Influence of Weathering and Correlations Between Wave Propagation Velocity and Durability with Physical and Mechanical Parameters in Phyllites

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Abstract. Ultrasonic longitudinal wave velocity (V_p) and durability are characteristics largely determined in geotechnical evaluations. These properties are useful in the analysis of weathered rocks because they usually have good relationships with physical and mechanical properties of rocks. Additionally, the tests to obtain these parameters are easy to perform. However, few studies have been performed specifically on low degree metamorphic rocks. The purpose of this study is to evaluate the influence of weathering on these parameters, as to propose correlations between V_p and some mechanical and physical parameters. This study was carried out using phyllites from three weathering profiles located along the highway BR-356, Minas Gerais, Brazil. The results reveal a clear influence of weathering on V_p and durability mainly due to increased porosity. However, as the variation of this parameter is heterogeneous, the relationship between V_p , durability, and weathering is not uniform, although they present general trends. The behavior shown by porosity reflects the complex role of chemical weathering on fractures. The non-uniform pattern of V_p and durability throughout the weathering classes is also a consequence of the heterogeneity and anisotropy intrinsic to these phyllites. The empirical relationships established exhibit good correlation coefficients.

Keywords: correlations, durability, Minas Gerais, phyllite, wave propagation velocity, weathering.

1. Introduction

Ultrasonic wave propagation test is non-destructive, easy to apply, and thus has been increasingly employed in the characterization of rocks for engineering purposes, including the determination of effects of weathering on rocky materials.

Several researchers have studied the relationship between ultrasonic longitudinal wave propagation velocity (V_p) and rock properties, finding an intimate relationship between them (Gardner *et al.*, 1974; Gaviglio, 1989; Souza *et al.*, 2005; Çobanoğlu & Çelik, 2008; Sharma *et al.*, 2011; Nefeslioglu, 2013; Jamshidi *et al.*, 2016; Wen *et al.*, 2018; Kanji & Leão, 2020). Although many attempts have been performed to correlate V_p with physical and mechanical rock properties, few studies have focused on low and medium degree metamorphic rocks (Sharma & Singh, 2008; Sarkar *et al.*, 2012; Khandelwal, 2013).

Ultrasonic longitudinal wave propagation velocity (V_p) in rocks is influenced by many factors such as lithology, density, porosity, grain size and shape, anisotropy, confinement pressure, weathering, bedding, joint characteristics (fill material, water, direction, dip, among others) (Kahraman, 2001).

Weathering is known to lead to rapid changes in the properties of rock materials. Alterations of a particular rock type and their rate of occurrence (alterability) are often described by a durability parameter (Crosta, 1998) known as the durability index (I_d) and obtained through slake durability test.

The slake durability test is used to evaluate the resistance to rock alteration as a function of the disintegration resulting from a standard wetting and drying cycle (Franklin & Chandra, 1972). Durability is a characteristic largely affected by mineralogy, texture, porosity, and water content and is strongly related to the history of alteration after its formation (Koncagül & Santi, 1999; Cetin *et al.*, 2000; Dhakal *et al.*, 2002; Yilmaz & Karacan, 2005; Gupta & Ahmed, 2007; Ioanna *et al.*, 2009).

In this sense, this study shows the effects of weathering on V_p and durability, as well as the correlation between these properties and physical and mechanical parameters in phyllites from the region of Minas Gerais, Brazil.

Phyllites were collected in road slopes located in the state of Minas Gerais, Brazil. These slopes are inserted in the geological context of the Iron Quadrangle, an important mineral province of Brazil, consisting of five main lithostratigraphic units (Alkmim & Marshak, 1998): crystalline

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Figure 1 - Geological map with the location of the studied weathering profiles, located in the contiguous cities of Mariana (Phy01) and Ouro Preto (Phy02 and Phy03) (adapted from da Silva *et al.*, 2005; Romano *et al.*, 2017). Ouro Preto is approximately 100 km from the capital of the State of Minas Gerais (Belo Horizonte, BH), Brazil.

basement, metamorphic complexes of Archean age; Rio das Velhas Supergroup, consisting of an Archean volcano-sedimentary sequence (greenstone belt); Minas Supergroup, formed by Proterozoic, metamorphosed, and folded sediments; post-Minas intrusions; Itacolomi Group, consisting of Proterozoic clastic metasediments. As shown in Fig. 1, the studied phyllites belong to the Minas Supergroup.

2. Methodology

Phyllite samples at different degrees of weathering were taken from three road slopes located along BR-356 in the state of Minas Gerais, Brazil (Table 1). The degrees of weathering were identified in each profile from the classification proposed by the International Society of Rock Mechanics (ISRM, 2015).

These samples were taken for laboratory tests to obtain physical indices, wave propagation velocity, point load strength index, durability, and mineralogical analysis. It is part of the scope of this paper to present and discuss V_p and durability data for materials at different levels of weathering, as well as correlate the properties V_p and durability, V_p and physical indices, and V_p and the point load strength ($Is_{(50)}$). Tests were performed according to the suggestions of ISRM (2007).

Listed next are the number of samples used for each weathering class contemplated in this study: 13 from phyllite W1/W2, 19 from phyllite W2, 20 from phyllite W2/W3, 38 from phyllite W3, 23 from phyllite W3/W4, 19 from phyllite W4.

Least-squares regression analyses were applied between V_p and durability, V_p and physical indices, and V_p

and $Is_{(50)}$ to verify the possible relationships between these properties. The best-fit line and the correlation coefficients were determined. Different relationships (linear, exponential, logarithmic, and power) were tested in order to obtain the highest correlation coefficient values.

Table 1 - Degrees of weathering of phyllites sampled for laboratory tests. The classification was carried out according to ISRM (2015) guidelines.

Weathering profiles	Class	Term
Phy01	Slightly weathered rock	W2
	Moderately weathered rock	W3
	Highly weathered rock	W4
Phy02	Sound to slightly weathered rock	W1/W2
	Slightly weathered rock	W2
	Slightly weathered to moderately weathered rock	W2/W3
	Moderately weathered rock	W3
	Moderately weathered to highly weathered rock	W3/W4
Phy03	Moderately weathered rock	W3*
	Highly weathered rock	W4

*In the Phy03 profile, three distinct collection points of the moderately altered phyllite (W3) were chosen to evaluate the influence of possible textural and mineralogical differences.

Figure 2 - Outcrops of phyllite W3 (a) and W4 (b) from profile Phy01, W3/W4 from profile Phy02 (c), and W3 from profile Phy03 (d), highlighting discontinuities parallel to foliation resulting from exposure of these rocks to weathering.

3. Results and Discussions

3.1. Main characteristics of the studied phyllites

The studied phyllites are composed of muscovite, quartz, opaque minerals and chlorite. The main products of weathering on primary minerals are iron oxide/hydroxide and kaolinite. Foliation is penetrative, millimeter-spaced, formed by the alternation of thin micaceous bands, quartz-micaceous bands, and quartz veins. There are also veins consisting of chlorite and opaque minerals, parallel to metamorphic foliation.

One of the main effects of the exposure of these rocks to atmosphere conditions is the formation of fractures parallel to the metamorphic foliation, which intensifies with the advancement of weathering (Fig. 2). There is also increased openness of these discontinuities that become more degraded in the most altered members. This striking characteristic observed in the studied profiles is also noticeable in the petrographic slide due to the presence of micro-fractures, especially transgranular and intragranular (Fig. 3). As physical weathering is processed, creating preferential spaces for water to enter the rock, opaque minerals are dissolved and iron oxides are precipitated. These results are in agreement with studies carried out in phyllites under tropical (Leão *et al.*, 2017) and subtropical (Marques *et al.*, 2017; Marques *et al.*, 2020; Robert & Hack, 2020) climates. Figures 4, 5, and 6 show the main implications of weathering on the matrix of this rock.

3.2. Physical indices

Dry and saturated apparent specific gravity, apparent porosity, and apparent water absorption capacity are shown

in Table 2. Physical parameters are clearly influenced by weathering processes. However, the variation of these parameters is not homogeneous in soil-rock transition materials (W3, W3/W4, and W4). It is mainly due to the increased number of micro-fractures and the widening of pre-existing discontinuities parallel to metamorphic foliation. This increase in porosity with the advancement of weathering is also accompanied by higher precipitation of iron oxide/hydroxide rich solutions, as previously discussed. These characteristics occur most sharply from phyllite W3. Sousa *et al.* (2005) observed that, unlike what happened in intact or slightly altered granites, the porosity variation was not homogeneous in a very altered granite. This is due, according to the authors, to the action of weathering on micro-fractures, making their performance increasingly complex and reflecting on the physical characteristics of the rock.

3.3. Durability

The lowest obtained durability index corresponds to phyllite W3 from profile Phy01 (Table 3). It can be explained by the reduced internal cohesion of its matrix, which was also pointed out by Leão *et al.* (2017) in altered sericite phyllites from the same site. These phyllites are characterized by levels of mafic and siliceous minerals that fill foliation (Fig. 4). Leão (2017) performed durability studies on phyllites located in profile Phy01 and obtained nonlinear behavior of I_{d2} values among phyllites with different degrees of weathering. The author attributed this behavior to the presence of cemented levels, whose origin would not be the result of the weathering action. These levels are unevenly distributed throughout the profile, causing heterogeneities in the rock. Thus, the conclusion reached

Figure 3 - Textural and mineralogical aspects of phyllites in petrographic slides. Slides are from samples collected from profile Phy03. The abbreviation means: *IrO* iron oxides/hydroxides; *Mu* muscovite; *Op* Opaque; *Qz* quartz. In (a) there is a fracture parallel to metamorphic foliation (phyllite W3). In (b and c) there is a transgranular fracture and precipitation of iron oxides/hydroxides due to the weathering of opaque (phyllite W3 and W4, respectively). In (d) there is a precipitation of iron oxides/hydroxides in the matrix and intragranular fractures of quartz grains (phyllite W3).

Figure 4 - Aspects of the phyllite matrix at different degrees of weathering of profile Phy01. Scale in centimeters (cm). SBG - Brazilian Geological Society.

Figure 5 - Aspects of the phyllite matrix at different degrees of weathering of profile Phy02. Scale in centimeters (cm). SBG - Brazilian Geological Society.

by this author is in agreement with the results from the present study, as these same levels were also identified in this research, which would explain the increase in durability found in phyllite W4 in relation to W3 from profile Phy01.

In profile Phy02, I_{d2} values obtained for slightly altered phyllites (W1/W2, W2, and W2/W3) are above 90 %.

Similar values were found by Ramamurthy *et al.* (1993) (97.56 % for intact micaceous phyllites), Andrade & Saraiya (2010) (90.7 to 98.9 % for phyllites W1 and W2), Marques *et al.* (2010) (durability values higher than 95 % for gneisses W1 and W2), and Silva & Lana (2012) (90.36 to 91.56 % for sericite phyllites W2).

Figure 6 - Aspects of the matrix of weathered phyllites of profile Phy03. Samples of phyllite W3 were collected from three different points of the profile, demonstrating the heterogeneity of the rock. Scale in centimeters (cm). SBG - Brazilian Geological Society.

Table 2 - Mean (M) and standard deviation (SD) of values of dry (ρ_{dry}) and saturated (ρ_{sat}) apparent specific gravity, apparent porosity (η), and apparent water absorption (abs) for different classes of phyllite weathering of the three weathering profiles.

	Class	ρ_{dry} (g/cm ³)	SD (g/cm ³)	ρ_{sat} (g/cm ³)	SD (g/cm ³)	η (%)	SD (%)	abs (%)	SD (%)
Phy01	W2	2.79	0.03	2.85	0.03	6.06	0.25	2.18	0.11
	W3	2.38	ND*	2.53	ND	14.29	ND	6.00	ND
	W4	1.95	ND	2.09	ND	14.07	ND	7.23	ND
Phy02	W1/W2	2.8	0.01	2.84	0.01	4.17	0.19	1.49	0.07
	W2	2.72	0.02	2.78	0.02	6.14	0.43	2.26	0.17
	W2/W3	2.75	0.05	2.83	0.04	8.57	0.29	3.12	0.16
	W3	2.44	0.03	2.59	0.03	14.89	0.52	6.09	0.29
	W3/W4	2.14	0.14	2.36	0.10	22.00	4.11	10.35	2.59
Phy03	W3	2.38	0.03	2.54	0.01	15.76	1.60	6.63	0.75
	W3	2.30	0.06	2.48	0.04	17.99	1.76	7.84	0.98
	W3	2.40	0.09	2.55	0.07	15.12	2.26	6.32	1.18
	W4	2.37	0.07	2.54	0.05	16.20	2.17	6.84	1.11

*ND Not determined.

Table 3 - Durability index (I_{d1} and I_{d2}) and wave propagation velocity (V_p) of phyllites at different states of alteration of the three weathering profiles.

Weathering profiles	Class	I_{d1} (%)	I_{d2} (%)	V_p perpendicular direction (m/s)	V_p parallel direction (m/s)
Phy01	W2	88.19	76.76	445.14	4795.00
	W3	8.19	1.66	126.00	3474.25
	W4	11.67	7.44	ND*	ND
Phy02	W1/W2	98.18	96.82	2040.10	5382.42
	W2	97.32	95.52	969.71	4601.33
	W2/W3	95.18	91.75	1011.42	4716.65
	W3	95.49	91.81	742.00	4243.79
	W3/W4	76.47	60.34	501.92	4415.32
Phy 3	W3	61.34	44.08	394.67	4011.83
	W3	85.51	73.83	366.00	3802.14
	W3	71.94	55.05	523.43	3830.78
	W4	75.56	65.65	945.78	3588.21

*ND Not determined.

The durability obtained from phyllites W3 is quite variable. Except for phyllite W3 from profile Phy01, which has a very low internal cohesion (a characteristic of this profile), I_{d2} ranged from 91.81 (profile Phy02) to 44.08 % (profile Phy03). High variations in moderately weathered phyllites were also reported by Andrade & Saraiva (2010) (between 59.6 and 98.2 %) and Silva & Lana (2012) (between 86.18 and 54.32 %).

The variation in durability found for phyllites W3 may be related to the following changes imposed by weathering, which increase significantly in this degree of alteration: increase in pore volume and significant presence of altered opaque minerals, *i.e.*, which had their crystalline form modified (Fig. 3d). Similarly to the present study, Dhakal *et al.* (2002) found a close relationship between durability and weathering in clastic rocks since it provided changes in pore volume and distribution and caused crystalline changes in smectites, which coincides with the results of the present study.

Graphs of Figs. 7 and 8 compare the average values of I_{d2} and porosity and I_{d2} and amount of oxides, respectively, in the different weathering classes, being possible to observe the influence of these factors on durability. The increased porosity, associated with permeability, provides a larger surface area of the rock available for contact with water (specific surface), which acts to decrease durability, by weakening chemical bonds, changing properties of mineral constituents and causing instability along weakness planes due to pore water pressure (Koncagül & Santi, 1999).

Figures 9 and 10 show, respectively, I_{d2} values with weathering progression and phyllite samples after being subjected to two wetting and drying cycles. As can be observed, although I_{d2} does not uniformly follow the evolution of the alteration, there is a general trend to reduce this parameter with weathering.

Figure 7 - Mean values of I_{d2} and porosity of each weathering class. A more significant reduction in durability is observed as there is a more significant increase in porosity from the moderately altered phyllite (W3).

Figure 8 - Mean values of I_{d2} and oxide concentration of each weathering class. There is a more marked decrease in durability while a more significant increase in oxide precipitation from the moderately weathered phyllite (W3). Elevated oxide concentration indicates a higher alteration in opaque minerals.

The variability found in durability between phyllites of the same alteration class is also attributed to the heterogeneity of the rock, including the same profile. It happened, for instance, in phyllites W3 collected at distinct points in profile Phy03 (Fig. 2). Depending on profile position, the rock may contain more or less opaque and hence, oxide content, as well as variations in quartz content. Thus, durability is influenced not only by secondary processes derived from weathering but also by the heterogeneity itself intrinsic to the mineralogical composition variation of these phyllites.

3.4. Wave propagation velocity

Some samples showed no detection of V_p signal measured perpendicularly to foliation, while in others (the majority), the intensity signal detected during tests was very low, rarely 100 %. The attenuation of V_p in the perpendicular direction is caused by the presence of fractures parallel to foliation that make the rock discontinuous, affecting it significantly. There are often reports in the literature of dif-

Figure 9 - Relationship between I_{d2} and different degrees of alteration of phyllite samples collected in three distinct weathering profiles (Phy01, Phy02, and Phy03).

Figure 10 - Results of samples of altered phyllites after two wetting and drying cycles.

ferences in V_p in the direction perpendicular and parallel to foliation in rocks with anisotropic properties (Ramamurthy *et al.*, 1993; Marques *et al.*, 2010; Kurtulus *et al.*, 2012; Nikrouz *et al.*, 2016). Jensen & Elming (2013) reported as potential causes of seismic anisotropy the micro-fissures, joints, faults, macroscopic foliation, stratification, and weathering. These authors found anisotropy in V_p in metarolites with microfoliation, obtaining the highest values in the direction parallel to it.

The values of V_p obtained in the parallel direction for slightly altered phyllites (W1/W2, W2, and W2/W3) are in the range of 4601.33-5382.42 (m/s), being compatible with the results of phyllites with similar mineralogical composition considered intact or little altered by other researchers (Ramamurthy *et al.*, 1993; Andrade & Saraiva, 2010).

As shown in Fig. 11, moderately to very altered phyllites (W3, W3/W4, and W4) transmit the ultrasonic waves with less efficiency. V_p is sensitive to the state of alteration of the studied rocks, showing a general trend of reduction as weathering increases.

Figure 11 - Relationship between the velocity of ultrasonic wave propagation measured parallel to foliation and the degree of alteration of phyllite samples collected in three weathering profiles (Phy01, Phy02, and Phy03).

3.5. Correlations

3.5.1. Correlation between I_{d1} and I_{d2} with Vp

The values of Vp measured in the direction perpendicular to foliation were not considered, due to the low intensity signal detected during tests.

Figure 12 shows the correlations between I_{d1} and Vp and I_{d2} and Vp . In Figs. 12a and 12b, correlations were performed between the mean values of each alteration class, while in Figs. 12c and 12d, the individual values were used, obtaining a much lower correlation coefficient. The dispersed values shown in Figs. 12c and 12d are the result of the influence of weathering and anisotropy of the studied phyllites.

Based on the obtained results, the use of mean values was adequate to correlate durability and wave propagation velocity. Khandelwal (2013) obtained a good correlation between Vp and I_{d1} for different rock types, including shales, for Vp values in the range from 1682 to 4657 m/s. Sharma & Singh (2008) also found a good correlation between these two parameters when evaluating seven different types of rock, including phyllites and shales.

3.5.2. Correlation between Vp and physical indices

Figure 13 shows that all the physical indices have a strong relationship with Vp , with a reduction in Vp as density decreases (increased porosity and water absorption). These results are in agreement with Gaviglio (1989), Tur-

grul & Zarif (1999), Yasar & Erdogan (2004), Kurtulus *et al.* (2010), Diamantis *et al.* (2011), Sarkar *et al.* (2012), Khandelwal (2013), and Azimian & Ajalloeian (2015), who studied the relationship between physical properties and Vp and obtained good correlations between these parameters.

3.5.3 Correlations between Vp and Is

Graphs in Fig. 14 show the relationship between Vp and $Is_{(50)}$. As expected, the lower the $Is_{(50)}$ is, the lower the Vp . There is a good relationship between Vp and $Is_{(50)}$ measured perpendicular to foliation, with a correlation coefficient of 0.7779 (Table 4), while the correlation coefficient between Vp and $Is_{(50)}$ measured parallel to foliation is lower ($R^2 = 0.6139$), unlike expected. Thus, despite showing influence on Vp and $Is_{(50)}$, metamorphic foliation is not sufficient to explain the good relationship obtained between these properties.

On the other hand, porosity is closely related to Vp (Fig. 13) and influences the resistance of weathered rocks (Marques *et al.*, 2010; Andrade & Saraiva, 2010; Leão *et al.*, 2017) since the presence of pores makes the rock less continuous, decreasing Vp and increasing the fragility of the matrix when subjected to compression (Sousa *et al.*, 2005). Thus, the increased porosity due to weathering processes may play a preponderant role in the variation of these properties (Vp and $Is_{(50)}$) in the studied phyllites.

Figure 12 - Correlations between I_{d1} and Vp (parallel to foliation) and I_{d2} and Vp (parallel to foliation). In (a) and (b), correlation between the mean values of each alteration class. In (c) and (d), correlation between the values obtained from all weathering grades of the three studied profiles.

Figure 13 - Correlations between V_p (parallel to foliation) and physical indices: dry (a) and saturated apparent specific gravity (b), porosity (c), and water absorption capacity (d).

Table 4 - Equations correlating V_p (parallel to foliation) and $I_{s(50)}$ in different types of rock.

Equations	Correlation coefficient	References	Rock
$I_{s(50)} = 6.67 \ln(V_p) - 51.9$	0.93	Jamshidi <i>et al.</i> (2016)	Travertine
$I_{s(50)} = 0.0018(V_p) - 1.9906$	0.95	Kurtulus <i>et al.</i> (2010)	Andesites
$I_{s(50)} = 0.0042(V_p) - 14.602$	0.90	Kurtulus <i>et al.</i> (2012)	Serpentine ultrabasic rocks
$V_p = -16.784 I_{s(50)} + 6078.9$	0.55	Jensen & Elming (2013)	Meta-riolites
$V_p = 859.02 I_{s(50)}^a + 3475.2$	0.78	Present study	Phyllite
$V_p = 3155.9 I_{s(50)}^b + 3574.1$	0.61	Present study	Phyllite

$I_{s(50)}^a$ Direction of loading perpendicular to foliation.

$I_{s(50)}^b$ Direction of loading parallel to foliation.

Figure 14 - Relationship between V_p (parallel to foliation) and $I_{s(50)}$ perpendicular to foliation ($I_{s(50)}^a$) and parallel to foliation ($I_{s(50)}^b$).

4. Conclusions

The slake durability test performed in the studied phyllites showed that weathering has a clear influence on this geotechnical property, affecting the texture and mineralogical composition of these rocks. As expected, the progressive increase in porosity and mineral alteration due to weathering was accompanied by a reduction in durability, but the intensity in which this process occurs was established.

V_p decrease with weathering is closely related to variation of physical indices, as proved by the significant correlation coefficients found. Intact rock strength and V_p are influenced by metamorphic foliation. Also, the very good correlation found between V_p and $I_{s(50)}$ may be influenced by the effects of weathering, which cause a higher increase in porosity when compared to the anisotropy intrinsic to phyllites resulting from mineral alignment.

V_p and durability, although presenting general trends, do not evolve uniformly with the weathering progression since porosity, the main physical parameter that influences strength has heterogeneous behavior. This behavior attributed to porosity is probably associated with physical weathering, due to the increase in spacing of pre-existing discontinuities and formation of a micro-fracture network. Therefore, the action of weathering on fractures and micro-fractures makes their effects increasingly complex, reflecting on the physical characteristics of the rock.

In addition to the influence of secondary weathering processes on the variability of physical and mechanical parameters, there is also the mineralogical heterogeneity intrinsic to these phyllites, observed between samples with the same degree of alteration in the same profile, but taken from different points. Both heterogeneity and anisotropy are also revealed in the correlation established between V_p and I_{d1} and V_p and I_{d2} when all values for each sample from all three slopes are incorporated. The use of mean values of each alteration class improves the correlation between these properties and allows concluding that the evaluated physical parameters should be used prudently in geotechnical projects, being important that they are associated with a field control, contemplating descriptions of the rocky massif (including discontinuity characteristics), petrographic and micropetrographic analyses, as well as other types of physical and mechanical tests.

Good correlations were found for V_p and slake durability index, for V_p and all physical indices, and for V_p and point load strength measured perpendicular to foliation.

Finally, the authors suggest that similar studies, with the same tests/analyses, should be performed on similar rock types (and also with other lithotypes) from other regions from Brazil.

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