irregularities and closely spaced irregularities.

The roughness evaluation of unpolished slabs obtained from sawed blocks was performed by using a portable apparatus—the surface roughness estimator (SRE; Ribeiro et al. 2007) specially developed to consider the adverse conditions encountered in the sawing industry. This machine (Fig. 7) consists of a steel body (1) which can be levelled by adjusting four screws (2). The digital measure (3) is equipped with a 1 mm precision deflectometer set in motion by a system of linked orthogonal arms, one of which is fixed to the extremity of a silicon carbide cutter. The measuring (set) car is moved by means of a screw thread that has no end and is manually driven such that the number of revolutions of a graduated cylinder (4) can be determined with a precision of 0.25 mm and the deflectometer readings sent to a computer (7).

Three slabs (length 1.9 m, height 1.8 m) were randomly chosen from a set of 70 obtained from the studied granite

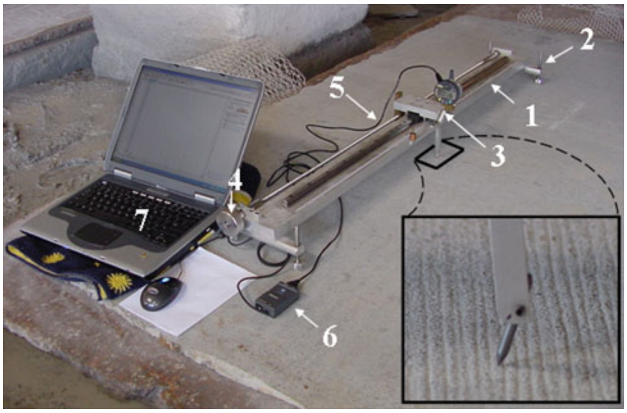

Fig. 7 Main components of an SRE: *1* steel body, *2* adjustable feet, *3* measurement car, *4* graduated cylinder, *5* connection cable, *6* measurement interface, *7* portable computer. *Inset* highlights the nature of the depressions caused by the cutting process

blocks. On each of the selected slabs, three lines, each consisting of 3,700 points, were made for the surface roughness measurement.

Based on computational calculations using Excel software, roughness parameters were defined. One of these parameters, the maximum amplitude (Rt), was defined as the greatest height between troughs and saliencies relative to the cutting direction. In practice, this maximum amplitude represents the thickness of the material to be removed during the polishing stages.

Another way to determine the slab roughness uses the slipperyness meter (SM), originally developed to perform measurements in ceramic tiles (ISO 10545-7 Code; Annex A, 1996). Based on these guidelines, the relationship between the roughness and the slab surface dynamic friction was established using representative values of each rock.

Results and discussions

Technological properties, sawing speed, roughness, and coefficient of dynamic friction

By comparing the slab roughness (Rt), technological properties, sawing speed, and coefficient of dynamic friction (DFC) it can be observed (Table 1) that:

Relative to the uniaxial compressive strength and abrasive wear strength:

(a) Rt shows a tendency to increase with increasing uniaxial compressive strength. The data shown in Fig. 8 indicate a correlation coefficient of $R^2 = 0.42$;

(b) An inversely proportional relationship exists between Rt and abrasive wear (Fig. 9; $R^2 = 0.70$); rocks of higher roughness show higher abrasive wear strength (or less reduction in mm).

(c) The rock microstructure, grain size, and distribution of quartz and biotite have a significant influence on the uniaxial compressive strength and abrasion. The Vermelho Brasília and Vermelho Capão Bonito syenogranites showed a high compressive strength and abrasion by Amsler wear. These rocks have 32–34 vol.% quartz and 5–6 vol.% biotite, with the quartz crystals forming a well-bonded fabric surrounding the feldspar crystals, hence giving greater cohesion to the rock. On the other hand, the Verde Labrador charnockite has 14 vol.% quartz crystals without any interlocking and the Café Imperial syenite does not have quartz crystals, while the Preto Indiano migmatite has on average 27 vol.% quartz, but a greater proportion of biotite (up to 23 vol.%) arranged as layers, which is responsible for the low strength.

(d) Due to the prominent gneissic banding, the uniaxial compressive strength and abrasive wear values for the

Table 1 Results of uniaxial compressive strength, Amsler wear, Knoop hardness, deep abrasion, roughness, dynamic friction coefficient and sawing speed of the studied granites

Test parameters	Statistics	Type of rock				
		Preto Indiano	Café Imperial	Verde Labrador	Vermelho Brasília	Vermelho Capão Bonito
UCS (MPa)	Mean	108.71	114.80	183.18	209.86	191.20
	Standard deviation	9.29	6.04	5.46	4.92	4.73
AW (mm)	Mean	1.07	0.90	0.86	0.51	0.47
	Standard deviation	0.08	0.04	0.04	0.03	0.03
KH (GPa)	Mean	5.66	5.87	6.78	6.73	6.49
	Higher value	6.14	6.37	6.97	7.39	7.14
	Lower value	5.58	5.61	6.58	5.85	5.81
DA (mm^3)	Mean	128.3	122.8	92.6	120.6	111.3
	Standard deviation	5.91	5.21	9.14	25.65	14.30
Roughness Rt (mm)	Higher value	0.30	0.36	0.36	0.46	0.82
DCF (non-dimensional)	Mean	0.74	0.80	0.82	0.89	0.90
	Standard deviation	0.04	0.04	0.06	0.04	0.04
Average sawing speed (cm/h)	Mean	4	4	3	2	2
Consumption of abrasive (kg/m^2)	Mean	0.6–1.0	0.6–1.0	1.0–2.0	3.0–4.0	3.0–4.0

Legend: *UCS* uniaxial compressive strength, *AW* Amsler wear, *KH* Knoop hardness, *DA* deep abrasion, *DFC* dynamic friction coefficient

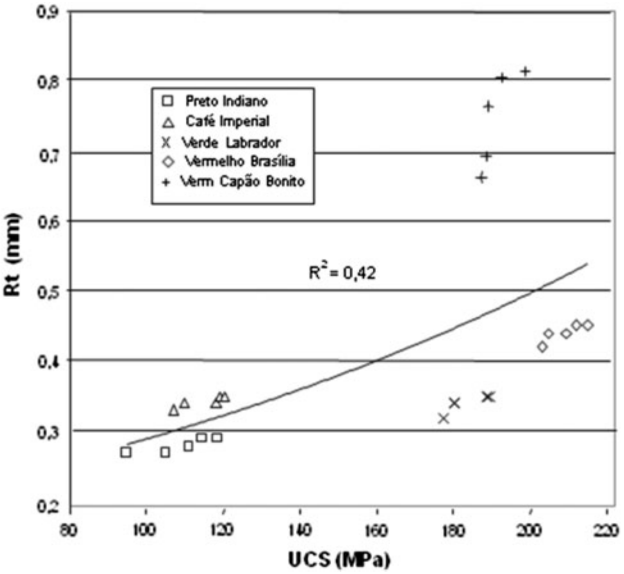

Fig. 8 The relationship between maximum amplitude (Rt) and uniaxial compressive strength (UCS)

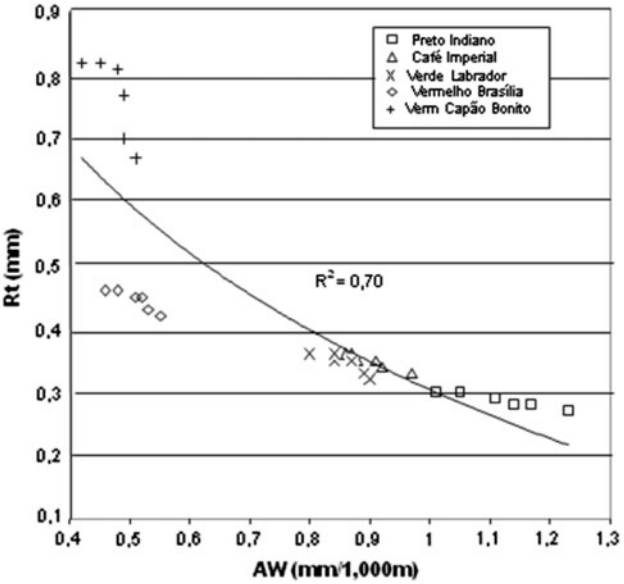

Fig. 9 The relationship between maximum amplitude (Rt) and abrasive wear (AW)

Preto Indiano migmatite were relatively higher than the other rocks tested.

Relative to sawing speed and coefficient of dynamic friction:

(a) As the Vermelho Brasília and Vermelho Capão Bonito syenogranites are more quartz-rich and have a web texture, these rocks are tougher and therefore more abrasive on the saw blades, such that the sawing plane is rougher. Their sawing speed is some 50–100% lower than that of the Verde Labrador charnockite, the Preto Indiano migmatite and the Café Imperial syenite. The lower cutting speed of the syenogranites represents an additional 45 h in the sawing of a 1.80 m high block of Preto Indiano and Café Imperial;

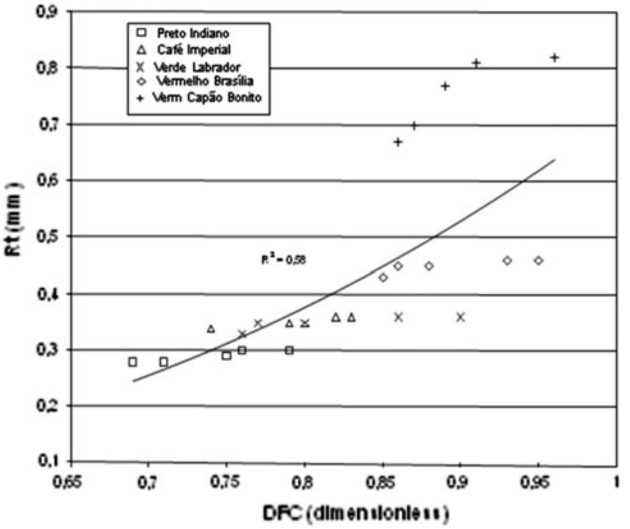

Fig. 10 The relationship between maximum amplitude (Rt) and dynamic friction coefficient (DFC)

(b) The higher roughness value observed for the syenogranite slabs is a clear indication of the greater amount of material which will need to be removed in the polishing stage in order to obtain a shiny surface;

(c) There is a tendency for Rt to increase with an increase in the coefficient of dynamic friction (Fig. 10; $R^2 = 0.58$).

Relative to the Knoop hardness and deep abrasion:

(a) There is a direct relationship between Rt and Knoop hardness. Given the higher amount of biotite and the absence of quartz in their mineral composition, the Preto Indiano migmatite and the Café Imperial syenite show a slightly lower Knoop hardness value than the Vermelho Brasília and Vermelho Capão Bonito syenogranites and Verde Labrador charnockite, which have a relatively more homogeneous microstructure;

(b) There was no correlation observed between Rt and deep abrasion. The rock microstructure is of key importance to determine deep abrasion. High variability shows that the test result depends in part on the portion of the rock studied.

Conclusions

The roughness of the unpolished slabs is a fundamental parameter that determines the volume of material to be removed during the polishing stage. The roughness is a consequence of the relationship between the rock, the sawing speed, and the operational conditions. From the mechanical tests undertaken on the five different rock types, the following conclusions can be drawn.

1. The mineral composition and microstructural features are largely responsible for the observed differences in slab roughness and sawability;
2. The roughness can be realistically evaluated using the SRE, specially designed for the sawing industry;
3. A comparison between the roughness results and the coefficient of dynamic friction indicates that roughness can also be determined using the SM;
4. The slab roughness is proportional to the uniaxial compressive strength, abrasive wear strength, Knoop hardness, and coefficient of dynamic friction and inversely proportional to sawability;
5. There was no correlation between deep abrasion and roughness.

Acknowledgments The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for their financial assistance (Process 06/52521-0); Universidade Estadual Paulista (UNESP), Instituto de Pesquisa Tecnológica do Estado de São Paulo (IPT), Fundação Parque de Alta Tecnologia de São Carlos (PARQTEC) and Granitos Itabira Ltda. for help and support during the experimental work.

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