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THE RELATIONSHIP BETWEEN P-WAVE VELOCITY AND SLAKE DURABILITY INDEX

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ABSTRACT

Many manmade structures such as tunnels, roads, bridges, dams, power plants, etc. have been built either on top or inside rocks. Therefore, it is highly crucial to determine the various parameters of rocks in construction designs. Slake durability index is one of the widely applied features in this respect. A great deal of time and money is required to prepare samples and conducts slake durability tests. For that reason, easier and less expensive methods are employed to determine slake durability index. This research project mainly attempted to propose an equation to estimate the slake durability index after the second cycle (Id_2) based on the speed of sound (V_P). In addition to the longitudinal wave velocity test and the Brazilian slake durability test, the point load was specified on the samples so as to further expand the study. The tests were conducted on samples of sandstone, tuffite, andesite, red sandstone, limestone, marl, marble and travertine. The simple regression yielded three separate equations, i.e. the first relationship between the slake durability index of the second cycle and velocity of longitudinal waves, the second relationship between slake durability index of the second cycle and tensile strength and the third relationship between the slake durability index of the second cycle and the point load index. The results demonstrated that the greatest coefficient of determination (R^2) was in the relationship between the slake durability index of the second cycle and the velocity of longitudinal waves. The results of comparison between this relationship and those proposed by other researchers suggested that the equation offered in this paper can accurately estimate the slake durability index in a broad range of rocks.

Keywords: P waves, Longitudinal waves, Empirical relationship, Velocity of waves, Rock, Slake durability index.

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Contribution/ Originality

This study is one of very few studies which have investigated the relationship between the sound velocity and slake durability index. This study documents that slake durability index can be estimated with a high level of accuracy by using the proposed equation.

1. INTRODUCTION

The slake durability test is intended to assess the resistance offered by a rock sample to weakening and disintegration when subjected to two standard cycles of drying and wetting. The slake durability index can be calculated at the second cycle using this test. A great deal of time and money is required to prepare samples and conducts slake durability tests. For that reason, easier and less expensive methods are employed to determine slake durability index. Sound velocity test can provide a simple and inexpensive text, another advantage of which is being non-destructive and the possibility of being carried out in a desert. The majority of previous studies concentrated on the application of P-wave velocity for estimating uniaxial compressive strength and tensile strength. For instance, Minaeian and Ahangari (2013) estimated uniaxial compressive strength based on P-wave velocity, which yielded desirable results. The equations obtained from the simple linear regression entailed a coefficient of determination (R^2) equal to 0.94 (Minaeian and Ahangari, 2013). Sharma and Singh (2010) proposed a linear equation with coefficient of determination at 0.93 so as to estimate the uniaxial compressive strength through the velocity of longitudinal waves (Sharma and Singh, 2010). Kurtulus *et al.* (2011) offered a linear equation with coefficient of determination at 0.92 so as to estimate the uniaxial compressive strength in serpentine stone through the velocity of longitudinal waves (Kurtulus *et al.*, 2011).

Altindag (2012) proposed an exponential equation with coefficient of determination at 0.79 so as to estimate the uniaxial compressive strength in sedimentary rocks (Altindag, 2012). Moreover, Khandelwal (2013) developed a linear equation with coefficient of determination at 0.87 so as to estimate the uniaxial compressive strength in different types of rock (Khandelwal, 2013).

Hosseini and Shirin (2015) proposed a cubic equation with coefficient of determination at 0.46 so as to estimate the tensile strength of rock through the velocity of longitudinal waves (Hosseini and Shirin, 2015). There are very few studies focusing on P-wave as a measure to estimate slake durability index. For instance, Nikudel *et al.* (2010) offered an exponential equation with a correlation coefficient of 0.48 so as to estimate the slake durability index of rocks at the second cycle (Nikudel *et al.*, 2010). Yagiz (2011) achieved a linear equation with coefficient of determination at 0.69 so as to estimate the slake durability index of rock at the second cycle (Yagiz, 2011). Moreover, Azimian and Ajalloeian (2015) achieved a linear equation with coefficient of determination at 0.9 so as to estimate the slake durability index of marl at the second cycle (Azimian and Ajalloeian, 2015).

2. EXPERIMENTS

The blocks used for coring included sandstone, tuff, andesite, red sandstone, limestone, marl, marble and travertine. The cores obtained from these blocks were all 51 mm in diameter. The experiments carried out on the samples comprised the determination of longitudinal wave velocity, point load, Brazilian test and slake durability.

Since these experiments are conventional in rock mechanics, the in-depth description is narrowed down to a few equations and test results. The velocity of longitudinal waves in the samples was obtained through Equation (1) (ISRM, 1978a).

$$V_P = \frac{L}{t} \times 1000 \quad (1)$$

V_P: The velocity of pressure wave (m/s), t: The pressure wave passage time (μs), L: Sample length (mm). The results of testing the velocity of longitudinal waves have been given in Table 1.

Table-1. Results from determining the velocity of longitudinal waves

Type of stone	velocity of longitudinal waves(m/s)
Lowshan grey sandstone	3702.38
Abyek grey limestone	6690.20
Abyek tuff	3983.18
Abegarm light limestone	4726.87
Buin Zahra andesite	4919.94
Shemshak red sandstone	3584.73
Abegarm travertine	4920.12
Qazvin marble	5200.12
Marl sample 1 in southwest of Iran	2049.65
Marl sample 2 in southwest of Iran	2628.43
Marl sample 3 in southwest of Iran	3630.55
Marl sample 4 in southwest of Iran	3830.65
Marl sample 5 in southwest of Iran	2411.25
Marl sample 6 in southwest of Iran	1200.71

The tensile strength of the samples was calculated through the Brazilian test based on Equation (2) (ISRM, 1978b).

$$\sigma_{t=0.636} \frac{P}{D\,t} \quad (2)$$

P: Load at failure (kN), D: Sample diameter (mm), t: Sample thickness (mm), σ_t: Tensile strength (MPa) .The results from the Brazilian test have been illustrated in Table (2).

Table-2. The results of Brazilian test

Type of stone	σ_t (MPa)
Lowshan grey sandstone	5.93
Abyek grey limestone	12.25
Abyek tuff	19.23
Abegarm light limestone	5.51
Buin Zahra andesite	12.21
Shemshak red sandstone	13.86
Abegarm travertine	4.15
Qazvin marble	5.71
Marl sample 1 in southwest of Iran	2.95
Marl sample 2 in southwest of Iran	4.31
Marl sample 3 in southwest of Iran	6.95
Marl sample 4 in southwest of Iran	7.45
Marl sample 5 in southwest of Iran	5.49
Marl sample 6 in southwest of Iran	2.73

The uncorrected point load strength index was determined through Equation (3) (ISRM, 1985)).

$$I_s=P/D_e^2 \quad (3)$$

Where:

P: Load at the moment of failure (N), De: Core diameter (mm), Is: Point load strength index (MPa)

The conventional diameter test involves $D_e^2=D^2$ (D represents the core diameter).

If the sample diameter is more than 50 mm, the value of $I_s(50)$ is calculated through Equation (4) (ISRM, 1985).

$$I_{s(50)}=F*I_s \quad (4)$$

Where *F* is calculated as the correction coefficient through Equation (5) below.

$$F=(D_e/50)^{0/45} \quad (5)$$

The results of this experiment are displayed in Table (3).

Table-3. The results of point load test

Type of stone	I_s (MPa)
Lowshan grey sandstone	5.21
Abyek grey limestone	8.34
Abyek tuff	9.61
Abegarm light limestone	4.87
Buin Zahra andesite	9.53
Shemshak red sandstone	10.64
Abegarm travertine	2.37
Qazvin marble	3.25
Marl sample 1 in southwest of Iran	1.37
Marl sample 2 in southwest of Iran	1.91
Marl sample 3 in southwest of Iran	3.11
Marl sample 4 in southwest of Iran	3.67
Marl sample 5 in southwest of Iran	2.39
Marl sample 6 in southwest of Iran	0.83

The slake durability index can be calculated at the second cycle. Equation (6) is proposed for the calculation of rock slake durability index (ISRM, 1979).

$$Id_2=((B_2-D)/(A-D))*100 \quad (6)$$

Id_2: Slake durability index at the second cycle

B_2 (gr): sample weight and perforated cylinder after the second cycle

D (gr): Weight of perforated cylinder

A (gr): Sample initial dry weight and perforated cylinder

Slake durability index at the second cycle obtained through experiments are given in Table (4).

Table-4. Results of slake durability test

Type of stone	Id_2 (%)
Lowshan grey sandstone	98.78
Abyek grey limestone	99.34
Abyek tuff	99.44
Abegarm light limestone	98.87
Buin Zahra andesite	99.73
Shemshak red sandstone	99.64
Abegarm travertine	99.37
Qazvin marble	99.25
Marl sample 1 in southwest of Iran	86.37
Marl sample 2 in southwest of Iran	87.81
Marl sample 3 in southwest of Iran	90.29
Marl sample 4 in southwest of Iran	91.67
Marl sample 5 in southwest of Iran	88.49
Marl sample 6 in southwest of Iran	85.73

3. ANALYSIS OF RESULTS

At this stage, simple regression yielded three equations. The first relationship was between the slake durability index of the second cycle and velocity of longitudinal waves, the second relationship was between slake durability index of the second cycle and tensile strength and the third relationship was between the slake durability index of the second cycle and the point load index. The results were analyzed through several graphs and visualization of relationships in TableCurve^{2D}. In the following, each step will be outlined in detail. The information in Table (5) was used to achieve the equations.

3.1. Equations Proposed To Estimate the Slake Durability Index through Simple Regression

Regression analysis is a technique adopted to examine the relationships between variables, and particularly to understand how one variable is dependent on other variables. In fact, the simple regression serves to evaluate a dependent variable versus an independent variable. Simple regression can be either linear or nonlinear; the higher the correlation coefficient of a function, the higher the reliability of that function for estimating a given component. Table Curve ^{2D} was employed to evaluate all the functions concerning the relationship between the two parameters of slake durability index at the second cycle and the velocity of longitudinal waves. In this regard, a function is selected with the highest correlation coefficient and lowest complexity. Figure (1) shows the graph and the corresponding equation.

Table-5. The values obtained from velocity of sound, point load, Brazilian and slake durability tests

Type of stone	velocity of longitudinal waves(m/s)	σ_t (MPa)	I_s (MPa)	Id_2 (%)
Lowshan grey sandstone	3702.38	5.93	5.21	98.78
Abyek grey limestone	6690.20	12.25	8.34	99.34
Abyek tuff	3983.18	19.23	9.61	99.44
Abegarm light limestone	4726.87	5.51	4.87	98.87
Buin Zahra andesite	4919.94	12.21	9.53	99.73
Shemshak red sandstone	3584.73	13.86	10.64	99.64
Abegarm travertine	4920.12	4.15	2.37	99.37
Qazvin marble	5200.12	5.71	3.25	99.25
Marl sample 1 in southwest of Iran	2049.65	2.95	1.37	86.37
Marl sample 2 in southwest of Iran	2628.43	4.31	1.91	87.81
Marl sample 3 in southwest of Iran	3630.55	6.95	3.11	90.29
Marl sample 4 in southwest of Iran	3830.65	7.45	3.67	91.67
Marl sample 5 in southwest of Iran	2411.25	5.49	2.39	88.49
Marl sample 6 in southwest of Iran	1200.71	2.73	0.83	85.73

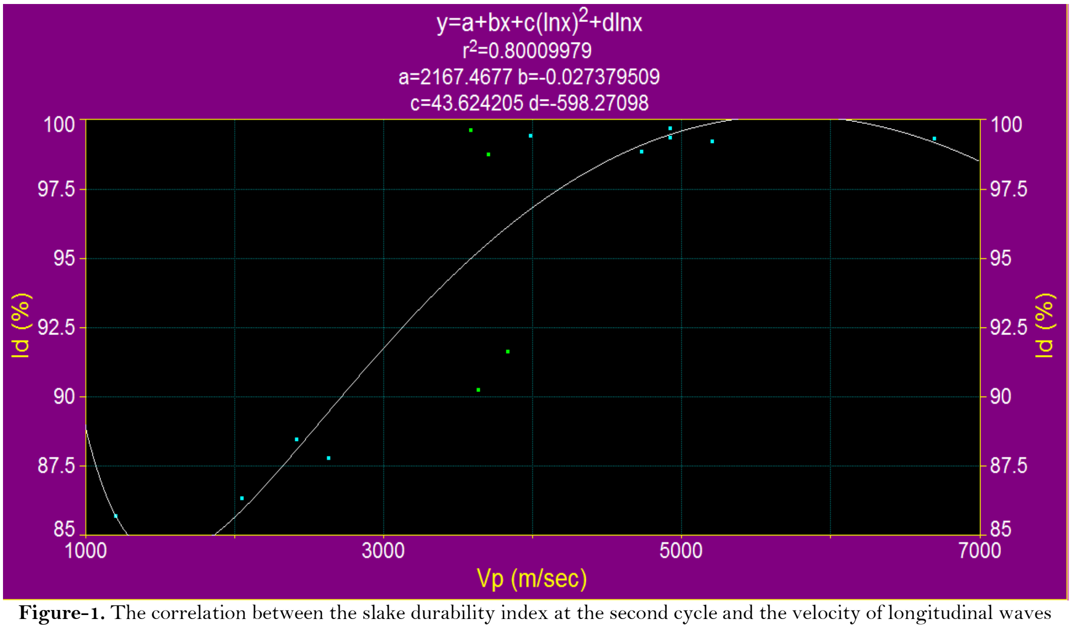

Figure-1. The correlation between the slake durability index at the second cycle and the velocity of longitudinal waves

Slake durability index was calculated through Equation (7). The coefficient of determination (R^2) is roughly 0.8.

$Id_2=2167.4677-0.027379509V_P+43.624205(\ln(V_P)^2)-598.27098(\ln V_P)$ (7)

3.1.2. The Relationship between Slake Durability Index and Tensile Strength

Figure (2) illustrates the graph and corresponding relationship between the slake durability index at the second cycle and tensile strength. The slake durability index was calculated through Equation (8). The coefficient of determination (R^2) is roughly 0.41.

$$Id_2=78.66883-63.267031(\sigma_t)+3.7516414(\sigma_t)^2 -0.085581(\sigma_t)^3+155.03841(\ln(\sigma_t)) \quad (8)$$

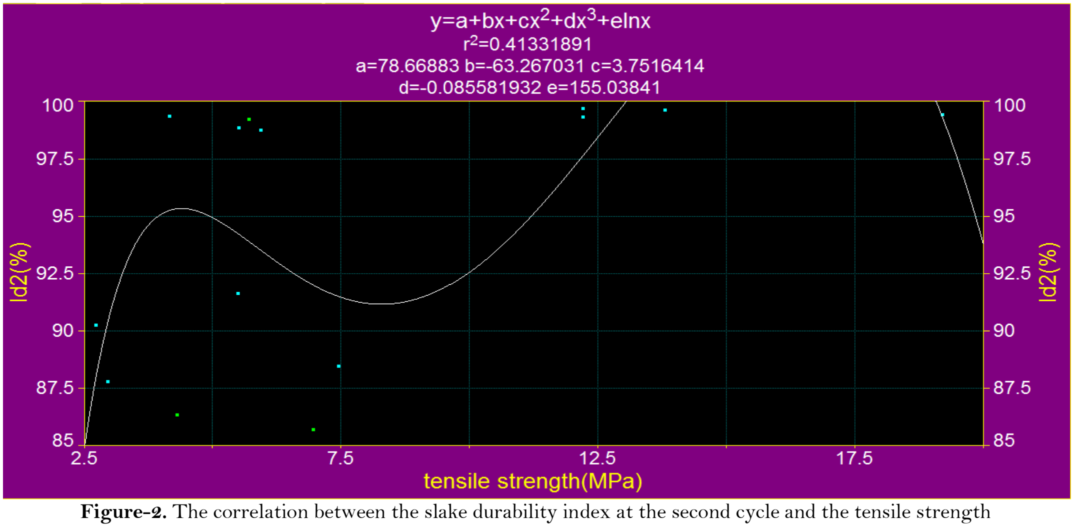

Figure-2. The correlation between the slake durability index at the second cycle and the tensile strength

Figure (3) illustrates the graph and corresponding relationship between the slake durability index and point load. The slake durability index was calculated through Equation (9). The coefficient of determination (R^2) is roughly 0.51.

$Id_2= 88.198519-0.029740247(Is)-0.7256788(Is)/\ln(Is)+ 6.846703(\ln(Is))$ (9)

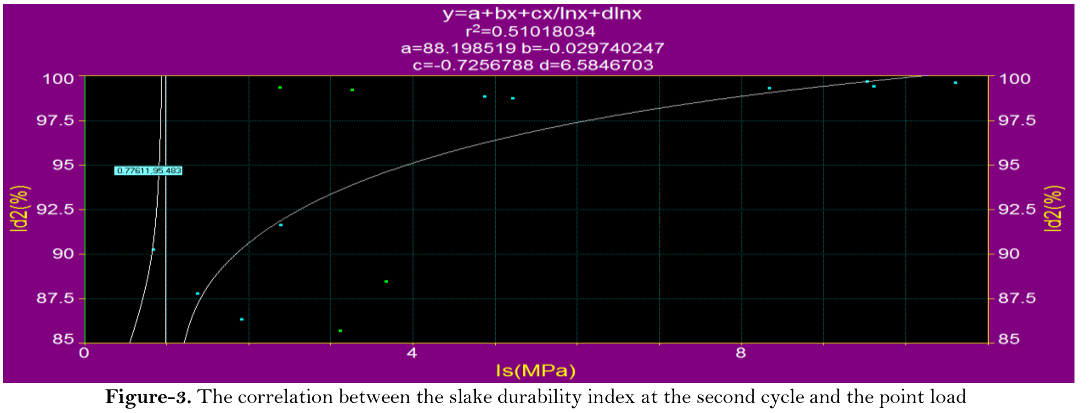

Figure-3. The correlation between the slake durability index at the second cycle and the point load

As can be seen, the relationship between the slake durability index at the second cycle and the velocity of longitudinal waves entail the highest coefficient of determination, which is preferred over the other two relationships. The few relevant studies similarly adopted the velocity of longitudinal waves to estimate the slake durability index.

3.2. Comparison the Equation Proposed In This Paper and Those by Other Researchers

A review of previous studies indicated that there are three equations for estimating slake durability index at the second cycle. Equation (10) was achieved through the experiments conducted by Nikudel *et al.* (2010).

$Id_2=95.732Vp^{0.0046}$ (10)

The coefficient of determination (R^2) in this Equation was 0.128.

Equation (11) was proposed by Yagiz (2011) with coefficient of determination at 0.69 (Yagiz, 2011).

$Id_2= 0.71Vp+ 95.7$ (11)

Equation (12) was proposed by Azimian and Ajalloeian (2015). It is applicable only for marl stone, and the coefficient of determination is about 9.0 (Azimian and Ajalloeian, 2015).

$Id_2= 0.0021Vp+ 82.8$ (12)

One of the advantages presented in Equation (7) is its application for rocks with low slake durability index. It is highly crucial to estimate the slake durability index for this category of rocks.

The performance of these Equations were evaluated through calculating the root mean square error (RMSE) obtained by Equation (13) (Minaeian and Ahangari, 2013). In this regard, y' is the slake durability index (second cycle) obtained from the experiments and corresponding relationships.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y - y')^2} \quad (13)$$

In an optimum mode, RMSE is zero. At the next stage, the equation with the greatest accuracy can be selected to estimate the slake durability index. Table (6) illustrates the results of Equations (7), (10) and (11) which can be compared against one another. This study intended to employ the experimental results of three researchers so as to better clarify the efficiency of the proposed equation.

Table-6. Compares the results of Equation (7) versus those of Equations (10) and (11)

experimental results of researchers	Vp (m/s)	Id_2 (%) experimental results	Id_2 (%) The results of the equation (7)	Id_2 (%) The results of the equation (10)	Id_2 (%) The results of the equation (11)
Azimian and Ajalloeian	2565.1	88.9	89.21	99.25	97.52
Azimian and Ajalloeian	3115.9	89.4	92.46	99.38	97.91
Hosseini	3700	97.64	95.8	99.41	98.32
Azimian and Ajalloeian	1826.8	86.8	85	99.09	96.99
Nikudel et al.	4750	99.41	99.49	99.53	99.07

The data in Table (6) were used to calculate the root mean square error for Equations (7), (10) and (11), the results of which can be seen in Table (7).

Table-7. Compares the RMSEs of the three Equations (7), (10) and (11)

Equation Number	RMSE
Equations (7)	1.72
Equations (10)	8.49
Equations (11)	7.08

As can be seen, the proposed equation can accurately estimate the slake durability index for a wide range of stones from high to low durablities.

4. CONCLUSIONS

This study focused on several samples of sandstone, tuff, marble, limestone, andesite, red sandstone, marl and travertine. It mainly attempted to obtain a relationship between the velocities of longitudinal waves and slake durability at the second cycle.

Speed of sound test can provide a simple and inexpensive text, another advantage of which is being non-destructive and the possibility of being carried out in a desert. In addition to the longitudinal wave velocity test and the Brazilian slake durability test, point load was specified on the samples so as to further expand the study. The simple regression yielded three separate equations, *i.e.* the first relationship between the slake durability index of the second cycle and velocity of longitudinal waves, the second relationship between slake durability index of the second cycle and tensile strength and the third relationship between the slake durability index of the second cycle and the point load index. The results demonstrated that the greatest coefficient of determination (R^2) was in the relationship between the slake durability index of the second cycle and the velocity of longitudinal waves. The few relevant studies similarly adopted the velocity of longitudinal waves to estimate the slake durability index. Furthermore, the equation was compared against those previously proposed by other researchers. In this respect, the newly proposed equation can be compared against Equations (10) and (11), where the RMSEs of Equations (7), (10) and (11) were 1.72, 8.49 and 7.08, respectively. As a result, Equation (7) is capable of accurately estimating the slake durability index in a broad range of rocks.

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