Evaluation of weathering of basaltic lithotypes based on pH, electrical conductivity, and point-load strength tests

Avaliação da alteração de litotipos basálticos com base em ensaios de pH, de condutividade elétrica e de carga pontual

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Abstract

This paper presents the results of an evaluation of the weathering of different basaltic lithotypes (dense basalts, vesicular-amygdaloidal basalts, and basaltic breccias) from four basaltic flows of the Serra Geral Formation of the Itaipu Dam region. Samples were classified according to their degree of weathering based on analysis with a 200X digital microscope and were subjected to pH, electrical conductivity, and point-load strength tests. The results show that pH and electrical conductivity values are effective for the evaluation of weathering, especially when tactile-visual classification does not provide an accurate evaluation of the rock's different degrees of weathering.

Keywords: *Weathering, basaltic rock, pH, electrical conductivity, point-load strength.*

Resumo

Apresentam-se, nesse artigo, os resultados da avaliação da alteração de diferentes litotipos basálticos (basaltos densos, basaltos vesículo-amigdaloidais e brecha basáltica). As amostras analisadas são oriundas de quatro derrames basálticos da Formação Serra Geral, da região das obras da barragem de Itaipu. Nesse trabalho, são apresentados a classificação do grau de alteração, análises em microscópio digital 200X e ensaios de *pH*, de condutividade elétrica e de compressão pontual. Os resultados mostraram que os valores de *pH* e de condutividade elétrica são significativos na avaliação do grau de alteração, especialmente quando as classificações tátil-visuais e de resistência não refletem com tanta precisão esse parâmetro.

Palavras-chave: Alteração de rocha, rocha basáltica, *pH*, condutividade elétrica, compressão pontual.

1. Introduction

In civil engineering, rock material is very broadly used and has many applications, either as a building material or as a support for various civil structures. A major problem in the use of various rock types is the characterization of their degree of weathering at a stage that cannot yet be visually observed or detected by routine physical tests. According to the intended application and the standards established in the project, specific methodologies are needed to accurately characterize rock material in geological-geotechnical terms to effectively qualify and quantify the parameters of interest.

An important component of these studies is the degree of weathering, which is related to the intrinsic characteristics of the rock and the severity of the weathering forces to which it is exposed (Reiche, 1943; Woodruff, 1966; Aires-Barros, 1971). To determine the degree of weathering, quality indexes that involve physical (apparent density, apparent porosity, and water absorption), geomechanical (modulus of elasticity, compressive strength, and shear strength), and chemical (pH, electrical conductivity, and the concentration of chemical components from the processes of weathering) characteristics are typically used. Studies using these indexes include those by Reiche (1943), Iliev (1966), Aires-Barros (1971), Nesbitt and Young (1982), Ladeira and Minette (1984a, 1984b and 1984c), Harnois (1988), Gupta et al. (1998), Verhoef and Van de Wall (1998), Maia et al. (2002, 2003), Moon and Jayawardane (2004), Gurocak and Kilic (2005), Lathan et al. (2006), Shalkowski et al. (2009), Olana et al. (2010) and several other authors.

There is no consensus on an effective index to describe rock weathering, but many approaches integrate data from different types of tests that reflect different characteristics of the rock materials. However, many of these tests require detailed treatment of the samples and costly equipment to ensure precise measurements.

Based on these considerations, this paper proposes to contribute to the integration of data from tests that reflect the mineralogical, chemical, and mechanical strength characteristics of rock material combined with the simple preparation of samples without the need for defined geometry and without using sophisticated equipment.

The proposed tests were developed in basaltic lithotypes of the Serra Geral Formation in the Itaipu Dam region. The use of these geological materials is justified because they are found over a large territory due to the occurrence of the Serra Geral Formation and have been used in the construction of several civil structures associated with the dam, such as concrete aggregate (including the main dam, the right wing dam, the connection dams, the diversion structure, and the spillway); in the rockfill dam (transitions, rockfill, and rip-rap); and in the earthfill dam (filters, protection of filters and in the upstream region).

2. Materials and methods

The proposed methods described below emphasize simplicity and the ease of operation and examine different characteristics of geological materials. The point-load strength test measures the mechanical strength, and the chemical measurements are designed to detect weathering.

Rock materials

The studied samples represent four different sequences of basalt flows within the Itaipu Dam region. The flows were assigned local denominations during construction of the dam (E, D, C, and B) and based on their respective lithotypes: dense basalt (the central part of the flow), vesicular-amygdaloidal basalt (the top of the flows), and basaltic breccia (the transition zone between the flows). The following materials were obtained from the excavation fronts during the construction phase and are representative of the main construction materials used during the construction of the dam: concrete aggregate, filters, transitions, rockfill, and rip-rap (ITAIPU, 1978; 1994).

Figure 1 shows a vertical geological profile with a general description of each studied rock group associated with the various basalt flows.

Methods

The point-load strength test

To determine the mechanical strength of the rock, a point-load strength test was performed according to the recommendations of the ISRM (1972) for blocks of irregular geometry. The value for $I_{S(50)}$ (Point load strength index for 50 mm diameter core) is determined with the equivalent core diameter of the specimens.

Weathering degree

The degree of weathering was classified using visual-tactile analysis according to the classification described by ISRM (1978), a digital microscope with 200X magnification, and chemical weathering tests.

pH and electrical conductivity

The tests used to measure these two properties aim to evaluate the degree of chemical weathering and are based on the work by Shalkowski et al. (2009), who used the mechanism of ion dissolution of the rock in aqueous medium by

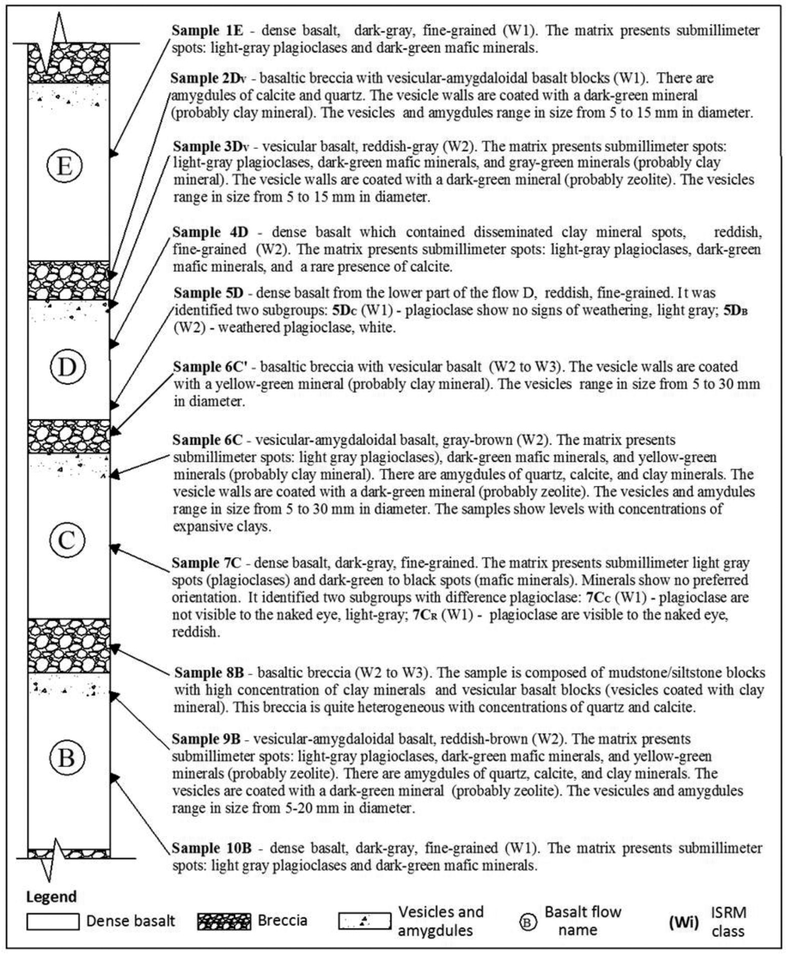

Figure 1
Schematic geological profile from Itaipu Dam region: relation between basaltic flows and study samples.

measuring the pH and electrical conductivity (EC). The pH and electrical conductivity measurements characterize levels of weathering that are very subtle but strongly affect the quality of rock materials (granites in the 2009 study by Shalkowski et al.) in terms of mechanical strength.

To perform the test, in each rock group, four samples of different particle size ranges were evaluated: Sample 1 (2.0 < # < 4.76 mm), Sample 2 (1.0 < # < 2.0 mm), Sample 3 (0.42 < # < 1.0 mm), and Sample 4 (0.063 < # < 0.125 mm). Different particle sizes from each rock group were obtained by grinding the rock.

Generally, the test consists of submerging 25 g of rock (wrapped in a polyester screen with 150 thread/cm) in 250 ml of bi-distilled water (18.2 μS/cm at 25°C). Immediately after sample immersion, the solution is homogenized on a magnetic stirrer for five minutes. Then, the pH and electrical conductivity are read over 10 minutes of testing at intervals of one minute (which theoretically measures the weathering state; subsequently, a reaction occurs with the ions released by the sample).

Figure 2 presents the device developed for this study using pH and conductivity meters and a container with a lid adapted to accommodate the electrodes, thermometer, and sample.

System calibration was performed in two stages: (a) an experiment with 250 ml of pure Milli-Q water (the neutral experiment) and (b) an experiment with a bag of polyester and no sample (the control experiment). According to Shalkowski et al. (2009), the control experiment represents the changes resulting from the interaction of the sample with the screen. Therefore, the difference between (a) and (b) was subtracted from the test results. The solution may interact with atmospheric gases or dissolve in the Milli-Q water; however, because of the controlled laboratory conditions and the water used, these interactions were taken into consideration in the calibration reactions. To reduce the effects of the external environment on the test, the container holding the solution was protected with a plastic film.

3. Results and duscussion

Figure 3 presents the images obtained with a 200X microscope from the basaltic matrix of each rock group studied. In these images, the plagioclase grains are highlighted (light gray minerals). The observation of the plagioclase grains present in the dense basalt matrix allowed for the verification of different behaviors associated with mineral weathering as indicated by the degree of discoloration, especially of the larger grains.

The samples were described and classified according to the following characteristics:

- Dark gray dense basalt (1E, $7C_C$, and $7C_R$): no signs of weathering.
- Dark gray (10B) and reddish dense basalt ($5D_C$): slightly discolored and more pronounced plagioclase.
- Reddish dense basalt ($5D_B$): weathered plagioclase that is quite pronounced and discolored.
- Reddish-gray dense basalt with clay mineral (4D): weathered plagioclase that is quite pronounced and discolored.

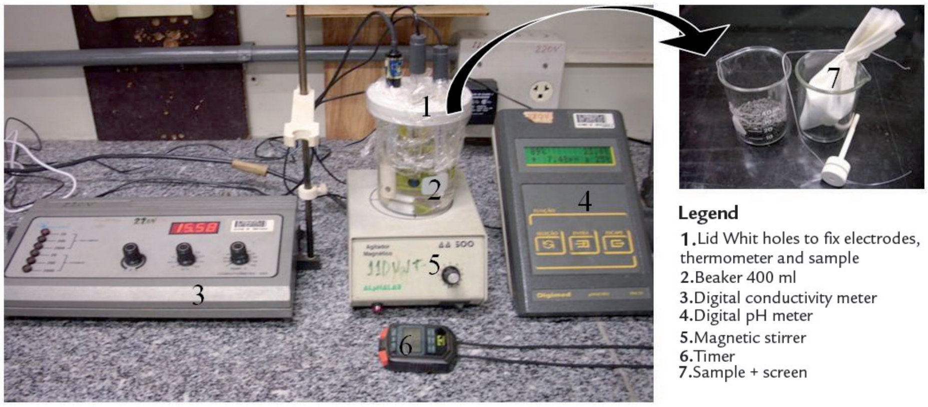

Figure 2
General view of equipment for physico-chemical measures.

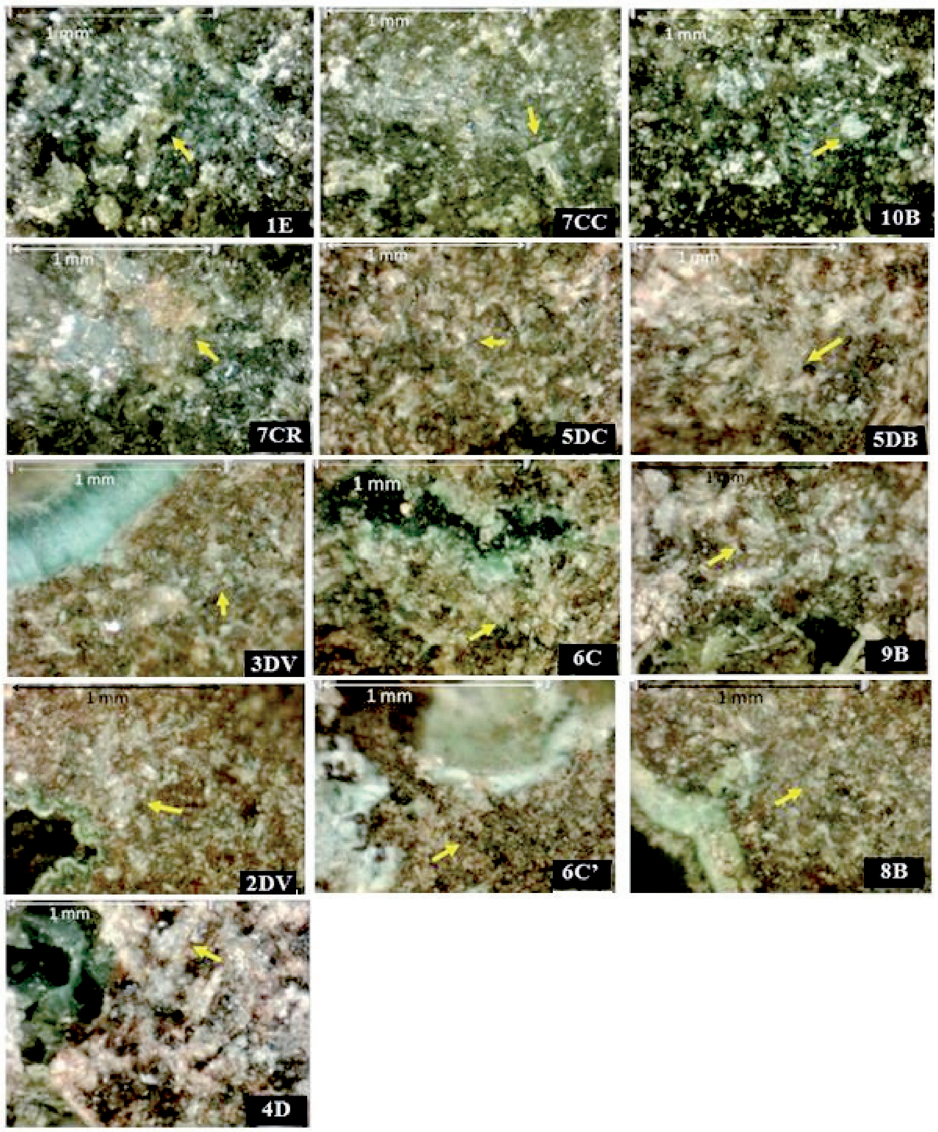

Figure 3
Images of the samples (200X). Some arrows indicate plagioclase grains.

With respect to the vesicular-amygdaloidal basalt and breccia, the following characteristics were of particular interest:

- Vesicular-amygdaloidal basalt ($3D_V$ and 9B): matrix showing somewhat weathered plagioclase that is slightly discolored.
- Vesicular-amygdaloidal basalt (6C): matrix with quite discolored plagioclase and a high concentration of clay minerals.
- $2D_V$ breccia, a component of the vesicular basalt: somewhat discolored plagioclase with a strong presence of calcite amygdales.
- 8B breccia, a component of the vesicular basalt: somewhat discolored plagioclase with a concentration of clay minerals in specific regions of the samples.
- 6C' breccia, a component of the vesicular basalt: very weathered matrix with evidence of a clay forming process.

The results of the point-load strength tests are shown in Table 1, illustrating that the different rock types exhibited different values of point-load strength. The dense basalts had point-load indices of 8.8 to 9.7 MPa, and the subgroups of the samples 5D ($5D_C$ and $5D_B$) and 7C ($7C_C$ and $7C_R$) exhibited very similar values, with no significant differences in mechanical strength. Sample 4D, a dense basalt with clay mineral content, exhibited a high strength, with an $I_{S(50)}$ value of 8.5 MPa. The vesicular-amygdaloidal basalt showed point strengths of 4.6 to 6.7 MPa. The lowest values were recorded for basaltic breccias ($2D_V$, 6C', and 8B), with $I_{S(50)}$ values of 3.7 to 5.5 MPa. In terms of weathering, the point-load test combined with analyses at 200X provided more detailed characteristics of vesicular-amygdaloidal basalts and basaltic breccias. For the dense basalts, mineralogical variations related to weathering were not evidenced by point compression.

In the chemical measurement test, which was conducted to evaluate the degree of weathering, the initial assessment indicated that of the four particle size ranges tested, the one that best represented the ion dissolution of the rock was 0.42 < # < 1.0 mm, which promoted the greatest release of ions in relation to the theoretical specific surface (Table 1). The particle size range of 0.063 < # < 0.125 mm presented high interference of the fine material resulting from the crushing process and therefore did not present the expected results.

Table 1
Point Load Test (IS(50)), pH and electrical conductivity of basaltic rocks.

Sample	Basaltic lithotypes	Point Load Strength			Physicochemical measures							
					2,0<#<4,76mm		1,0<#<2,0mm		0,42<#<1,0mm		0,063<#<0,125mm	
		Number of sample	R^2	$I_{S(50)}$ (MPa)	pH	EC (µS/cm)	pH	EC (µS/cm)	pH	EC (µS/cm)	pH	EC (µS/cm)
1E	Dark gray dense basalt	6	0.96	8.84	8.08	2.11	6.62	2.61	7.44	3.19	7.30	4.05
$7C_C$		6	0.89	8.53	8.53	2.49	7.75	3.71	7.91	4.69	7.32	2.97
$7C_R$		6	0.82	8.39	7.70	1.42	7.30	2.27	7.76	1.94	7.53	2.18
10B		10	0.89	9.52	7.67	1.84	8.42	2.80	9.14	4.20	7.27	2.60
$5D_B$	Reddish dense basalt	5	0.86	9.52	8.53	3.14	7.93	5.27	8.53	8.64	7.61	3.99
$5D_C$		8	0.82	9.73	7.57	3.15	7.55	5.87	7.30	7.89	7.42	5.58
4D	Dense basalt with clay mineral	10	0.9	8.54	8.07	10.24	7.68	17.39	7.97	24.65	7.39	9.14
3D	Vesicular-amygdaloidal	6	0.81	4.69	8.79	7.28	8.51	14.43	8.31	25.12	7.53	9.96
6C		11	0.85	5.51	8.78	5.13	8.00	10.02	7.94	13.54	7.48	4.53
9B		14	0.9	6.71	7.23	9.54	7.91	17.75	7.25	17.87	6.60	7.25
$2D_V$	Basaltic breccia	9	0.67	5.48	10.12	13.00	10.28	22.25	10.42	31.32	9.86	16.81
6C'		10	0.76	3.75	8.03	12.95	8.23	23.32	8.22	30.32	7.16	15.18
8B		6	0.84	3.80	9.49	6.94	9.15	12.02	9.34	19.78	7.51	7.26

R^2 = Coefficient of determination; $I_{S(50)}$ = Point load strength index; CE = Electrical conductivity

By analyzing the relationship between the pH and EC parameters, the results could be individualized according to the different lithotypes, as shown in Figure 4. In this graph, the dotted lines are illustrative and do not represent the actual variation among rock types. In general, the following division occurred:

- Dark gray dense basalts: EC from 0 to 5 µS/cm and pH of 7 to 9.5.
- Reddish dense basalts: EC from 5 to 10 µS/cm and pH from 7 to 8.5.
- Dense basalt with disseminated clay mineral: EC from 25 µS/cm and pH of 8.
- Vesicular-amygdaloidal basalts: EC from 13 to 26 µS/cm and pH from 7 to 8.5.
- Basaltic breccia: EC from 19 to 32 µS/cm and pH from 8 to 9.5.

The results confirmed that the presence of secondary minerals tends to increase the sample's electrical conductivity and pH value. This graph should not be considered for samples with high calcite concentrations because it biases the result toward high pH values. Therefore, the sample $2D_V$ (pH = 10.5) was not included in this graph.

Comparing the pH and EC parameters (0.42 < # < 1.0 mm) with the point-strength index ($I_{S(50)}$) confirmed that for the dense basalts, the measurements are highly divergent; in addition, the R^2 value did not support the use of this combination (Figure 5A). However, the EC x pH data (Figure 4) showed good potential for use with dense basalts. For the vesicular-amygdaloidal basalts and breccias, the pH tended to increase with decreasing strength (Figure 5B). There was no correlation of EC with point compression for these lithological types.

The laboratory results indicated significant differences within basaltic

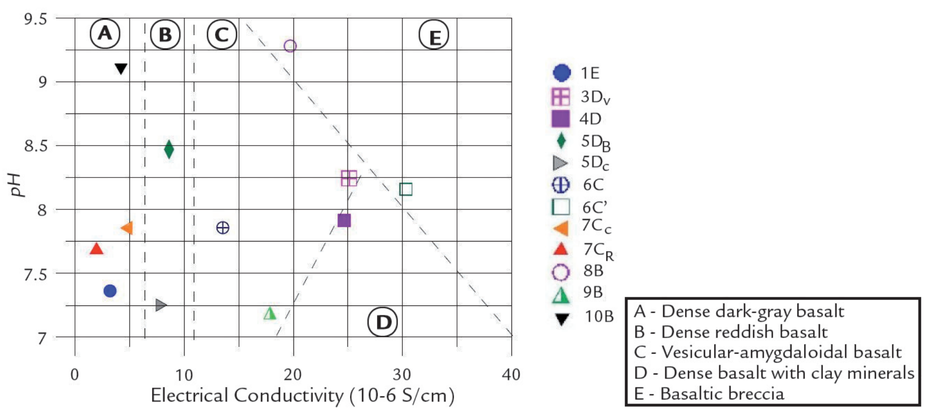

Figure 4
Correlation between pH and electrical conductivity.

lithotypes, which are difficult to detect with visual-tactile evaluation aimed at determining the degree of weathering or by the point-compression test. The dark gray, dense basalts (1E, $7C_C$, $7C_R$, and 10B) were all classified as W1 (non-weathered material) and exhibit high strength (according to the classification of Verhoef and Van der Wall (1998) for $I_{S(50)}$ > 8 MPa). However, sample 10B presented significant variation in terms of pH. Among subgroups $5D_C$ (W1) and $5D_B$ (W2), both with $I_{S(50)}$ > 9 MPa, the pH meter results were even more distinct. The point-load test was not effective in the evaluation of weathering in these dense basalt groups, and only a partial association of weathering with EC was found.

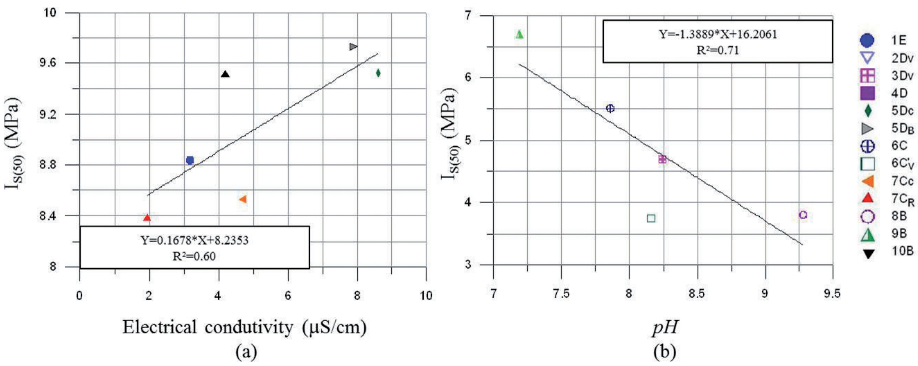

Figure 5
(a) Correlation between electrical conductivity and point load strength for dense basalt.
(b) Correlation between pH and point load strength for vesicular-amygdaloidal basalt and basaltic breccia.

4. Conclusion

One of the greatest challenges in the evaluation of rock materials for different uses is the diagnosis of incipient weathering that cannot be visually observed. The results of the present study support the view that pH measurements combined with microscopic analyses appear promising for the assessment of the degree of rock weathering. In dense basalts, based on microscopic analyses, pH values above 8 are indicative of the early stages of weathering. In vesicular-amygdaloidal basalts and basaltic breccias, the mechanical strength has no correlation with electrical conductivity; however, there is a decreasing trend in point-load strength with an increase in pH. Although the low strength of these basaltic lithotypes is associated with the presence of vesicles and amygdales, a relationship can be verified between point-load strength and the level of weathering: the higher the pH, the lower the mechanical strength. Incipient weathering in the plagioclase can be seen in these groups, but the increased pH is closely associated with the presence of secondary minerals, such as clay and calcite.

The graph presented here provides a contribution to the field of geotechnical characterization of basaltic rocks, mainly for analyzing the degree of weathering. For dense basalts with electrical conductivities between 0 and 15 µS/cm, the following weathering classification in terms of pH is suggested:

- W1 (unweathered rock): 7 > pH ≤ 8.
- W2 (slightly weathered rock): 8 > pH ≤ 10.
- pH > 10, the rock should be analyzed under a microscope for the classification of weathering.

For vesicular-amygdaloidal basalts and breccias, the following classification is suggested:

- W2 (slightly weathered rock): 7 > pH ≤ 8 and 10 > EC ≤ 30.
- W3 (moderately weathered rock): 8 > pH ≤ 9 and 30 > EC ≤ 40.

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