Mineralogical Characteristics of "Entablature" and "Colonnade" Basalt Occurrences in the Northern Portion of the Paraná Basin, Brazil

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Abstarct. This work presents the results of mineralogical characterization carried out on samples obtained from massive ("colonnade") and columnar jointed basalt ("entablature") located in the northern portion of the Paraná basin, more precisely, in lava-front associated outcrops of some quarries of São Paulo State, Brazil. Besides some traditional material test methods, alternative tests such as the methylene blue adsorption, abrasion pH and conductivity were carried out. The joint analysis of this information assisted in material qualification, providing a comparative analysis between the "Colonnade" and "Entablature" relative to its use as aggregate for civil construction purposes.

Key words: aggregates, mineralogical characterization, basalts, construction materials.

1. Introduction

The concept of "entablature-colonnade" was first applied in basaltic rocks of the Parana basin by Souza Jr (1992). According to this author, with the exception of the outlying portions of amygdaloidal nature, certain lava flows present structural compartmentations that can be divided in two distinct jointing systems known as "colonnade" and "entablature".

In general, the core of basaltic flows normally corresponds to a coarser texture rock with more widely spaced fractures due to lower cooling speed of the lava at the interior of the flow. On the other hand, the upper and inferior peripheral zones present faster cooling and are consequently characterize by a more expressive fracturing and fine vitreous texture of the constituent minerals. In general however, the entablature located in the interior of the flow is found to present a characteristics degree of fracturing and mineral texture which are compatible with fast cooling lava which is contrary to expected. The first scientific works establishing the basic characteristics and the relating nomenclature of these joints were published by Tomkeieff (1940) and Spry (1962).

The genesis model of "entablature-colonnade" concept conceived by Long & Wood (1986) considers the flows were covered by surface water soon after overflow. This water must have percolated through the already consolidated surface crust of the flow, penetrating right into its interior and thus causing rapid cooling and consequently a high degree of cracking of the entablature compartment. Both the "entablature" (columnar jointed basalt) and the "colonnade" (massive basalt) compartments present mineralogical paragenesis typical of basic rocks constituted of plagioclase feldspar, pyroxenes (augite), magnetite and variable amounts of vitreous substance. The amount of vitreous substance and the mineral texture are the main differences between the two compartments. In general, the "entablature" presents 60% vitreous substance whereas for the "colonnade", this amount is about 20%. Another differentiating mineralogical characteristic between the two compartments is the morphology of magnetite crystals. The "entablature" presents a dendritic morphology for this mineral while the "colonnade" presents well-formed crystals due to a more gradual cooling.

In several cases, the degradation of rocks used as construction materials, especially basaltic rocks, has been linked to clay content (Scott (1955), Day (1962), Collet *et al.* (1962), Smith (1970), Schneider *et al.* (1968), Struillou (1969), West *et al.* (1970), Farjallat (1972), Hayase *et al.*(1972), De Alba & Sesana (1978), Rimoldi (1982), Frazão & Caruso (1983), Roisenberg *et al.* (1984)). In general, the tendency to degradation results of interaction of internal and external variables. The internal variable is in the rock itself, for example: type and clay content, cation exchange capacity, concentration of ions available on clay with reflections on the cation exchange, particle size and initial content of water. The external variables comprise external conditions to which the rock is exposed and features induced bay mining, transport and processing (Kuhnel, 2003), for example: clay mineral ability to access water, possibility of expansion of the clay mineral and nature concentration of ions dissolved in water that sometimes can reduce the expansion. These variables affect the mechanical behavior and, therefore, their quality as construction materials (Kuhnel, 2003; Korkanç & Tudrul, 2004).

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In this way, the vast majority of scientific publications produced in the last four decades on the degradation of rocky materials of basaltic flow origin (Korkanç & Tudrul, 2004; Moon & Jayawardane, 2004; Kühnel & Katshi, 1997; Scott, 1955; Sveinsdottir, 1999; Van Atta & Ludowise, 1976; Van Rooy, 1991 and Wylde, 1976) do not approach the concept of "entablature-colonnade". This fact raises various questions with respect to these materials as to: whether the great amount of vitreous substance present in the "entablature" is would compromise its use as aggregate for civil construction purposes, what behavior these materials might present under alteration tests and consequently what resulting alterability they might show. However, the ease of identifying compartments in the field makes this concept being used unconsciously by professionals in the field basalt exploitation. Massive basalt is informally known as "massive" whereas the more fractured "entablature" (columnar jointed basalt) is called denominated "granulated" or "granular". On the other hand, vesicular basalt are called "frog eye".

In this context, the objective of the present work is to present a mineralogical characterization of these rocks with the aim of generating information that can be used for the evaluation of the rock quality when used as aggregate for civil construction purposes.

2. Study Method

The method applied was initially aimed at classifying different types of basaltic flows according to the "entablature-colonnade" concept. To do this, a detailed geological-geotechnical mapping of the surface rock and mining front in ten quarries in the interior of the São Paulo State was carried out. The field studies carried out permitted the definition of the principal types of flows and their classification based on the "entablature-colonnade" concept. Details of this classification can be found in Gomes & Rodrigues (1999) and Gomes (2001).

Each sample studied refers to an "entablature" or "colonnade" compartment of flow profiles. The vesicular basalt was used in only one case. With the objective of comparing the technological and alterability characteristics of the basaltic flows of colonnade joints to those of intrusive basic rocks, a sample was collected from a diabase quarry. Table 1 presents the sample designation, the joint type and the origin of the samples.

In general, the samples used in the test were crushed material obtained from the quarry. In the case of the vesicular basalt, blocks of this material were collected and later crushed in the laboratory. For tests in which cylindrical test samples were necessary, such as those used for the uniaxial compression, representative rock blocks were collected from the sampling point.

Firstly, routine material characterization tests such as the determination of physical indexes (ABNT, 1984), uniaxial compressive strength (ISRM, 1978), determination of the crushing strength, Los Angeles abrasion value (ABNT, 1983), and the soundness test by ethylene glycol immersion (ABNT, 1992), were conducted with the aim of identifying and prequalifying the material. Besides these well known technological tests, alternative tests such as Methylene Blue Adsorption test (MBA) (Verhoef & Van de Wall, 1998), pH abrasion (Grant, 1969 and Malomo, 1980) and conductivity abrasion test (Gomes, 2001) were carried out. Parallel to these tests, X-ray difractometry was used mainly for detecting and quantifying deleterious minerals. Techniques employed for detailed observation such as optical and Scanning Electron Microscope (SEM) was used to obtain a detailed insight on the mineralogy, petrography and microstructure of the samples.

Mineralogical and textural characteristics of the rock were determined from studies thin section samples. According to these studies, mineralogical composition, texture, pore structure, opaque and secondary mineral content and rate of weathering of the basalt in different compartments were evaluated using the *K1* and *K2* Petrographical Indexes proposed by Frazão & Paraguassu (1994) and Frascá (1998), and the Rsm Index "Secondary mineral rating" proposed by Cole & Sandy (1980).

Table 1 - Location and type of the studied samples.

Sample	Compartment	Localization
SCC	Colonnade	Washington Luís High Way Quarry, São Carlos, São Paulo State
SCE	Entablature	São Carlos City Quarry, São Carlos, São Paulo State
SAN	Colonnade	Santo Antônio Quarry, Araraquara, São Paulo State
ANT	Entablature	Santo Antônio Quarry, Araraquara, São Paulo State
IND	Colonnade	Inderp Quarry, Ribeirão Preto, São Paulo State
SAD	Entablature	Said Quarry, Ribeirão Preto, São Paulo State
VES	Vesicular basalt	Said Quarry, Ribeirão Preto, São Paulo State
PAV	Colonnade/ diabase	Paviobras Quarry, Rio Claro, São Paulo State
BP	Colonnade	Bica de Pedra Quarry, Jaú, São Paulo State
SM	Colonnade	Pedralite Quarry, São Manuel, São Paulo State
SIQ	Entablature	Siqueira Quarry, Assis, São Paulo State
WS	Colonnade	Ws Quarry, Assis, São Paulo State

3. Mineralogical Characterization

3.1. Petrographical characteristics

From the macroscopic point of view, basalts possess a certain coloration that varies from dark ash to greenish. They also present a fine granulation, are mesocracratic to melanocratic, have a homogeneous aspect, without apparent structures with exception of the vesicular- amygdaloidal basalts. Sample PAV (diabase) has an average granulation, a greenish gray coloration and homogeneous aspect. Under a petrographic microscope, both the basalts as well as the diabase are composed of ripiform crystals of plagioclase (labradorite) among which are prismatic crystals of clinopyroxene (augite) and opaque minerals (titanite and magnetite) thus configuring a subophitic or intergranular textural array (Table 2). In the case of basalts, mainly in the "entablature" (columnar jointed Basalt), concentrations of volcanic glass and clay minerals confer to the rock, locally, an "intersertal" textural aspect. It can also be noted that the samples studied show marked differences relative texture, more specifically, with regards to the size of the plagioclase and clinopyroxene crystals. The samples "entablature" (columnar jointed Basalt) associated are shown to present a finer texture than colonnade (massive basalt) samples which confirms the genesis of the "entablature-colonnade" concept. It is also observed that the values maximum and minimum plagioclase and clinopyroxene crystal sizes are related respectively to samples of diabase and vesicular-amygdaloidal basalt.

With exception of sample *SAN* (massive basalt) which presents a high amount of iron oxides and hydroxides as a result of its more advanced stage of alteration, the amounts of clay minerals, volcanic glass and iron oxides and hydroxides are found to present higher values in the columnar jointed compartment samples than in the colonnade samples.

Except for the vesicular basalt with about 25% of its total volume consisting of vesicles and amygdales, the studied samples were found to present only rare occurrences of these structures. These amygdales generally are always encountered filled by green and brownish clay minerals and often accompanied by chalcedony, quartz, zeolites and carbonate.

Observations of sample PAV under a petrography microscope as well as the naked eye accused the occurrence of small metallic mineral points of colored yellow coloration (reflected light) scattered out within the sample. These minerals were preliminarily identified as possible sulphides. In order to ascertain what type of metallic mineral was present, a punctual chemical analysis was carried out using an electronic microprobe. Analyzes were carried out on three occurrence points of the sample and in all points analyzed, the presence of sulfur and iron elements was accused. However, the analysis did not furnish any quantitative data relative to the percentages of the elements necessary to identify the type of sulphide. Notwithstanding, for the present work, the most probable occurring mineral was supposed to be pyrite.

Table 3 shows the main mineralogic features necessary to determine the *K1* and *K2* indexes proposed respectively by Frazão & Paraguassu (1994) and Frascá (1998). These indexes, correlate sane essential minerals (S1) and the corresponding altered minerals (S2), the smectites-filled amygdales (S3), interlinked smectites (S4), smectite-filled microcracks (S5), other types of microcracks (S6), the amount of volcanic glass (S7), and the amount of secondary minerals including oxides and hydroxides of iron (S8) according to the following expressions:

$$K1 = S1/(S2 + S4 + S5) \quad (1)$$

$$K2 = S1/(S2 + S3 + (S4 * 2) + (S5 * 2) + S6) \quad (2)$$

It is worthwhile pointing out that an increase in the two indices increase translated into a better quality of the rocky material for use for civil construction purposes.

An alternative method of analyzing the petrographic characteristics would be for use of the R_{sm} index - "Secondary mineral rating" considered by Cole & Sandy (1980). This index is based on the mineralogical and textural characteristics of the rock through the following:

$$R_{sm} = (P*M)T \quad (3)$$

where R_{sm} = the rate of secondary mineral; P = percentage of secondary mineral; M = the secondary mineral value and T = the texture value.

The obtained secondary mineral value M was 10. This corresponds to clay minerals of the smectite group. The obtained textures associates to the clay minerals present are given by: (T = 0.3) partial alteration of the phenocrystals and incomplete filling of vesicles; (T = 0.4) completely altered phenocrystals; (T = 0.5) homogeneous distribution in the matrix; (T = 0.6) complete filling of vesicles; (T = 0.7) irregular distribution in the matrix and with filling of isolated microcracks; (T = 1.0) filling of irregular microcracks and (T = 2.0) filling of interconnected microcracks. Table 4 presents the values of R_{sm} index for the sample studied.

The samples SM, SCC, PAV, BP and WS showed the highest rates of *K1* and *K2* indexes and SIQ, SAN and VES the lowest. The samples SCE, IND, ANT and SAD showed intermediate values. The presence of approximately 28% of volcanic glass in the mineralogy of sample ANT was responsible for the reduced petrographic index, *K2* of this sample. Sample SAD was shown to present a low value of the petrographic index *K2* due to the presence of interlinked smectites observed under a petrographic microscope. This could thus adversely influence its quality. However, its very compact structure which confers a low porosity and water absorption to this sample can nullifies the influence of these clay minerals on the results of the alterability tests.

Table 2 - Petrographical characteristic of the studied samples.

Sample	Lithology	Texture	Mineralogy	Hydrothermal alteration	Weathering	Amygdalas	Clay minerals	Microcracks
SCC	Basalt/ Colonnade	Subophitic Granulation: Plagioclase (0.40-0.1 mm) Clinopyroxene (0.6-0.05 mm)	Plagioclase (35%) Clinopyroxene (30%) Opaques (10%) Clay minerals(03%) Volcanic glass (22%)	Weak Some type of argilation, mainly in the clinopyroxenes	Weak or absent No presence of oxides or hydroxides of iron detected	Absent	Presence of a brownish green coloration clay mineral (smectite) associate to the alteration of clinopyroxenes	Absent
SCE	Basalt/ Entablature	Ophitic to subophitic Granulation: Plagioclase (0.15-0.05 mm) Clinopyroxene (0.02-0.04 mm)	Plagioclase (30%) Clinopyroxene (25%) Opaques (10%) Clay minerals(05%) Volcanic glass (27%) Oxides-Hidroxides of iron (03%)	Weak Associated to vitreous clayey/argilaceous mesostasis and the argilation of clinopyroxenes	Weak Presence of oxides and hydroxides of iron filling microcracks of the clinopyroxenes	Absent	Presence of a brownish green coloration clay mineral (smectite) associate to vitreous clayey/argilaceous mesostasis and the alteration of cpx	Presence of microcracks in the pyroxenes
SAN	Basalt/ Colonnade	Ophitic to subophitic Granulation: Plagioclase (0.16-0.24 mm) Clinopyroxene (0.16 mm)	Plagioclase (30%) Clinopyroxene (25%) Opaques (05%) Clay minerals(10%) Volcanic glass (20%) Oxides-Hydroxides of iron(10%)	Average Associated to the vitreous clayey/argilaceous mesostasis and the argilation of clinopyroxenes	Average Presence of oxides-hydroxides of iron surrounding the opaques and filling pyroxenes microcracks	Rare occurrence of amygdalas filled by greenish clay minerals associates to calcedony and carbonate	Presence of a brownish green coloration clay mineral (smectite) associate to vitreous clayey/argilaceous mesostasis	Presence of microcracks in the rock, pyroxenes and Plagioclases
ANT	Basalt/ Entablature	Subophitic Granulation: Plagioclase (0.15-0.05 mm) Clinopyroxene (0.02-0.04 mm)	Plagioclase (30%) Clinopyroxene (25%) Opaques (10%) Clay minerals(05%) Volcanic glass (28%) Oxides-Hydroxides of iron(02%)	Weak Some argilation in clinopyroxenes and Plagioclases	Weak	Absent	Presence of a brownish green coloration clay mineral (smectite) associate to vitreous clayey/ argilaceous mesostasis and the alteration of cpx	Absent
IND	Basalt/ Colonnade	Subophitic Granulation: Plagioclase (0.16-0.3 mm) Clinopyroxene (0.04-0.08 mm) Opaque (0.04-0.08 mm)	Plagioclase (35%) Clinopyroxene (30%) Opaques (10%) Clay minerals(05%) Volcanic glass (20%)	Weak Some argilation in clinopyroxenes, forming zones of alteration in the rock	Weak or absent Presence of oxides and hydroxides of iron not detected	Absent	Greenish clay mineral distributed in zones throughout the rock due to the alteration of clinopyroxenes	Absent
SAD	Basalt/ Entablature	Subophitic Granulation: Plagioclase (0.08-0.24 mm) Clinopyroxene (0.04-0.08 mm) Opaque (0.02-0.04 mm)	Plagioclase (35%) Clinopyroxene (30%) Opaques (05%) Clay minerals (20%) Volcanic glass (10%)	Weak Some argilation, mainly in the clinopyroxenes	Weak or absent No presence of oxides and hydroxides of iron detected	Absent	Presence of brownish green clay mineral (smectite) associate to the alteration of clinopyroxenes	Absent
VES	Basalt/Vesicle-amygdaloidal	Intersertal Granulation: Plagioclase (0.04-0.12 mm) Clinopyroxene (< 0.02 mm) Tonsils/amygdalas (0.8-3.0 mm)	Plagioclase (25%) Clinopyroxene (20%) Opaques (05%) Clay minerals+ Volcanic glass + Oxides-Hydoxides of iron (50%)	Average argilation in clinopyroxenes and Plagioclases	Weak Rare presence of oxides and hydroxides of iron surrounding the opaques	Presence of amygdalas representing about 25% of the volume of the rock filled with greenish clay minerals, calcedony and carbonates	Presence of brownish green clay mineral filling the interlinked amygdalas and interstices (> 0.5 mm)	Presence of intragranular (clinopyroxene) and intergranular (Rock)microcracks

Table 2 (cont.)

Sample	Lithology	Texture	Mineralogy	Hydrothermal alteration	Weathering	Amygdalas	Clay minerals	Microcracks
PAV	Diabase	Intergranular to subophitic Granulation: Plagioclase (0.3-0.8 mm) Clinopyroxene (0.2-0.3 mm)	Plagioclase (45%) Clinopyroxene (40%) Opaques (10%) Sulphides (05%)	Weak Some argilation in clinopyroxenes and Plagioclases	Weak or absent No presence of oxides and hydroxides of iron detected	Absent	Presence of brownish green clay mineral (smectite) associated to the alteration of clinopyroxenes	Microcracks present in rock, pyroxenes and Plagioclases
BP	Basalt/ Colonnade	Subophitic Granulation: Plagioclase (0.10-0.4 mm) Clinopyroxene (0.05-0.6 mm)	Plagioclase (35%) Clinopyroxene (30%) Opaques (10%) Clay minerals(05%) Volcanic glass (20%)	Weak Some argilation, mainly in the clinopyroxenes	Weak or absent	Absent	Presence of brownish green clay mineral (smectite) occupying intergranular spaces	Absent.
SM	Basalt/ Colonnade	Subophitic Granulation: Plagioclase (0.35-0.1 mm) Clinopyroxene (0.1-0.05 mm)	Plagioclase (35%) Clinopyroxene (30%) Opaques (15%) Clay minerals(05%) Volcanic glass (15%)	Weak Presence of argilation in the clinopyroxene-opaque contacts	Weak Presence of oxides-hydroxides of iron surrounding the opaques and filling microcracks of the pyroxenes	Absent	Presence of chestnut color clay mineral in the contacts between cpx and opaque and filling some cracks in the Plagioclase.	Rare in Plagioclases and clinopyroxenes, and absent in rock
SIQ	Basalt/ Entablature	intergranular Granulation: Plagioclase (0.1-0,15 mm) Clinopyroxene (0,04 mm)	Plagioclase (30%) Clinopyroxene (30%) Opaques (05%) Clay minerals(20%) Volcanic glass (15%)	Average Associated to vitreous argillaceous mesostasis and the argilation of clinopyroxenes	Weak. Presence of oxides-hydroxides of iron surrounding the opaques and filling microcracks of the pyroxenes	Absent	Presence of brownish green clay mineral (smectite) associate to vitreous clayey/argilaceous mesostasis and the alteration of Plagioclases and clinopyroxenes	Microcracks present in rocks, pyroxenes and Plagioclases
WS	Basalt/ Colonnade	Subophitic Granulation: Plagioclase (0,4-0,2 mm) Clinopyroxene (0,15-0,06 mm)	Plagioclase (40%) Clinopyroxene (35%) Opaques (10%) Clay minerals(05%) Volcanic glass (10%)	Weak Presence of argilation in the clinopyroxene-opaque contacts	Weak Presence of oxides-hydroxides of iron surrounding the opaques and filling microcracks of the pyroxenes	Absent	Presence of chestnut color clay mineral in the contacts between cpx and opaque and filling some cracks in the Plagioclase	Rare in Plagioclases and clinopyroxenes, and absent in rock

Table 3 - Petrographical Characteristic of the samples (modal analyzes (%)).

	SCC	*SCE*	*SAN*	*ANT*	*IND*	*SAD*	*VES*	*PAV*	*BP*	*SM*	*SIQ*	*WS*
S1	73	62	50	60	72	68	40	90	72	77	55	80
S2	2	3	10	5	3	2	10	5	3	3	10	5
S3	0	0	1	0	0	0	20	0	0	0	0	0
S4	1	3	2	4	5	8	0	0	1	0	5	0
S5	0	0	1	0	0	0	0	0	0	0	3	0
S6	0	0	2	0	0	0	0	0	0	0	2	0
S7	22	27	20	28	19	10	25	0	20	15	15	10
S8	2	5	10	2	1	2	5	5	3	5	10	5
K1	24.3	10.3	3.8	6.7	9.0	6.8	4.0	18.0	18.0	25.7	3.1	16.0
K2	18.2	6.9	2.6	4.6	5.5	3.8	1.3	18.0	14	26.0	2.0	16.0

Note: S1 = plagioclase + clinopiroxene + sane opaque; S2 = plagioclase + modified clinopiroxene ; S3 = amygdala with smectites; S4 = interlinked smectites ; S5 = smectite filled microcracks ; S6 = other microcracks; S7 = volcanic glass; S8 = secondary mineral + oxides and hydroxides of iron; *K1* = petrographic Index (Frazão & Paraguassu, 1994); *K2* = Frascá, 1998).

Table 4 - Values of Rsm for the sample studied.

S	M	T	(%)	R_{sm}	S	M	T	(%)	R_{sm}	S	M	T	(%)	R_{sm}	S	M	T	(%)	R_{sm}
SCC	10	0.3	2	23	VES	10	0.3	10	175	ANT	10	0.3	5	53	SM	10	0.3	3	34
		0.6	0				0.6	20				0.6	0				0.6	0	
		0.7	1				0.7	0				0.7	4				0.7	0	
		1.0	0				1.0	0				1.0	0				1.0	0	
		0.5	2				0.5	5				0.5	2				0.5	5	
SCE	10	0.3	3	55	PAV	10	0.3	5	40	IND	10	0.3	3	49	SIQ	10	0.3	10	145
		0.6	0				0.6	0				0.6	0				0.6	0	
		0.7	3				0.7	0				0.7	5				0.7	5	
		1.0	0				1.0	0				1.0	0				1.0	3	
		0.5	5				0.5	5				0.5	1				0.5	10	
SAN	10	0.3	10	110	BP	10	0.3	3	31	SAD	10	0.3	2	72	WS	10	0.3	5	40
		0.6	1				0.6	0				0.6	0				0.6	0	
		0.7	2				0.7	1				0.7	8				0.7	0	
		1.0	1				1.0	0				1.0	0				1.0	0	
		0.5	10				0.5	3				0.5	2				0.5	5	

S: sample; M: mineral; T: texture.

3.2. X-ray diffractometry

X-ray diffractometry accused the presence of plagioclase, pyroxene and metallic minerals of the magnetite/hematite type and titanite in all the samples. Clay minerals of the smectite group were identified in various amounts in samples *IND, VES, BP, SM and WS*. In the other samples, the diffractogram peaks, representative of these clay minerals, were not significant enough to be identified. On comparing the diffractogram of the columnar jointed basalt and massive basalt samples, it is easy to note that the difference between the plagioclase peak intensity and pyroxene peak of intensity is higher for the massive basalt samples. This comparison was made discounting the influence of the test "background" values. This difference in diffractograms is better observed on comparing the diffractograms of samples *SCC* with those of samples *SCE*, of samples *IND* with those of samples *SAD* and of samples *SAN* with those of samples *ANT*. One observes that the diffractograms of the columnar jointed basalt ("entablature") samples (*SAD, ANT and SCE*) present peak plagioclase values, approximately as high as the peak pyroxene value. For the massive

basalt ("colonnade") samples (*IND, WS, BP, SM, SCC* and *SAN*), this relation varies approximately between two the five times. From the obtained diffractogram results, the SAI index ("Smectite Alteration index") considered by Houston & Smith (1997) (Table 5) was determined for each sample. This index is based on the correlation between the Smectite peak of intensity (cps) - 15 Å and the Plagioclase peak intensity (3,2 Å) after deducing the test "background" level.

High values of this index, that varies of 0 the 1, indicate a marked presence of clay minerals of the smectite group was detected from the diffractogram.

3.3. Physical indexes

The average apparent dry specific mass was observed to vary between 2.948 (g/cm^3) corresponding to sample *BP* and 2.243 (g/cm^3), corresponding value sample *VES*. However, the saturated apparent specific mass was found to vary between 2.958 (g/cm^3) and 2.415 (g/cm^3), corresponding respectively to samples *SIQ* and *WS,* and *VES*. The apparent porosity varied between 17.27% and 0.60% values associated respectively to samples *VES* and *IND* while the water absorption was shown to present values between 7.78% and 0.20% also corresponding to samples *VES* and *IND* (Table 6).

3.4. Strength indexes

The direct compression strength was found to vary between 60 MPa and 290 MPa, corresponding to samples *VES* and *SAD* respectively. In many of the studied samples, the Los Angeles abrasion strength values were found to be inferior to the 31,6% loss. Samples VES and IND showed extreme values of the modified crushing strength from average, respectively 20.73% and 11.85% loss (Table 6).

3.5. Ethylene glycol immersion

This test was carried out to rapidly simulate the reaction between water and expansive clay minerals in the sample. Ethylene glycol is one of the materials that reacts with swelling clays of the smectite group to form an organo-clay complex having a larger basal spacing than that of the clay mineral it self.

The samples were immersed in an ethylene glycol solution for a period of 21 days and the amount of particles affected evaluated after every 3 days.

Table 6 and Fig. 1 presents results of the ethylene glycol immersion test for all samples with exception of samples *SCC, SCE, PAV, IND and SAD* which were not affected by this test.

It is noted that at the ninth cycle, samples *VES*, *SAN* and *SIQ* presented the first trace of spalling, corresponding to respectively, 30%, 10% and 10% of fragments affected. Then after in the tenth second cycle, samples *WS* (16%) and *ANT* (8%) also manifested fragmentation with the percentage of fragments affected shown in parentheses for each case while during the fifth cycle, sample *SM* presented 8% of fragments affected. Finally, in the eighteenth cycle of the

Table 5 - Values for determining the SAI index.

Sample	Plagioclase		Smectite		SAI
	"Background" (cps)	Peak (cps)	"Background" (cps)	Peak (cps)	
SCC	241	941	202	212	0.014
SCE	286	632	238	247	0.026
SAN	241	1297	201	217	0.015
ANT	296	627	195	228	0.100
IND	284	656	199	221	0.059
SAD	294	560	181	204	0.086
VES	350	654	293	488	0.641
PAV	291	645	206	210	0.011
BP	243	842	240	282	0.070
SM	244	861	200	230	0.049
SIQ	295	1016	208	220	0.017
WS	267	770	201	238	0.074

Table 6 - Results of technological and alterability tests for the samples studied.

Sample/test	SCC	SCE	SAN	ANT	IND	SAD	VES	PAV	BP	SM	SIQ
Dry unit weight (kg/m^3)	2.912	2.893	2.910	2.889	2.923	2.916	2.243	2.862	2.948	2.921	2.945
Water absorption (%)	0.27	0.30	0.29	0. 54	0.20	0.29	7.78	0.27	0.33	0.47	0.39
Porosity (%)	0.77	0.87	0.84	1.57	0.60	0.83	17.27	0.77	0.97	1.38	1.15
Ethylene glycol index (%)	0	0	59	8	0	0	86	0	8	8	22
MBA (g/100 g)	0.22	0.52	0.60	0.60	0.22	0.22	2.41	0.22	0.45	0.37	0.68
CEC (meq/100 g)	0.70	1.62	1.88	1.88	0.70	0.70	7.56	0.70	1.41	1.16	2.12
Uniaxial compressive strength (Mpa)	265	242	160	230	175	290	60	191	180	124	86
Crushing test (%)	12.20	14.10	13.48	14.15	11.85	14.31	20.73	14.00	13.34	13.62	11.98
Los Angeles abrasion (%)	13.09	14.91	16.65	14.84	13.87	13.32	31.58	16.32	15.88	13.26	16.33

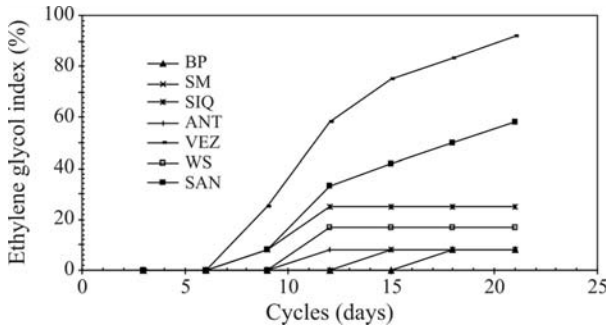

Figure 1 - Evaluation of the immersion in Ethylene glycol.

test, sample *BP* also showed about 8% of its fragments affected by ethylene glycol immersion (Fig. 1).

A close look at Fig. 1 shows a constant behavior of samples *SM*, *WS*, *ANT* and *BP* vis-à-vis the percentage of fragments affected by the immersion test. However, this was not the case for samples *VES* and *SAN*. Here, a gradual increase in the amount of fragments affected with time until the end the end of the test was noticed while sample *SIQ* showed a rather increasing disaggregation up to the 12th cycle and later maintained this behavior constant.

From the above-exposed, the studied samples can thus be ranked in decreasing order disaggregation of fragments affected as a function of the time (cycles) necessary for the first disintegration as follows: *VES* > *SAN* > *SIQ* > *WS* > *ANT* > *SM* > *BP*. It is worth emphasizing here that samples *SCC, SCE, PAV, IND and SAD* were not affected by this test.

3.6. Methylene blue adsorption test

Verhoef & Van de Wall (1998) define the index MBA (Methylene Blue Adsorption) as a mass of methylene blue necessary to recover, with a monomolecular layer, the particles contained in 100 g of sprayed fragments of aggregates. Depending on the amount and type of clay mineral present, the adsorption of methylene blue will be variable.

The concentration of the solution test was 3 g of methylene blue per liter of distilled water as suggested by Verhoef & Van de Wall (1998). The test is based on determining the peak of maximum adsorption of methylene blue dye to 2 g rock material sprayed, by the addition in quantities of 1 to 5 cm^3 the solution of methylene blue, added to the slurry (2 g of material + 30 mL distilled water).

The maximum adsorption occurs when there is saturation of dye in aqueous solution, indicated by the emergence of an "aureole" bluish around the core of the drop of the suspension when put on filter paper. From the volume of the solution of methylene blue consumed in the saturation of slurry (rocky material sprayed + water) it is estimated the values of CEC and MBA.

The methylene blue test results expressed as the amount of methylene blue adsorbed (MBA), the cation exchange capacity (CEC) are presented in Table 6. Observation shows that the maximum value of MBA is 2.41 (g/100 g) corresponding to sample *VES* while the least value is 0.22 (g/100 g) for samples *PAV, IND, SAD* and *SCC*.

Considering the cation exchange capacity, the observed maximum value was 7.56 (meq/100 g) for sample *VES* while the minimum value was 0.70 (meq/100 g) corresponding respectively to samples *PAV, IND, SAD* and *SCC*.

3.7. Abrasion pH

According Malomo (1980), during weathering, the feldspars are undergoing hydration and as a consequence the release of ions, in general, alkali and alkaline earth elements. These ions combine with the free OH^- ions in the solution. Thus, the greater the amount of ions of alkali and alkaline earth elements released lower the concentration of OH^- free in solution and thus will lower the pH value. The pH of abrasion is known as the pH of the solution comprises the feldspar sprayed more distilled water, in different concentrations.

The sample consisted of pulverized material (# 0063 mm) resulting from the crushing testing. The test was based on the measurement of pH of sample mixed in distilled water, as follows: a) addition of 0.75 g of sample in 48 mL of distilled water; b) shake the solution for 3 minutes; c) after resting for 1 min, achieve a measure of pH; d) adding more 0.75 g of the sample and repeating the above procedure; e) adding more 0.5 g of the sample and repeating the above procedure and f) adding more 1.0 g of the sample and repeating the above procedure.

The measured pH values at concentrations of 1/64, 1/32, 1/24 and 1/16, for all samples, are given in Table 7. A concentration of 1/16, that is 0.063 (g/mL) was adopted as the representative of the abrasion pH for the studied samples.

From Fig. 2, three different pH zones can easily be noticed for all concentrations. The first zone characterized for pH values above of 9.34 is representative of sample *VES* while the second zone associated to pH values varying between 8.04 and 9.09 is representative of samples *SCC, SCE, SAN, ANT, IND, SAD, BP, SM, WS and SIQ*. The third zone on the other hand presents pH values between 6.26 and 6.28 and is associated to results of sample *PAV*. This permits us ascertain the applicability of pH abrasion test as a viable identification tool for samples containing a marked presence of clay minerals (Zone 1) represented in the present case for vesicular-amygdaloidal basalt samples.

Grant (1969) related the abrasion pH to the presence of clay minerals in samples which adsorb part of primary ions in solution and consequently increasing OH^- ion concentration and the pH. Clay minerals, mainly of the 2:1 type, present distributed negative charge on their surface. This charge also adsorbs free hydrogen ions in solution thus causing an increase in OH^- concentration and consequently the pH.

The low pH values sample *PAV* represented Zone 3 are indicative of the presence metallic mineral rock in the rock, in particular, the sulphides. Pyrites (FeS_2) and the pyrrhotite ($Fe_{1-x}S$) are the most abundant sulphides of iron in rocks and a study of their oxidation is of prime importance in the evaluation of the durability and quality of aggregates for civil construction purposes. In general, the oxidation of sulphides is known to produce sulfates, oxides and free ions of H^+. As this reaction progresses, the concentration of H^+ free ions increases and consequently the acidity of the solution.

3.8. Abrasion conductivity

Following the same procedure adopted for determination of abrasion pH, the conductivities measured at concentrations of 1/64, 1/32, 1/24 and 1/16 are presented in Table 7. The representative abrasion conductivity of the sample adopted at a concentration of 1/16 was (0,063 g/mL).

In accordance with Fig. 3, three groups of conductivities can be identified. Group 1, represents high conductivity values representative of sample *PAV* followed by Group 2, representative of the values of sample *VES* while Group 3 is made of conductivity values representative in the remaining samples which are found to show low conductivity.

The increase in conductivity is due mainly by the increase in ions concentration and type of ions in the solution. In the case of sample *PAV*, representative of high conductivities of Group 1, the prominent cause of increased conductivity is the increase in H^+ concentration resulting from the oxidation of sulphides present in the sample which in

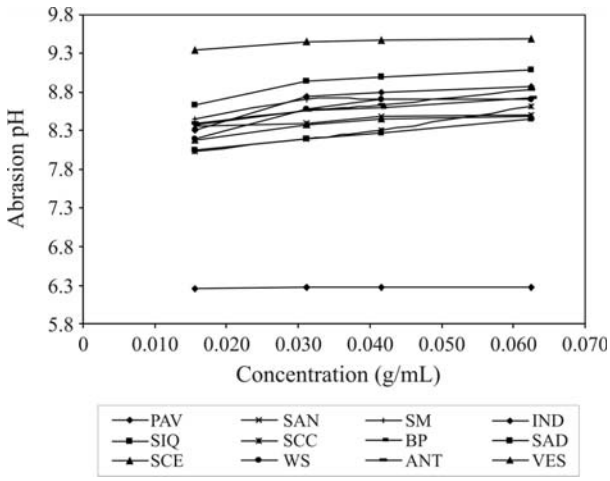

Figure 2 - Values of abrasion pH of the samples studied.

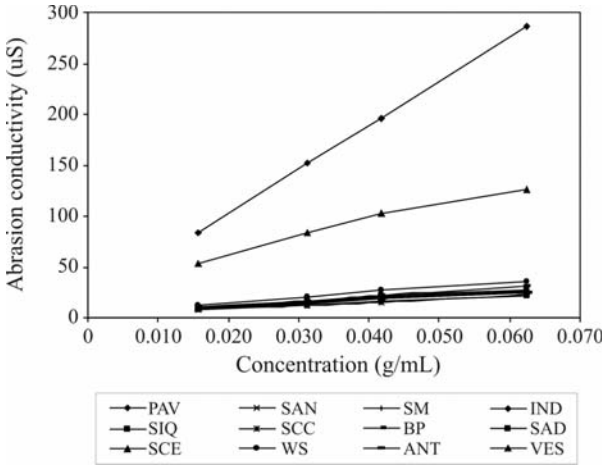

Figure 3 - Values of abrasion Conductivity of the samples studied.

Table 7 - Values of abrasion pH and Conductivity of the studied samples.

Concentration / sample	0.016 (g/mL)		0.031 (g/mL)		0.042 (g/mL)		0.063 (g/mL)	
	pH	Conductivity (uS)	pH	Conductivity (uS)	pH	Conductivity (uS)	pH	Conductivity (uS)
SCC	8.03	8.04	8.19	12.00	8.31	15.20	8.61	23.00
SCE	8.18	9.80	8.37	15.70	8.44	20.30	8.48	26.50
SAN	8.35	9.90	8.41	15.00	8.48	19.00	8.51	24.00
ANT	8.39	11.00	8.56	17.00	8.64	22.50	8.83	31.00
IND	8.31	9.20	8.74	14.30	8.80	19.00	8.87	24.70
SAD	8.63	10.00	8.94	16.30	9.01	21.50	9.09	28.00
VES	9.34	54.00	9.45	83.00	9.47	102.50	9.49	126.00
PAV	6.26	84.00	6.27	152.00	6.27	196.00	6.28	203.04
BP	8.37	9.00	8.56	14.30	8.61	18.50	8.72	25.00
SM	8.44	10.76	8.70	17.00	8.70	22.00	8.70	27.00
SIQ	8.04	8.52	8.19	13.00	8.26	17.00	8.45	22.00
WS	8.19	12.00	8.57	20.00	8.71	28.00	8.71	36.00

turn is responsible for the fall in pH of the solution. Concerning the Group 2 sample (*VES*), the observed relatively higher conductivities than for samples of Group 3 are probably associated to the increase alkaline and alkaline earth elements ions in the solution and, also due to high concentration of OH^- which results, as mentioned before, in high pH values. The Group 3 sample conductivity is probably influenced only by the amount of alkaline and alkaline earth metal ions in solution.

4. Conclusions

The application of the Long & Wood (1986) model for the classification of the studied basaltic flows was found to be very satisfactory given its capability of reproducing the origin of the "entablature-colonnade" compartmentation.

From the geological engineering point of view, the mineralogical, textural and structural differences between the "entablature" (Columnar jointed basalt) and "colonnade" (massive basalt) compartments reflect the different geotechnical and technological behaviors. The "entablature" being highly fractured and containing high amounts of vitreous substances in its mineral composition is found to presents some characteristics which may not favor its use for civil construction purposes.

The fact that the technological characterization tests were carried out almost simultaneously provided excellent information for determining numerous quality indices such as: the petrographic *K1* and *K2* indexes, petrographic index R_{sm} (secondary mineral rating), SAI Index (smectite alteration index).

Despite the very close similarities between the petrographic characteristics of the studied samples, the petrographic indices *K1*, *K2* and R_{sm} clearly indicated the low quality samples *SIQ*, *SAN* and *VES*.

The x-ray diffractometry identified different amounts of clay minerals of the smectite group in samples *IND, VES, BP, SM* and *WS*. In the other samples, the diffractograma peaks, representative of these clay minerals, did not permit their identification.

With exception of sample *VES* corresponding to vesicular basalt, the physical indices, direct compression strength, Los Angeles abrasion strength and the crushing strength, when analyzed separately, were found to furnish insufficient information to differentiate the samples according to quality.

The test results obtained from the immersion of rock fragments in ethylene glycol were found to be effective in differentiating the samples according to their likelihood of disintegration.

The alternative tests the methylene blue adsorption test, abrasion pH and conductivity were all found to be useful. The methylene blue test was applicable in determining the presence and amount of clay minerals while the abrasion pH and conductivity tests were used in verifying the presence of metallic mineral of the sulphide type. In general, these tests are quite outstanding due to the ease and rapidity of obtaining test results.

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