

Railroad ballast of granites and basic rock in tropical regions: relationships between petrography, physical-mechanical properties and alterability

Lastro ferroviário de granitos e rocha básica em regiões tropicais: relações entre petrografia, propriedades físico-mecânicas e de alterabilidade

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ABSTRACT

The objective of this study was to evaluate, comparatively, the evolution of this degradation of three rock types, two granitoids and a microgabbro which, eventually, could be used as ballast, due to the proximity of the quarries to the design route of a railroad to be built between São Paulo and around Campinas, State of São Paulo, southeastern Brazil. They were tested for alterability in sodium sulfate and ethylene glycol solutions. Based on detailed petrographic analysis, Micro-Deval and Slake Durability Index tests were performed with and without conjugation to the referred alterability tests. The results obtained are punctual, valid and positive for the samples of the rock masses carefully selected and described, considering the different characteristics of the granitoids belonging to the Morungaba and Cantareira Complexes. In the case of basic rock, the microgabbro, should not be used as ballast in the studied tropical climate area, since the exposed fragments that make up the ballast are intensely affected by chemical weathering (notably reactions accelerated by water and temperature), which culminate in the decomposition of primary minerals and, consequently, in the faster physical-mechanical degradation of this rock. In practice, more frequent periodic maintenance and higher costs.

RESUMO

O objetivo deste trabalho foi avaliar, de modo comparativo, a evolução desta degradação em três tipos de rochas, dois granitóides e um microgabro os quais, eventualmente, podem ser utilizados como lastro, devido à proximidade das pedreiras ao traçado de uma ferrovia a ser construída entre São Paulo e a região de Campinas (SP), região sudeste do Brasil. A alterabilidade das rochas foi testada utilizando-se soluções de sulfato de sódio e de etilenoglicol. Com base em análises petrográficas detalhadas, ensaios Micro-Deval e de abrasão à umidade (“Slake durability test”) foram realizados conjugados ou não aos referidos ensaios de alterabilidade. Os resultados são pontuais, válidos e positivos para as amostras dos maciços rochosos cuidadosamente selecionados e descritos, considerando as diferentes características dos granitóides pertencentes aos Complexos Morungaba e Cantareira. No caso da rocha básica, o microgabro, não deve ser usada como lastro na região estudada, de clima tropical, pois os fragmentos expostos que constituem o lastro são intensamente afetados pelo intemperismo químico (notadamente reações aceleradas pela água e temperatura), culminando na decomposição dos minerais primários e, conseqüentemente, na degradação físico-mecânica mais rápida desta rocha. Na prática, manutenções periódicas mais frequentes e de custos mais elevados.



1. INTRODUCTION

Railroad is an essential and strategic means of transport that plays a key role in the economy of many countries. In recent years, Brazil has carried out research to implement new ballast railroads and/or readjust the existing ones, in general for the flow of agricultural products between producing regions and ports. The studies also focus on projects to be constructed that involve passenger transport, interconnecting, for example, some of the main cities in the southeastern region through medium- and high-speed trains (Cagnon *et al.*, 2015; Revista Ferroviária, 2019).

Ballast railroads are the most used all over the world for several reasons, including savings in implementation, efficient rainwater drainage and easy maintenance. Regarding the maintenance cost, a remarkable technological advance is occurring in the manufacture of rails and sleepers, and it is also necessary to encourage studies on the knowledge of the technological characteristics of the most adequate rocks for use as aggregate in the ballast. Some of the most recent studies include those on petrographic aspects, mechanical properties to provide engineering design parameters and alterability (Apaydin and Yilmaz, 2020; Esfahani *et al.*, 2019; Paiva *et al.*, 2018; Van Blerk *et al.*, 2017; Sadegui *et al.*, 2016), especially considering the weathering conditions imposed on these rocky materials in a tropical climate, dominant over a large area of the Brazilian territory. In other words, it is important to stress that the rock aggregates used to make up the ballast of railroads are subjected to constant exposure to the weathering, being under stronger influence of the environment in terms of decomposition of minerals by chemical reactions. That is, studies on alterability become as important as those on geomechanical characterization of rocks aiming at this type of use.

In this approach, the present study is part of a multidisciplinary line of research, involving the expertises of Engineering Geology and Transportation Engineering.

In addition to the physical-mechanical qualification, the objective was to evaluate aggregates comparatively, based on non-routine and poorly disseminated tests in studies of characterization in Brazil, the evolution of the degradation of three rocky materials from quarries located in the city of São Paulo and in the surroundings of the city of Campinas (southeastern Brazil). These materials were chosen for several reasons, among them: they have been used for decades as aggregates for concrete and paving, but still little analysed for railroad ballast, and for logistical reasons, due to the proximity to the layout of the route planned for the Inter Cities Train "TIC" (Revista Ferroviária, 2019).

To this end, based on detailed petrographic analysis (mineralogy, texture, degree of alteration, microcracking, among others), physical-mechanical and alterability tests were carried out, combined or not with Micro-Deval abrasion and Slake Durability Index tests, on samples collected in sites of the massifs that presented better quality, which were adopted as parameters to quantify the mechanical degradation of the studied rocks. The proposed characterization, from the technological point of view, represents very well the mechanical demands (compression, abrasive wear, crushing and toughness) and as well as the weathering effects imposed on the ballast of a railroad in use in a tropical climate.

2. MATERIAL AND SAMPLING

Among the lithologies studied by Remédio (2017) to compose railroad ballast, Morungaba Complex (MOR), Cantareira Granite (CAN) and Basic Intrusives of the Serra Geral Formation (GAB) were selected, due to their technological qualities and the proximity to the possible route

designed for the Inter Cities Train “TIC” that will connect the capital of the State of São Paulo, Brazil, to the city of Americana. These rocks are exploited in several active quarries near existing railroads and have been in operation for decades, driving the growth of the metropolitan regions of Campinas and São Paulo (Figure 1).

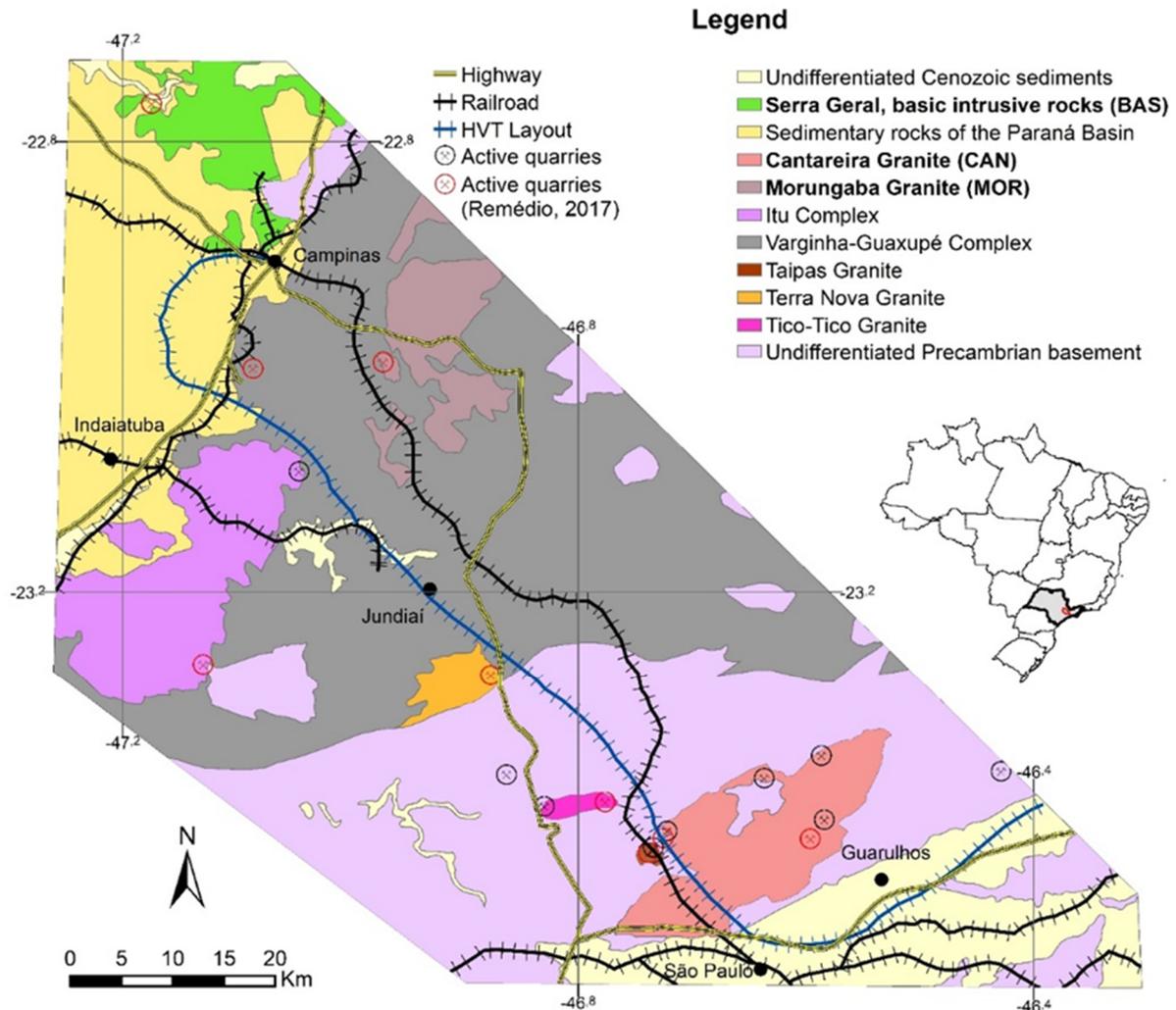


Figure 1. Location of the area. The three geological units that make up the present study are highlighted in bold in the legend

A fundamental aspect to be highlighted (but usually neglected in Brazilian engineering practice) is that, in the case of railroad ballast, the analysis of the field works should precede the sampling steps and, obviously, the technological tests. There is no homogeneous rock massif, but higher or lower geological variability. In other words, every study should begin with a detailed geological description of the quarry, especially the heterogeneities of the rock mass regarding the exploitable rocks among those existing.

Based on these premises, before sampling, geological observations and petrographic descriptions were made on the fronts of the quarries, where rocks are extracted for engineering applications to define the portions of the massif with better quality. Rocks for ballast are extracted from these portions, where the aggregate is required for its mechanical quality and, especially, for the greater resistance to weathering. The other portions of the massif are used for

the extraction of rocks for other applications, such as concrete and paving, which use aggregates with binders, in which other properties gain relevance, for example, the alkali-aggregate reactivity and the adhesion to the asphalt.

Subsequently, new observations were made, with regard to the integrity found in the diverse dimensions of the disassembled rock, along with the collection of blocks and irregular fragments of such material (Figure 2). Coarse aggregates were produced in laboratory, for the exact origin of the material, different from what occurs when the material is crushing in the quarry, which may contain rocks from different domains of the rock mass.



Figure 2. Careful inspection of dismantled material in terms of sample representation for technological testing. At the bottom, a bench exposing the rock mass of the microgabbro and the presence of little to medium-persistent fractures, usually closed and with decimetric spacing

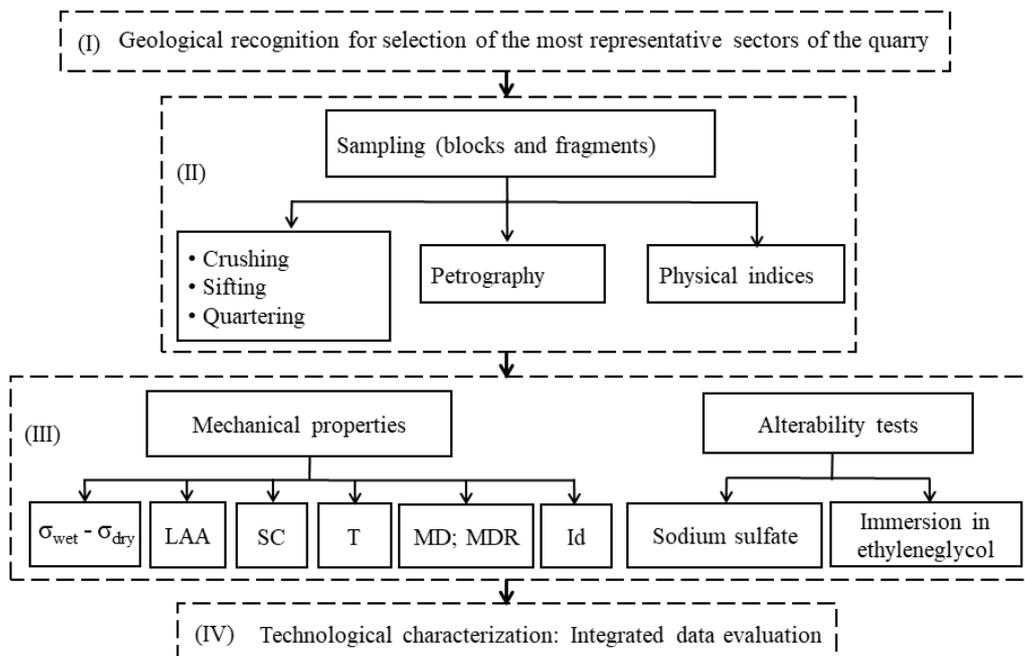


Figure 3. Experimental flowchart

The methodological flowchart (Figure 3) is show below: (I) Geological field recognition to define the quarry sector to be studied; (II) Collection of samples in front of rock dismantling (blocks and irregular fragments). After crushing, the material was sieved, homogenized and quartered, with the separation of the aliquots for the mechanical and accelerated alteration tests; petrographic analysis and determination of physical indexes; (III) Determination of the values of the mechanical and alterability testing; Micro-Deval abrasive wear (MD and MDR) and Slake Durability Index (Id) served as a reference to assess the mechanical degradation of rocks: MD associated with soundness tests by use of sodium sulfate and Id to soundness tests by immersion in ethyleneglycol; (IV) Integrated assessment of data obtained in technological characterization tests.

3. TEST METHODS

Petrographic analyses and physical-mechanical testing procedures (physical indices, uniaxial compression strength – σ_{dry} and σ_{wet} , Los Angeles abrasion - LAA, crushing strength - SC, Treton toughness index - T, Micro-Deval abrasion - MD and Slake Durability Index - SD_i) and alterability followed the guidelines of the Brazilian Association of Technical Standards (ABNT), American Standard Testing Machines (ASTM) and National Department of Transportation Infrastructure (DNIT). Table 1 presents the synthesis of these tests and their respective technical standards, type/amount of sample and execution procedures.

The uniaxial compressive strength tests were carried out on specimens dried in an oven at 110° C and also on saturated specimens, to assess the possible hydraulic weakening of each rock in relation to the efforts applied on them. The hydraulic weakening coefficient *R* (Kowalski, 1970 according to Mesquita, 2002 and Mattos *et al.*, 2013), relates the strength of a dry and saturated material and allows to evaluate the effect of water on the strength of rocky materials, and is calculated by Equation 1.

$$R = (\sigma_{wet} / \sigma_{dry}) \times 100 \quad (1)$$

where σ_{wet} and σ_{dry} are the tensile strength of the material in saturated and dry conditions, respectively.

To obtain information about the weathering of rocks as fragments (ballast), two types of alterability tests were conducted: with sodium sulfate and with ethyleneglycol, all with oven drying. During these cycles, all samples were qualitative and quantitatively evaluated by measuring mass losses, by visual examinations and photographic records of any damages (fissures, cracks, flaking, oxidation and disintegration) in the specimen. Additionally, the MD and SDI tests, which are not routine in studies on the characterization of aggregates in Brazil, were adopted as auxiliary parameters to quantify the disaggregation (Figure 4), because they are tests performed with saturated samples, in which the altered material is discarded from the sample mass.

Based on the guidelines of the D6928 standard (ASTM, 2017), the MD test was used to quantify the abrasion resistance and durability of rocky aggregates. This test is widely used worldwide, but not in Brazil. Each test used a sampled with about 1,500g of fragments with diameters passing through a 19.50 mm sieve, and retained in a 9.50 mm sieve. The “Micro-Deval Residual” (MDR) index, proposed by Benediktsson (2015), was also calculated by the ratio of the sum of the masses retained in the sieve of the lowest fraction of the chosen grade of the test to the initial sample mass.

Table 1 – Types and condition of aggregate tests adopted in the present study

Test	Standard	General remarks
Petrographic analysis	NBR 7389 (ABNT, 2009) NBR 15845 (ABNT, 2015)	Optical microscopy in thin sections obtained from representative fragments of rocks.
Dry weight Apparent porosity Water Absorption	NBR 5564 (ABNT, 2012)	Measurements of the dry, saturated and submerged masses of 10 specimens randomly chosen from the rock fragments sampled in the field.
Uniaxial Compressive Strength	NBR 5564 (ABNT, 2012)	Cylindrical specimens, 76mm diameter, 2/1 height/ diameter ratio; tests in dry and saturated conditions.
Los Angeles Abrasion	NM 51 (ABNT, 2001)	“F” grade: 10000 ± 75g particles 50 to 25mm sieve; abrasive load 5000 ± 25g; drum speed: 30-33rpm; 1000 rotations. Final mass is retained in the 1.7mm sieve. Dry testing.
Micro-Deval Abrasion ⁽¹⁾	D6928 (ASTM, 2017)	“A” grade: 1500 ± 5g particles 19 to 9.5mm sieve; abrasive load: 5000 ± 25g; drum speed: 100 ± 1rpm; 12,000 rotations. Final mass is retained in the 1.19mm sieve. Water testing.
Treton Toughness Index	NBR 5564 (ABNT, 2012)	Three sets of 20 fragments 19 to 16mm diameter each; final mass of the test sample is retained in a 1.7mm sieve.
Strenght to crushing	NBR 9938 (ABNT, 2013)	About 10,000 g of particles 12.7 to 9.5 mm sieve; load of 40 ton per sample; rate 4 ton/min. Final sample mass is retained in a 2.4 mm sieve.
Slake Durability Index ⁽²⁾	D4644 (ASTM, 2016)	About 500 g of particles 19.5 to 9.5 mm sieve; two standard wetting and drying steps. In the present study, 5 complete cycles were performed for each rock.
Soundness of aggregates by use of Sodium sulfate	C88 (ASTM, 2018) DNER-ME 089/94 (DNIT)	Same grade and quantity of the sample used in the MD abrasion test; 05 cycles of immersion in sodium sulfate solution (18 hours) and drying in an oven (8 hours). Final sample mass is retained in a 9.5 mm sieve.
Soundness by immersion in ethyleneglycol	NBR 12697 ⁽³⁾ (ABNT, 1992)	As above; 06 cycles of immersion in ethyleneglycol (48 ± 1hs and 72 ± 1hs) and oven drying (4 hours or more). Final sample mass is retained in a 9.5mm sieve

⁽¹⁾ Mechanical test combined with the accelerated alteration test with sodium sulfate solution; ⁽²⁾ Mechanical test combined with soundness tests by immersion in ethyleneglycol; ⁽³⁾ In the case of comparative studies, the alteration processes on which the rule is based are considered to verify the alterability of the rocks studied.

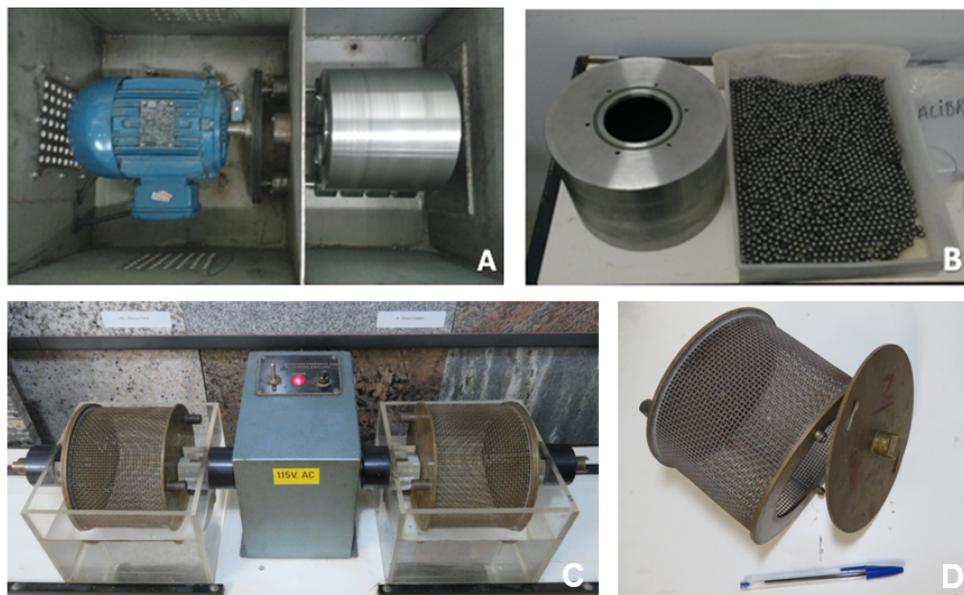


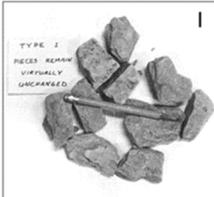
Figure 4. ABOVE: (A) Micro-Deval wear equipment: drive motor and cylinder; (B) Detail showing cylinder and abrasive load (9.5mm diameter spheres). BELOW: (C) Slake Durability Index wear equipment; (D) Detail showing the drum and its sealing cap

In the case of the SD_I test, although originally used in soft and low-strength rocks, with an expansive nature and with high disintegration when wetted (Franklin and Chandra, 1972), there are several examples of application of this test in research involving the alterability of igneous rocks and their behavior in geological massifs used by engineering (Momeni *et al.*, 2017; Gupta and Ahmed, 2007; Arel and Tugrul, 2001). For comparative purposes between the rocks, adjustments to the guidelines of the D4644 standard (ASTM, 2016) were established, using approximately 500 g of fragments with diameters between 19.5 mm and 9.5 mm (same grade of the MD test) before and after the accelerated alteration tests. In the present study, five complete cycles were run for each rock.

Table 2 lists the classification of rock durability proposed by Gamble (1971), taking into account the Id values obtained in the tests, and each sample retained in the drum should be visually categorized in comparison to the standards established in the D4644 standard (ASTM, 2016), as follows: Type I: retained samples remain practically unchanged; Type II: retained samples consist of large and small fragments and Type III: retained samples are exclusively small fragments.

Table 2 – Durability classifications: (A) Slake Durability Index (Gamble, 1971); (B) Visual characterization of samples submitted to SDI tests. Modified from D4644 standard (ASTM, 2016)

	Id (%)	Classification	Symbol
	100-98	Very high	VH
	98-95	High	H
(A)	95-85	Medium high	MH
	85-60	Medium	M
	60-30	Low	L
	30-0	Very low	VL

(B)			
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4. RESULTS AND DISCUSSION

The results of the tests performed are presented following the order of the methodology used in the study.

4.1. Petrographic analysis

The information regarding the degrees of microcracking and rock alteration are discussed below, with the most important petrographic features analyzed at the microscopic level presented in Table 3 and Figure 5.

The studied materials refer to intrusive rocks with homogeneous aspects, massif and isotropic structures with equigranular to unequigranular phaneritic textures (discretely porphyritic). Considering the composition, there are two granitoids: the first, called Morungaba Granite (MOR), a fine-grained and pink-colored syenogranite; the second, Cantareira Granite (CAN), a coarse-grained, porphyritic and poikilitic monzogranite, light gray in color. The other rock is a medium to fine grained microgabbro (GAB), dark gray in color.

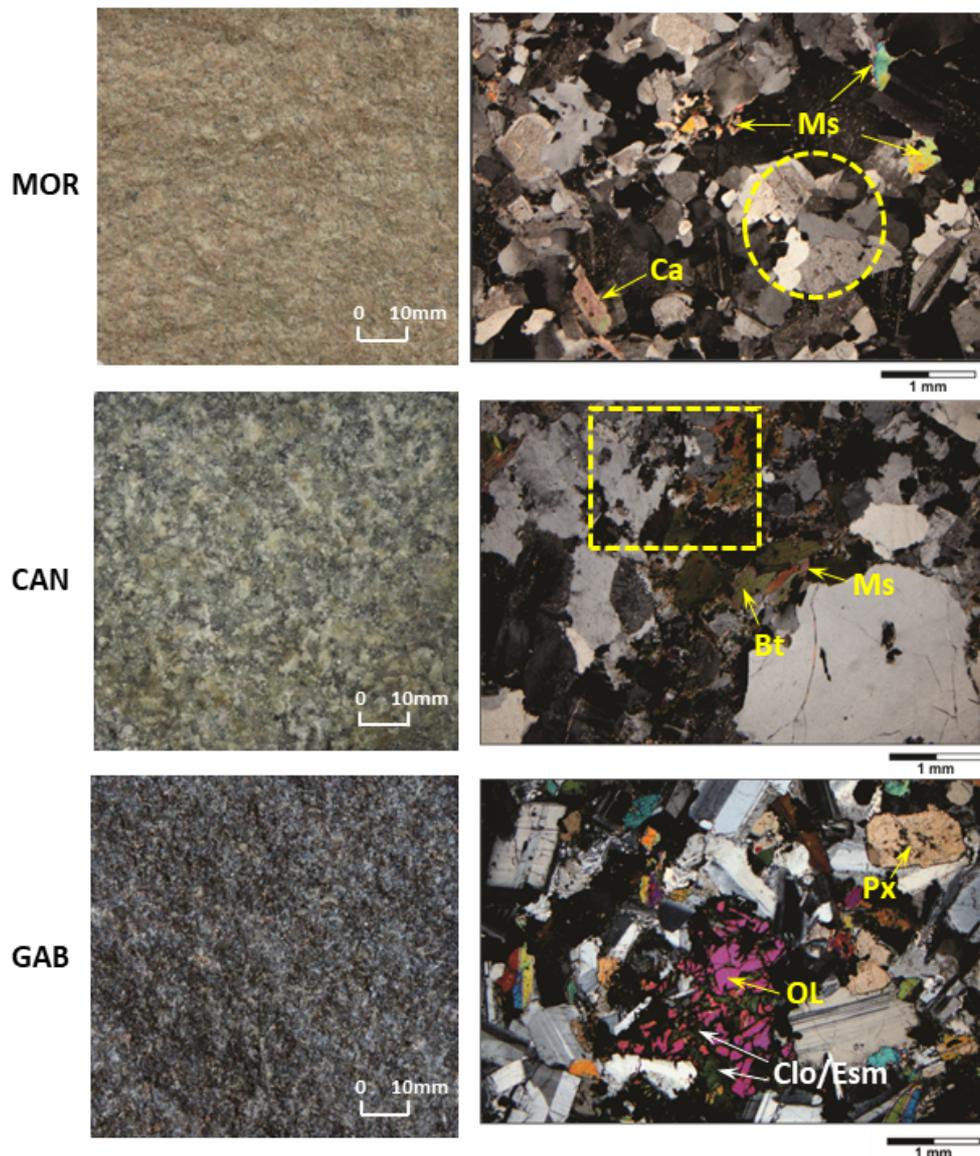


Figure 5: LEFT: Macroscopic appearance of natural rock surfaces; RIGHT: Photomicrographs (crossed nicols). MOR syenogranite: observe equidimensional arrangement, incipient alteration and strong interlacing of the quartz-feldspar matrix (detail encircled with dashed line); CAN monzogranite: noting relatively more intense alteration in plagioclase and alkaline feldspar crystals (example in rectangle with dashed line); GAB microgabro exhibiting subophytic texture and secondary minerals (chlorite and smectites) filling cracks especially in olivine crystals. Minerals key: Px-pyroxene; Ol-Olivine; Clo/Esm- chlorite and smectite aggregates (expansive clay minerals); Bt-biotite; Ms- Muscovita; Ca- carbonate.

The microcracking degree of the three materials is scarce to low, essentially intragrain, relatively more intense in the mafic minerals (olivine and clinopyroxenes) of the microgabro. As for the alteration of this rock, it is more intense close to the concentrations/aggregates of mafic minerals. The predominant secondary minerals occurring in a powdery form, represented by chlorite, biotite, fibrous amphiboles and cloropheite, which would represent a fine greenish aggregate and possibly composed of chlorite, fibrous amphiboles, greenish biotite and clay minerals, such as celadonite and nontronite (especially on clinopyroxenes and olivines). As shown in the Figure 5, olivines are the most intensely microfractured minerals, with open microcrack systems and filled with a thin mass of secondary minerals, such as opaques, chlorite, amphiboles and some mineral clay.

Table 3 – Petrographic analyses by optical microscopy

Material	MOR	CAN	GAB			
Texture	Equigranular hipidomorphico to alotriomorphico	Phaneritic discretely porphyritic	Subophytic			
Grain contact	Good contact with other minerals and interpenetrated	Good contact with other minerals and interpenetrated	Good mineral interlacing and contacts geared			
Mineralogy	Orthoclase	44%	Plagioclase	30%	Plagioclase	53%
	Quartz	31%	Quartz	29%	Augite	27%
	Plagioclase	19.5%	Microcline	24%	Opaques	8.5%
	Biotite	0.5%	Biotite	8.5%	Orthoclase	1.7%
	Muscovite	2%	-	-	Olivine	1.5%
	Accessories	0.5%	Accessories	2%	Accessories	0.3%
	Secondary	< 2%	Secondary	6.5%	Secondary	8%
Microcracking degree	Incipient (intragrain)	Low (intragrain)	Low (intragrain)			
	Discreet and closed (orthoclase/plagioclase); rare and closed (quartz)	Moderate to high (quartz); low (microcline); incipient (plagioclase)	Low to moderate (olivine/augite); low (plagioclase)			
Alteration degree	Moderate sericitization (orthoclase); weak chlorination (biotite) and saussuritization (plagioclase)	High undulating extinction (quartz); intense saussuritization (plagioclase); low sericitization microcline	Moderate to intense (olivine/augite/opaques) weak saussuritization (plagioclase/epidote)			
Classification	Sienogranite	Monzogranite	Microgabbro			

4.2. Physical-mechanical indices

Information from the petrographic analysis allows to set some correlations with the values of the physical indices. A brief comparison between the studied materials (Table 4 and Figure 6) indicates the GAB microgabbro as the rock with relatively more expressive values of apparent porosity ($\eta a = 1.73\%$) and water absorption ($\alpha a = 0.59\%$).

In the first case, as shown in Figure 7, it exceeds the maximum value of 0.8% recommended by the NBR 5564 standard (ABNT, 2012). These higher values of ηa and αa seem to be related to the coarser particle size of the rock and to a greater communicability of its pore network. They depend on the conditions of mineralogical alteration (especially of plagioclases) and the microcracking pattern with predominance of intragrain fissures with some transgrain cracks. In relation to the apparent specific mass (ρa), the three rocks meet the requirements of standard NBR 5564 (ABNT, 2012), which recommends a minimum value of 2,500 kg/m³. As expected, the microgabbro was the rock with the highest ρa (2,940 kg/m³), with a content of 37% heavy minerals (augite, opaques and olivine).

Table 4 – Synthesis of average values in physical-mechanical tests

Properties	Recommendation	MOR	CAN	GAB
ρa (kg/m ³)	2500 (Min.) ¹	2,600	2,670	2,940
ηa (%)	1.5 (Max.) ¹	0.57	0.75	1.73
αa (%)	0.8 (Max.) ¹	0.22	0.28	0.59
σ_{dry} (MPa)	n.s.	281.92	197.73	189.05
σ_{wet} (MPa)	100 (Min.) ¹	264.82	188.28	175.87
R (%)	n.s.	93.9	95.2	93.0
LAA (%)	30 (Max.) ¹ ; 6 a 24 ²	17.5	23.6	16.5
SC (%)	29 (Max.) ³	19.5	19.3	17.6
T (%)	25 (Max.) ¹	26.7	27.5	19.5

ρa : dry weight; ηa : apparent porosity; αa : water absorption; σ_{dry} e σ_{wet} : uniaxial compressive strength in dry and saturated conditions; R: Hydraulic weakening coefficient (Mesquita, 2002; Mattos et al., 2013); LAA: Los Angeles abrasion; SC: strength to crushing; T: Treton toughness Index. ¹ NBR 5564 standard (ABNT, 2012); ² EN 13450 standard (DIN, 2013); ³ SABS 1083 standard (2014); n.s.: not specified.

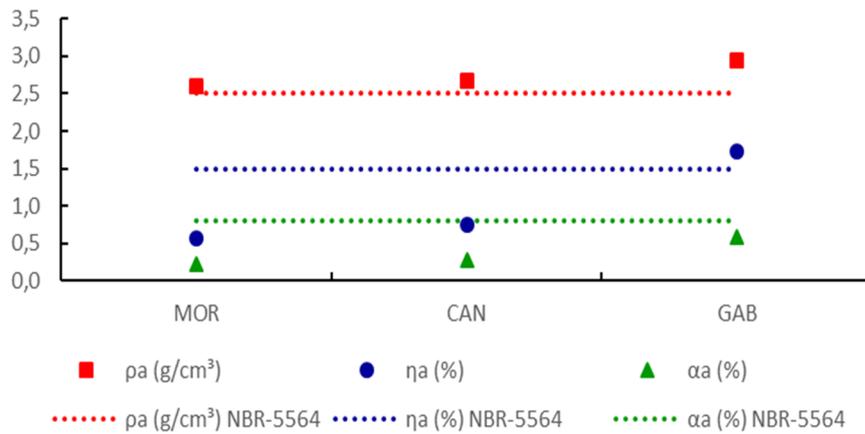


Figure 6. Results of physical index tests. The dotted lines in red, blue and green indicate the minimum limits of dry weight and maximum limits of apparent porosity and water absorption, respectively, recommended by the NBR 5564 standard (ABNT, 2012)

With respect to uniaxial compressive strength, both under dry condition and saturated in water, all the rocks presented values that exceed the 100 MPa required by the NBR 5564 standard (ABNT, 2012), as one of the requirements for use in railway ballast. They had very high (above 170 MPa) to extremely high (above 260 MPa) strength in the case of MOR syenogranite, a solid, homogeneous, compact and fine-grained rock. Values of σ_{sat} decreased for the three studied rocks, with R indices that varied from 95.2% to 93.0%, indicating, respectively, a decline in mechanical strength of the order of 4.8% to 7.0%. The reduction for GAB microgabbro was slightly more pronounced and is related, in large part, to its higher values of porosity, water absorption, microcracking conditions and mineral alteration which, together, are responsible for resulting in a relative weakening of the rock.

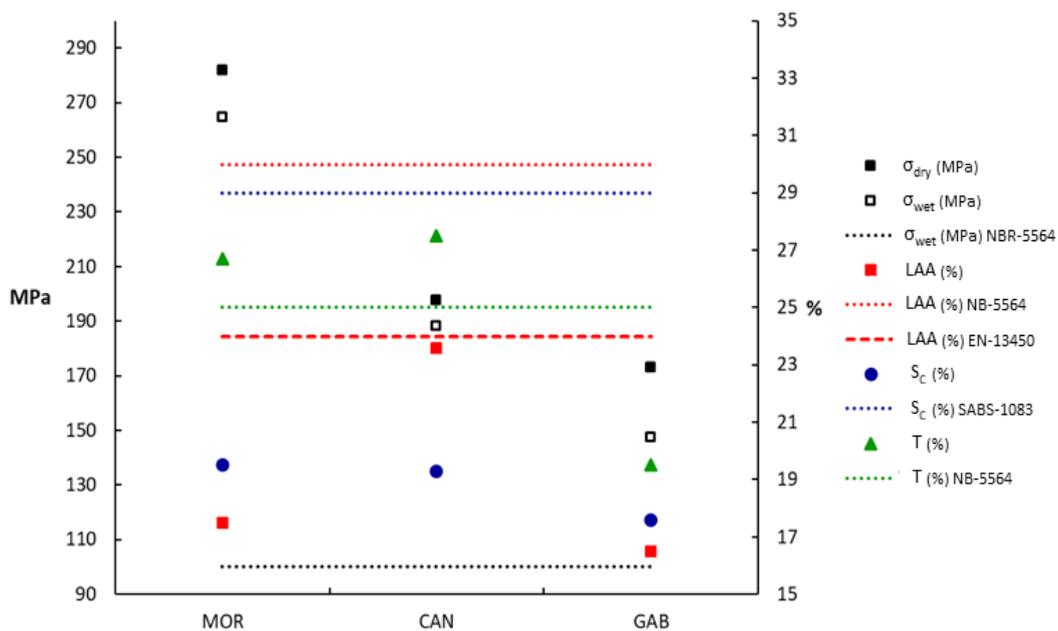


Figure 7. Results of mechanical tests. The dotted (or dashed) lines in black, red, blue and green, indicate the minimum limits of uniaxial compressive strength and maximum Los Angeles abrasion, strength to crushing and Treton impact, respectively, recommended by the NBR 5564 (ABNT, 2012), EN 13450 (DIN, 2013) and SABS 1083 (2014) standards.

The average results of all mechanical properties are in Figure 7. MOR and CAN granites exceeded the requirement of strength to Treton impact of 25% recommended by the NBR 5564 standard (ABNT, 2012). However, considering the Los Angeles abrasion and strength to crush tests, the most representative for being performed with larger volume samples, the three samples studied met the regulatory requirements, including the more conservative limits of the EN13450 standard (DIN, 2013), which set forth a maximum LAA abrasion loss of 24% for passenger trains, an index better related to the present study.

These results are valid for the conditions and sampling sites in the quarries visited and should not be used as a criterion for the acceptance or rejection of these rocks for use as aggregate in railroad ballast, since all materials are explored and commercialized for other purposes, notably for use in concrete with Portland cement and in paving. In addition, the more extensive the study area, the more important the geotechnical qualification of the rock mass. In practice, as stressed by Remédio *et al.*, (2018), it is essential to carry out studies at the extraction sites to optimize the dismantling and crushing operations and, thus, to meet the strict selection criteria for use as ballast in a large engineering work, as may be the case of the Inter-Cities Train (TIC). Anyway, it is reiterated that the scope of this research was to compare different types of rock aggregates, discussing their suitability and limitations aiming at their use as railroad ballast, but not specifying them and also avoiding any type of commercial connotation as to the quarries studied.

As for the Treton Impact, a limitation of this test refers to the “artisanal” preparation to remove the edges and avoid elongated axes, to approach the equidimensional shape and adapt to the test grade (12.5 to 9.5 mm). Small differences in the shape of the fragments that make up the standard sample can cause the impact of the test socket to be, even partially, absorbed by slightly more prominent fragments (Figure 8). That is, it may not accurately represent the fracture toughness of the tested material. A schematic illustration of this test is given below.

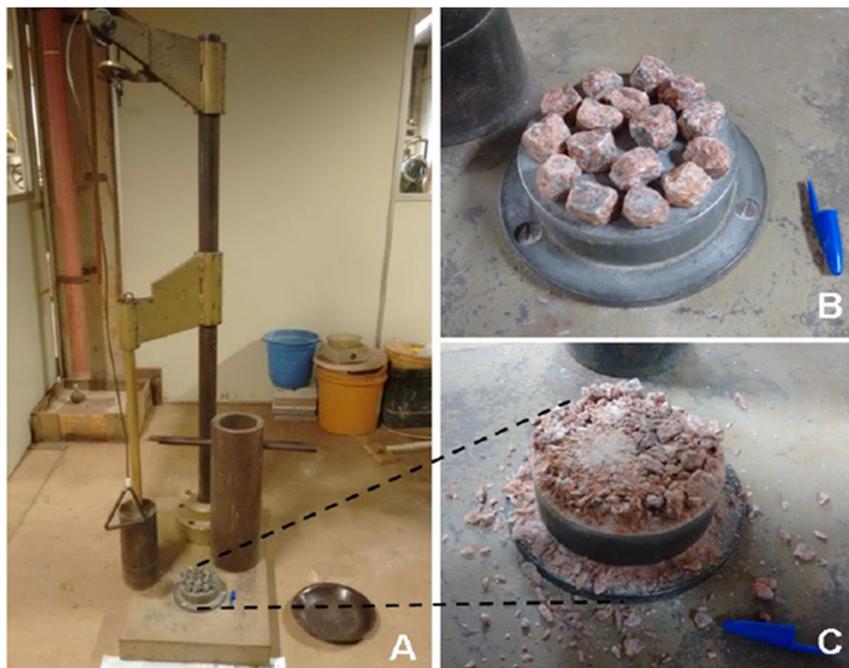


Figure 8. (A) Treton equipment used to determine the impact strength of MOR syenogranite; (B, C) Details showing, respectively, a set of fragments before and after the socket impacts, according to the procedures of NBR5564 standard (ABNT, 2012).

In this sense, some international references highlight the need to use the grade effectively used in ballast to specify rocks for this purpose. According to Lim (2004) and Bach (2013), the rupture indices of the fragments are very poorly related to those of the conventional crushing test (that is, with small particles), but very well with tests carried out in proportionally larger devices using larger particles. As for impact strength, the EN 14350 standard describes the sample and test conditions: about 3 kg fragments between fractions 40 and 31.5 mm and an apparatus similar to the national Treton, but with obviously larger dimension. This equipment does not exist in Brazil.

MD and SD_i tests are not conventionally applied in aggregate studies, but were used as a reference for mechanical degradation in the alterability tests, thus, their results are discussed together with the alterability tests, below.

4.3. Alterability tests

The accelerated alteration tests were carried out considering the feasibility of the experiments and also to check their suitability in testing laboratory conditions that seek to reflect the conditions of the rocky materials studied.

4.3.1. Soundness of aggregates by use of sodium sulfate

Although the differences in texture between the two granitoids (MOR and CAN) are pronounced, they were not sufficient to obtain significant results in mass losses. The low degree of alteration of these rocks also contributed to the low laboratory degradation observed, with average mass losses of 0.53% and 0.47%, respectively.

In relation to microgabbro (GAB), with a slightly greater loss of mass (0.67%), a greater effect of the crystallization of sodium sulphate inside the rock was expected during the soundness tests, as it has porosity (1.73%) above specification of NBR 5564 (ABNT, 2012), since it has fine to medium grains and subophitic texture. Considering the composition, the mineral most intensely altered by chloritization is olivine, which is also the most intensely microfractured mineral, filled with secondary minerals that correspond to 8% total rock, including opaques, chlorite, fibrous amphiboles and clays (celadonite and nontronite). This would result in greater cracking of the materials subjected to cycling, which did not occur, possibly due to the discontinuous and intragrain microcracking pattern, as shown in petrographic analyses.

When the rock samples were subjected to soundness cycles and combined with the MD test, the results of the degradation surprisingly were lower compared to the fresh rocks (Table 5), except for CAN granitoid, which showed an increase of only 1% of its value. The low degradation of the rocks due to accelerated alteration with Na_2SO_4 is because the tensile stress cycles, exerted by the crystallization and dilation of the salts in the rock voids (pores and fissures), were not enough to cause significant fragmentation during the Micro-Deval assay.

As already mentioned for crushing and impact strength, there is also an international specification for Micro-Deval abrasion. The standard EN 1097-1 (DIN, 2011) presents in Annex A, for tests of railroad ballasts, the 50 mm sieves for passing particles and 31.50 mm for retained particles. It uses 10 kg aggregates, and a cylinder height 2.6 times greater than the conventional drum, without water. In order to better represent the tropical climate conditions, comparative tests with this apparatus and the Los Angeles abrasion test ("G" grade), both with saturated samples, would be advisable.

Table 5 – Results of Micro-Deval tests with sound and degraded rocks by cycling with sodium sulfate

Material	Rock condition	M _i (g)	M _f (g)	M _R (g)	MD (%)	MD _R (%)
MOR	Fresh	1,501.51	1,437.21	1,331.41	4.3	88.7
	Degraded	1,492.45	1,429.59	1,326.47	4.2	88.9
CAN	Fresh	1,501.36	1,391.95	1,211.82	7.3	80.7
	Degraded	1,493.49	1,373.94	1,170.41	8.0	78.4
GAB	Fresh	1,501.39	1,347.16	1,188.15	10.3	79.1
	Degraded	1,490.46	1,348.39	1,174.17	9.5	78.8

M_i: initial mass; M_f: final mass (retained in the 1.19mm sieve); M_R: sum of the masses retained in the sieve of the smallest fraction of the test graduation (9.5mm).

4.3.2. Soundness by immersion in ethyleneglycol

As previously described, the petrographic analysis of the microgabbro indicated the occurrence of expansive clays (celadonite and nontronite) in the microcracks among the secondary minerals that, in the presence of water, produce internal stresses in the rock leading to its degradation.

This motivated the performance of soundness tests with immersion in ethyleneglycol, an organic compound that easily penetrates the microcracks of the rock and by expansive forces lead to its fragmentation. With particle size fractions between 19.00 and 9.52mm, comparative tests with ethylene glycol indicated the following mass losses: 0.39% (MOR), 0.69% (CAN) and an expressive value of 41% (GAB), with important evidence of damage (fissures, cracking, flaking and fragmentation) in the samples of this last rock.

Table 6 – Results of the Slake durability index tests with samples of fresh and degraded rocks by artificial weathering by immersion in ethyleneglycol for MOR sienogranite, CAN monzogranito and GAB microgabbro

MOR sienogranite								
Id	Fresh rock			Class / Types of fragments	Immersion in ethyleneglycol			Class /Types of fragments
	Mi (g)	Mf (g)	%		Mi (g)	Mf (g)	%	
1	462.65	462.64	100.0	VH (I)	466.79	465.70	99.8	VH (I)
2		461.89	99.8			465.30	99.7	
3		461.32	99.7			464.55	99.5	
4		461.11	99.7			464.00	99.4	
5		460.60	99.6			463.31	99.3	
CAN monzogranite								
Id	Fresh rock			Class / Types of fragments	Immersion in ethyleneglycol			Class /Types of fragments
	Mi (g)	Mf (g)	%		Mi (g)	Mf (g)	%	
1	460.72	462.64	100.0	VH (I)	468.14	466.09	99.6	VH (I)
2		461.89	99.7			464.40	99.2	
3		461.32	99.6			463.49	99.0	
4		461.11	99.5			462.17	98.7	
5		460.60	99.4			461.72	98.6	
GAB microgabbro								
Id	Fresh rock			Class / Types of fragments	Immersion in ethyleneglycol			Class /Types of fragments
	Mi (g)	Mf (g)	%		Mi (g)	Mf (g)	%	
1	453.39	453.33	100.0	VH (I)	462.13	416.76	90.2	MH (II)
2		450.45	99.4			404.74	87.6	
3		447.75	98.8			398.38	86.2	
4		444.68	98.1			392.84	85.0	
5		453.33	97.8			389.69	84.3	

M_i: initial mass; M_f: final mass (retained in the 2.0mm sieve); Durability classes (Gamble, 1971): VH- very high, H- high, MH-medium to high and M- medium; (I) e (II): types of fragments retained in the test drum, D4644 (ASTM, 2016) standard.

Considering the amount and the low quality (several fragments) of sample available from material degraded by ethylene glycol (Figure 9B- 9C), SDI tests were performed to quantify the mechanical degradation of material saturated in this substance, comparing to samples of fresh rocks as a reference.

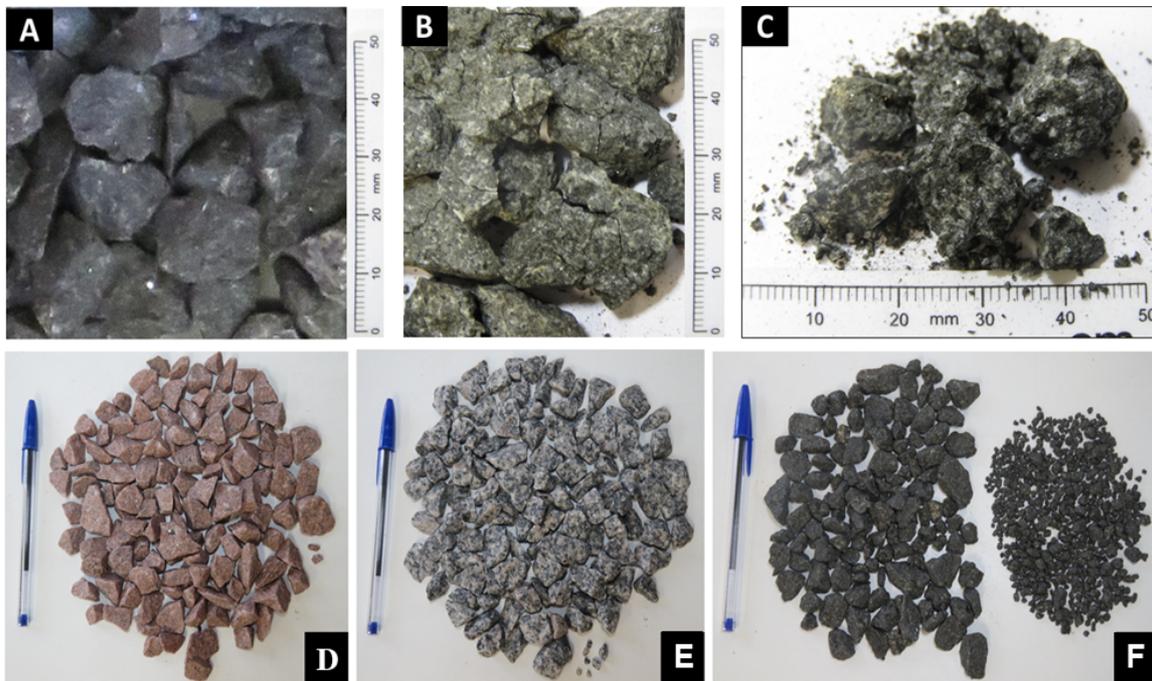


Figure 9. ABOVE: Aspect of the GAB samples before (A) and after (B, C) of the soundness tests by immersion in ethyleneglycol, showing intense cracks and fragmentation, respectively. BELOW: Visual aspect of the samples degraded by ethylene glycol with subsequent performance of the Slake Durability tests: (D, E) type I fragments of the MOR and the CAN samples, respectively; (F) type II fragments of the GAB microgabro.

4.3.3. Relationships between petrography and alterability tests

In general, the information and evidence presented by the three types of alterability tests are corroborated by the following mineralogical characteristics of the three rocks studied, in part already discussed by Santos *et al.*, (2019):

1) The MOR sienogranite has continuous fractures in two different directions filled by fine mass of secondary minerals (muscovite, carbonates, clay minerals and others). The microcracking of the quartz crystals which correspond to 31% of the constituent minerals are rare and closed. These characteristics result in the lower MD coefficient (4.28%) of the rock when compared to the other two studied. A smaller amount of fragmented material is also observed when the MDR index (88.67%) is applied. This coefficient represents, therefore, greater resistance of the rock producing more particles retained on the 9.50 mm sieve (Fig. 3). Petrographic aspects also lead to the lowest mass losses observed in the lower values of mass losses verified in soundness tests by immersion in ethyleneglycol.

2) For the CAN monzogranite, the average of the MD (7.3%) and MDR (80.7%) coefficients are intermediate in relation to the other two non-cycled MOR and GAB rocks. The effect of abrasive wear can be explained by its phaneritic discreetly porphyritic texture, characterized by microcline mega crystals. Microscopically, quartz crystals correspond to 29% of the total rock and have a high degree of microcracking, filled with secondary minerals (epidote and carbonates).

The petrographic study also showed a recrystallization indicated by the strong undulating extinction of quartz crystals, because they were subjected to conditions of ductile-rupture tectonic stresses.

3) The GAB microgabbro consists of 27% augite and 8% secondary minerals (iron oxides and hydroxides and celadonite and nontronite clay minerals). These minerals have lower abrasive resistance and consequently reflect in their lower strength, especially when compared to granite rocks where the percentage of quartz crystals exceeds 20%, resulting in a higher average of the coefficients MD (10.3%) and MDR (79.1%) of the rocks studied. Similar trends verified in the ethyleneglycol oven tests, where the presence, even subordinate, of expansive minerals lead to very intense degradation and fragmentation of the microgabbro samples. These simulations represent, in a more accelerated way, the chemical weathering processes to which the exposed fragments that make up the ballast will be subjected, in a region of tropical climate. The most expressive alterability implies the faster physical-mechanical degradation of this rock. In practice, more frequent, periodic and higher-cost maintenance.

5. CONCLUSIONS

The three rocks have physical-mechanical characteristics that are highly suitable for use in railroad ballasts, however, as in the studied region they would be exposed to conditions of altitude tropical climate, the microgabbro should not be used, due to the high susceptibility to alterations of its minerals under these climatic conditions.

In the case of the two granitoids studied, for correct application, the necessary tests should be carried out, considering the punctual character of the results, which are from the best quality portions of the rock mass observed in the present study. The technological information already obtained is quite detailed and can serve as subsidies to government agencies responsible for making decisions regarding the use of the materials available in the studied region, for use in ballasted railroads.

As for the tests, the following aspects stand out:

- The Micro-Deval test is widely used, especially in Europe, USA and Canada. It provides important information on the behavior of rock aggregates for engineering works, particularly when used in railway ballast and possibly should be part of the NBR 5564 (ABNT, 2012) under review.
- It is recommended to continue studies with larger equipment that allow tests on aggregates in the dimensions that make up the railroad ballast. This because with the particle size distribution used in the present study, it was already possible to obtain important results, on wet abrasive wear of the rocks that best represents the field conditions, especially when they are used in tropical regions.
- The perspective of using more robust equipment also in crushing and impact tests is also important, aiming at establishing more effective parameters for Brazilian rocks to be specified for conventional railroad ballast or for passenger transportation.
- The values obtained in the SD_i tests proved to be good indicators of the more intense degradation of the microgabbro when subjected to the soundness test by immersion in ethylene glycol, which should be mandatory for the characterization of any basic rock, in terms of the potential for use as aggregate without binders and.

- It is evidenced the importance of petrographic knowledge, which must precede the characterization tests of rocks for a particular use as material in engineering works.

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