Rock properties and steel blades and grit consumption in granite multi blade sawing process

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Abstract. Among the dimension stones’ production processes, block’s splitting into slabs is very important in terms of time, costs and quality of final products. The world reference equipment for granite blocks cutting is the multi blade gang saw, in which sawing is the consequence of the combined action of a set of steel blades settled in an oscillating frame and an abrasive slurry containing water, steel shot and lime or bentonite. As the blades enter into the block, stone powder is added to the abrasive slurry and as commercial granites include very different rock types, slurry’s characteristics also depend on the rock nature. Consequently, parameters of the cutting process have great variability. Depending on those parameters, the steel blades and shot are worn out differently during this process having great influence on costs. Due to its complexity, stone cutting mechanisms are still not well understood but compression, abrasion, impact and stone’s characteristics seem to influence the most. Aiming to help the understanding of that process and based on previous studies, this work intends to establish correlations between granites petrographic and technological characteristics and steel blades and shot consumption. Laboratorial studies that include petrographic analysis, physical indexes measurement, and abrasion, impact and compression standardized testing of a selected group of stones are being crossed over with steel blades and steel shot consumption measurements in gang saws from several Brazilian processing companies. Preliminary results show a relationship between the selected stones characteristics and steel blades and shot consumption within the sawing process. The higher the quartz contents of the rock the higher its abrasion resistance, which results in higher consumption of steel shot during sawing. It can be also pointed out that beyond quartz and k-feldspar contents, microfissures have great influence on compression strength of the stones and this strength it is directly related to the steel blades consumption. This can allow not only a better understanding of slabs production in multi blade gang saws process, but also to improve that process control.

Introduction

Commercial granites’ slabs are mainly produced in multi-blade gang saws (known as conventional gang saws) by the splitting of quarried blocks. Blocks are split into slabs by disaggregation of their minerals, with the aid of a steel blades frame, bathed by an abrasive mixture constituted of steel shot or grit, water, lime or bentonite and the very stone’s powder which is added during sawing. Silveira [1] describes sawing in conventional gang saws, under tribological environment, as a three bodies wearing process, where the steel shot is the abrasive element that promotes mineral disaggregation by sliding over two surfaces: stone and blade.

The blade, in turn, exerts compressive and impact mechanical stress on the rock, transferring kinetic energy to the block being cut. All this slabbing process is conditioned by the presence of the abrasive mixture that carries the abrasive body (shot/grit) to the grooves cut into the rock. This slurry is formed, in an average, of 66.6% by volume of water, 3.1% of useful cutting grit, 1.2% of calcium oxide and 29.4% of rock minerals comminuted during cutting [2].

Operational control of this process is very complex, depending on many parameters and on experience of operators and it is essential to ensure the quality of slabs produced and reduce the costs involved. The
cost of the blade and the shot can reach 48% of the total cost of sawing. Furthermore, stone materials are natural materials and which, even along the same deposit, present considerable variations in the mineralogical composition, structure and texture, which further complicates the control, since each material will behave differently when subjected to this process (sawing time, consumption of inputs, … etc.).

It seems that the mechanical parameters that promote the stone cutting are compression, abrasion and impact. For this reason, preliminary studies have tried to correlate technological characterization tests results of different stones’ types with cutting parameters. Although none has achieved definitive conclusions, compression strength, abrasive wearing, porosity, load failure and others have shown, in some way, to have influence on cutting process [3, 4]. Rock’s hardness has also been studied [5,6,7], as it is known that the harder the stone, the more difficult the splitting, but no one has been able to give an exact correlation because the laboratorial methods used to measure hardness are not fit for rocks but for minerals or homogenous materials. Many others have studied the relationship between mechanical resistance of stones and petrographic characteristics, as the former depends on the latter, as Rzhovsky & Novik said [apud 3]:

“the interaction between the composition, textures and structures of rocks, is the factor that defines their resistance to chemical, physical and mechanical agents, that is the result of the combination of the petrophysical characteristics of the material”.

**Petrographic characteristics that affect mechanical strength:** A detailed petrographic description of thin sections by polarized light microscopy becomes a very efficient tool for understanding and modeling the behavior of the rock under physical and even chemical stresses during the processing of commercial granites.

In petrographic description is essential to consider the mineralogical composition, measuring the volumetric percentage of constituent minerals. *A priori* the percentage of quartz crystals (SiO$_2$) and crystals of the group of feldspars [(K, Na, Ca) (Si, Al)$_4$O$_8$] have greater influence on the abrasive wear resistance of the rocks [8]. However, the percentage and sizes of minerals that can develop cleavage such as those of the mineral group of phyllosilicates (biotite, muscovite, secondary sericite and others), amphiboles and pyroxenes, can also significantly influence this resistance [6].

Materials with coarse grains, according to the theory postulated by Griffith's [9] on fractures, will be less resistant than those of fine grains.

The texture may be important in the mechanical strength of the rock. For example, equigranular textures that facilitate the distribution of tensions in contacts between minerals in the rock happen more smoothly than in unequigranular ones, rendering greater resistance.

Intercrystalline textures as perthitic textures in feldspars, coronas (rims) in amphiboles, and glomeroporphyritic textures may somehow affect the resistance. Perthitic texture in crystals of potassium feldspar (KAl Si$_3$O$_8$) offers intracrystalline weakness planes, generated by the thin lamellae of Albite (NaAlSi$_3$O$_8$) that define the texture. Similarly, the growth of synthetic porphyroblasts consuming mineral phases with high chemical affinity and unstable in the new pressure and temperature conditions during the deformation process, can generate areas with concentration of crystals such as minerals of the group of garnets, amphiboles, pyroxenes and biotite, that depending on the shape, size and spatial distribution, generate regions where the propagation of stress becomes more efficient.

In some cases, the presence in the rock of other materials more easily alterable, as the films of amorphous silicon filling crystalline contacts in some commercial granites of the Espírito Santo State, may also decrease the strength of that rock. Similarly, the presence of clay minerals such as illite, sericite, smectite and vermiculite facilitate mineral breakdown during the sawing as these clay minerals have the physical property of expanding when exposed to moisture.

**Intracrystalline plasticity processes:** Crystals with perfect crystal lattices, very difficult to be deformed, are extremely difficult to occur. Normally the majority of crystals present lattice defects, which allow the deformation of the crystal lattice with less effort. The defects may be with punctual with atomic vacancies within a few crystal lattices or the occurrence of additional atoms within a lattice, or may be by linear dislocations due to deformational processes or during crystal growth, which aligned can generate
walls of unconformities. Lattice dislocation density, which is expressed as the total length of lines of dislocations per unit of volume, shows that non-deformed quartz crystals have dislocation densities close to $10^3$ cm / cm$^2$, while crystals intensively deformed present values of up to $10^{12}$ cm / cm$^2$ [10].

Under deforming stress, the dislocations propagation in the crystal lattice of each crystal occurs by migration. Within this movement can happen a phenomenon called ‘strain hardening’, in which the dislocations end up entangled stopping its spread to the edges of the crystal. If the deformation is continuous new grains will grow inside the one deformed, so it will be more brittle and more easily comminuted.

Being quartz easily deformable and, at the same time, very important for mechanical properties of rocks, this type of microstructure may affect their behavior in the sawing process. This could explain different strengths for materials with similar contents of quartz. Some studies show the importance of plastic deformation by linear and helicoidal dislocations acting on crystals [11]. Static recrystallization processes (Fig. 1) also affect the strength of the rock and its crystalline thermodynamic stability depends on the recrystallization stage observed in the crystals contacts. For example, amoeboid and serrated contacts are less stable, having high Gibbs free energy. The more stable contacts are polygonal in a triple junction at 120° as in undeformed quartz crystals, with less internal free energy [12].

**Figure 1** – Types of intercrystalline contacts during the static recrystallization processes [12].

Finally, it is important to understand the formation and tectonic evolution of rocks to better interpret their characteristics and possible behavior under mechanical stress. In example, the green ‘granites’ of the States of Espírito Santo and Minas Gerais look alike and producers use the same cutting control parameters for all of them, but as they were formed during different evolutionary stages of the same orogeny, they present different petrographic features and, consequently, different behavior under stress.

**Objectives**

This study aims to find a relationship between the consumption of blade and grit in the process of sawing of commercial granites and petrographic features such as intracrystalline textures and some technological of these rocks: abrasive wear and compression strength.
Materials and methods

For the present work we selected nine types of well-known and widely traded ornamental stones. Samples and sawing control worksheets of those materials were provided by a local firm. The mean consumption of steel blades and grit, in kilograms per square meter of produced slabs, for each material, were extracted from the sawing operational data from the year of 2010, in different gang saws of the company.

An extensive literature review about petrographic properties as intercrystalline textures, mineral fabric and descriptive and discursive papers on characterization tests and mechanical properties of stones were also analyzed in order to promote better understanding of the parameters involved in the sawing of commercial granites in conventional multi-blade gang saws.

Data from technological characterization tests of the selected materials were obtained from the data bank of the Center for Mineral Technology Laboratory (CETEM/MCTI), but also from the Brazilian Catalogue of Dimension Stones, available at ABIROCHAS website and others, made by Technological Research Institute of the State of São Paulo (IPT) were also provided by the local firm. Amsler’s Abrasive Wear Strength and Uniaxial Compressive Strength were the tests selected for this study.

For each sample it was made the petrographic analysis following the Brazilian Standard NBR-ABNT 15845:2010 by analyzing 40x images under natural and polarized light in a Olympus BX-51 petrographic microscope, in the Microscopy Laboratory of the Geology Department of the Federal University of Espirito Santo, in the Alegre City Campus.

Results and Discussion

The petrographic study of samples confirmed the relationship between their mineralogical composition, textures and structures and their mechanical strength. We also observed a relationship between the consumption of inputs (steel blades and shot) during sawing and this resistance, but it seems that petrographic characteristics that seem to have most influence are different depending on the type of resistance that was assessed. [8].

There is a direct relationship between the consumption of shot/ grit and abrasion resistance of each material. The larger the latter the greater the consumption of grit in the gang saw and it is usually said, in this industry, that the rock is more ‘abrasive’. This abrasiveness of stones is closely linked with their content of harder minerals such as quartz and k-feldspar.

Moreover, the blades consumption depends on the stones’ compressive strength and this, in turn, with the triad: mineral composition, texture and structure, in particular the degree of micro-cracking [8]. An inverse correlation between compressive strength and blades consumption was observed for all of the materials.

Table 1 shows the materials selected for study with their respective commercial names and petrographic data, technological characterization results, and consumption of inputs in their sawing. It may be noted that the only material that is very different in mineralogical composition, which is the norite known as Black San Gabriel, with the highest concentration of mafic minerals with good cleavage (28.5%) and near-zero values of quartz (5%) and k-feldspar (0.5%) has the lower mechanical strength and consumption of inputs. All the other materials are more similar in mineralogical composition, having around 50-60% of quartz plus k-feldspar.
Table 1 – Selected samples mineral composition, technologial charaterization data and sawing inputs consumption. Pl = plagioclase; Qz = quartz; K-f = potassium feldspar;Opx = orthopyroxene; Cpx = clinopyroxene; Anf = amphibolium; Bt = biotite; Sil = sillimanite Ms = muscovite; Gr = garnet; Op = opaques; Ac = accessories.

<table>
<thead>
<tr>
<th>Trade Name</th>
<th>Mineralogy</th>
<th>Petrographic Name</th>
<th>Abrasive Wearing (mm)</th>
<th>Compressive Strength (Mpa)</th>
<th>Inputs consumption (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>500 m</td>
<td>1.000 m</td>
<td></td>
</tr>
<tr>
<td>Giallo Ornamental</td>
<td>45% K-f; 25% Qz; 20% Pl; 5% Bt; &gt;1% Ac (Gr, Bt)</td>
<td>Syenogranite with garnet</td>
<td>0,62</td>
<td>1,19</td>
<td>152,00</td>
</tr>
<tr>
<td>Giallo Santa Cecília</td>
<td>34% K-f; 25% Qz; 20% Pl; 10% Bt; 7% Gr; 4% Ac.</td>
<td>Protomylonitic Monzogranite with garnet and sillimanite</td>
<td>0,60</td>
<td>-</td>
<td>103,30</td>
</tr>
<tr>
<td>Giallo Fiorito</td>
<td>50% K-f; 25% Qz; 10% Pl; 10% Bt; 5% Ac.</td>
<td>Coarse-grained Porphyritic Syenogranite</td>
<td>0,80</td>
<td>1,52</td>
<td>142,20</td>
</tr>
<tr>
<td>White Dallas</td>
<td>40% K-f; 25% Qz; 15% Pl 10% Gr; 5% Bt; 5% Sil.</td>
<td>Leuco syenogranite with garnet and sillimanite</td>
<td>0,76</td>
<td>-</td>
<td>163,60</td>
</tr>
<tr>
<td>Imperial Silver</td>
<td>31,95% Qz; 31% K-f; 20,7% Pl; 8,7% Bt; 4,75% Ser; 1,9% Op; 1% Ac.</td>
<td>Biotite monzogranite</td>
<td>-</td>
<td>1,3</td>
<td>127,70</td>
</tr>
<tr>
<td>Green Pearl</td>
<td>35% Pl; 25% K-f; 25% Qz; 5% Ac (Opx, Gr, Bt).</td>
<td>Coarse-grained, heterogranular Charnokite</td>
<td>0,77</td>
<td>1,37</td>
<td>127,20</td>
</tr>
<tr>
<td>Green Butterfly</td>
<td>50% K-f; 30% Pl; 12% Qz; 8% Op.</td>
<td>Quartz mangerite</td>
<td>0,41</td>
<td>-</td>
<td>101,20</td>
</tr>
<tr>
<td>Green Panorama</td>
<td>26,6% de Pl; 25,8% K-f; 23,2% Qz; 9,1% Bt; 8,45% Opx; 3,1% Op; 2,5% Anf; 1,25% Ac.</td>
<td>Heterogranular Quartz mangerite</td>
<td>0,38</td>
<td>0,86</td>
<td>146,00</td>
</tr>
<tr>
<td>Black San Gabriel</td>
<td>52,7% Pl; 15,5% Bt; 10,4% Opx; 7,7% Cpx; 5,3% Qz; 2,8% Op; 2,6% Anf; 0,5% K-f; 2,5% Ac.</td>
<td>Equigranular, medium-grained Norite</td>
<td>-</td>
<td>1,76</td>
<td>75,30</td>
</tr>
</tbody>
</table>
The low resistance to abrasion of the San Gabriel Black can be explained by its very low amount of quartz and k-feldspar (around 5%) which, as proposed by other studies [3], is the primary factor influencing the abrasion resistance of the rocks, while the texture and the structure have a supporting role. Supporting this hypothesis, all other samples (granitoids with more than 50% of harder minerals) show a higher resistance to abrasion.

It can be noted that the norite has the lowest consumption of inputs (0.58 ± 0.22 kg / m² for grit - 0.37 ± 0.13 for steel blade). More resistant materials such as the leucogranite White Dallas (163.6 MPa) and the syenogranite Giallo Ornamental (152.0 MPa) have a high consumption of blade. However, a difference is observed when comparing the behavior of these two materials against abrasion; both have good wear resistance, but the Giallo Ornamental consumes more abrasive grit than the White Dallas.

Despite the differences are small, the Giallo Ornamental contains 5% more of quartz and k-feldspar than the White Dallas which would justify the higher consumption. The "abrasivity" (term used in industry for materials more resistant to abrasion and that consumes more steel grit during sawing) of this material may also be influenced by its inequigranular porphyritic texture with phenocrysts, because although the granular heterogeneity may facilitate the tearing out of larger grains, when those are very large (in this case 4 cm), the hardness of the minerals themselves will have the opposite effect as they will be cut instead of torn out.

Likewise, the green granitoids show different mechanical strength although their mineralogical composition is similar. These differences in the resistance of stones of similar compositions, led to investigate micro structural differences that could justify them, as grain size, inter and intracrystalline textures, percentage of minerals with cleavage and alteration degree, among others (Table 2).

Another factor that should be highlighted in green materials is the microcracking pattern, medium to high in all the green samples. But with a more detailed petrographic microscopy can be seen that it is much more intensive on the Green Butterfly, followed by the Green Pearl and the Green Panorama, this one as the less microfractured (Fig. 2). This is reflected in the uniaxial compressive strength: the Green Butterfly is the least resistant among the three samples and the toughest is the Green Panorama, confirming the microfissural state’s great influence on the compressive strength of rocks. But Green Butterfly also has much bigger volume percentage of k-feldspar (50%) than Green Panorama (25.8%), corroborating other authors which stated that this percentage is the primary factor negatively influencing compressive strength [6]. On the other hand, the blades consumption of Green Butterfly was the same as the Green Panorama, which needs to be better studied. In fact, standard deviations of sawing inputs consumption are so big that those values cannot be correlated to detailed observations of petrographic features on the samples, as we would be comparing numbers in such different scales that it wouldn’t be reliable.

Values of wear resistance for those green granitoids didn’t follow exactly the higher or lower Qz content, but their grit consumption did, as expected.

In this work we could not verify the decrease in mechanical strength due to the presence of minerals with cleavage, as some authors [8], since it was not possible to measure the sizes of grains of these minerals and the content does not seem to affect resistance significantly, as in the case of the Green Panorama.

<p>| Table 2 – Samples petrographic features discussion in relation to their mechanical strength. Qz max (mm) = maximum size of quartz crystals; Qz med (mm) = medium size of quartz crystals; k-f max (mm) = maximum size of k-feldspar crystals; % cliv = cleavage minerals percentage (considering Bt, Ms, Opx, Cpx). |</p>
<table>
<thead>
<tr>
<th>Qz max (mm)</th>
<th>Qz med (mm)</th>
<th>k-f max (mm)</th>
<th>%cliv - Bt, Ms, Cpx, Opx</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.88</td>
<td>4.13</td>
<td>6.25</td>
<td>5%</td>
<td><strong>Giallo Ornamental:</strong> The high degree of alteration does not appear to have a significant importance in the resistance values as it has high proportions of Qz and k-f and low of cleavage minerals. The low to medium microfissural state of k-f crystals also help the higher resistance. The porphyritic crystals of Qz with undulant extinction don’t seem to diminish the strength of the rock.</td>
</tr>
<tr>
<td>5.88</td>
<td>4.13</td>
<td>3.93</td>
<td>10%</td>
<td><strong>Giallo Santa Cecilia:</strong> Small quartz crystals showing dynamic recrystallization process by edge migration may reduce its resistance to abrasion and compression. The higher microfissural state of k-f crystals together with the highly deformed Qz ones also make the compression strength lower (103.6 MPa). The presence of amorphous silica (more susceptible to alteration) can also diminish the resistance of the rock.</td>
</tr>
<tr>
<td>8.58</td>
<td>7.23</td>
<td>21.70</td>
<td>10%</td>
<td><strong>Giallo Fiorito:</strong> Even with high percentages of Qz and k-f it has low abrasive strength, which could be explained by the fact that the rock has megacrystals of k-f. It doesn’t affect its compressive strength as it shows low microfissural state, no dynamic recrystallization microstructures in quartz crystals and low amount of cleavage minerals. Its high alteration degree doesn’t seem to have great effect in its resistance.</td>
</tr>
<tr>
<td>3.13</td>
<td>3.13</td>
<td>13</td>
<td>5%</td>
<td><strong>White Dallas:</strong> This rock presented the highest compressive strength of all. As it has similar content of Qz + k-f as others, its higher strength could be influenced by its equigranular texture and low micro-fissural state. Also the Qz crystals don’t show microstructures of recrystallization.</td>
</tr>
<tr>
<td>0.48</td>
<td>0.80</td>
<td>1.33</td>
<td>13%</td>
<td><strong>Imperial Silver:</strong> It has medium values for both resistance values. The incipient foliated structure and equigranular fine texture of the rock provide more resistance against abrasive and compressive stresses. Showing strong evidences of dynamic recrystallization by edge migration of Qz crystals, which could reduce mechanical strength and could explain the medium values. The presence of small clusters of muscovite and hornblende may have secondary importance for the resistance.</td>
</tr>
<tr>
<td>3.75</td>
<td>0.80</td>
<td>3.13</td>
<td>10%</td>
<td><strong>Green Pearl:</strong> The low wear resistance of this rock is probably due, in part, to the fact that there is a high comminution by dynamic recrystallization of crystals of Qz with the miemekitic envelope usual in k-f phenocrystals. Although it has a low content of minerals with cleavage, it microfissural state is high which could explain its medium compressive strength values. The polygonal crystal contacts also have an influence on the compressive strength because of the small contact area.</td>
</tr>
<tr>
<td>1.50</td>
<td>1.00</td>
<td>4.68</td>
<td>12%</td>
<td><strong>Green Butterfly:</strong> The abrasive wear values are consistent with the percentages of k-f and Qz as seen in other studied granitoids, but its low compressive strength can be due to the high amount of crystals with very high microfissural state. Even with low amount of minerals with cleavage, the values of compressive strength proved to be low among the granitoids, indicating the importance of microfractures over that parameter.</td>
</tr>
<tr>
<td>2.20</td>
<td>1.90</td>
<td>11.90</td>
<td>20,05%</td>
<td><strong>Green Panorama:</strong> The values of mechanical strength of this rock are the highest among the green granitoids. By presenting a smaller percentage of Qz and k-f (10% lower than the others) and high amount of minerals with cleavage, the resistance should be somewhat lower, which is not observed in the results of the characterization. The presence of unaltered phenocrystals of k-f with microperthitic texture can be a factor that helps its higher resistance than expected. The lacking of indications of dynamic recrystallization in the Qz crystals and its low microfissural state may also be of importance.</td>
</tr>
<tr>
<td>0.60</td>
<td>0.50</td>
<td>Nd</td>
<td>28,60%</td>
<td><strong>Black San Gabriel:</strong> The amount of crystals with cleavage in norites is usually high, and quartz and orthoclase percentages are very low. Therefore, the wear resistance and compression strength of this rock is the smallest among all samples. Even showing equigranular, medium-grained texture and low process of sericitization in plagioclase crystals, the mineral composition proved to be the most important factor for the mechanical strength. Interlobated contacts, dominant in this rock may also unstabilize the mineral web favoring the mineral disaggregation.</td>
</tr>
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</table>
Conclusions

It seems clear that the grit consumption is directly related to the abrasion resistance of the rocks which, in turn, depends on their mineralogical composition. The consumption of blades seems to be related to the compressive strength of the rocks, which also depends mainly on the mineralogical composition, but also on other features such as petrographic texture and, in particular, on the microfissural state.

The high standard deviation values of the consumption of grit and blades analyzed in this study corroborate the existence of many factors to be controlled in the sawing process and make more difficult a judicious correlation between this and petrographic characteristics in greater level of detail. Therefore, it is suggested here to continue working with a more comprehensive survey in other processing companies, hopefully (as this can may not happen), to reduce the dispersion of results from inputs consumption and compare them more adequately with petrographic measurable details.

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