IJST (2015) 39A2: 147-163
Iranian Journal of Science & Technology

http://ijsts.shirazu.ac.ir

Estimating the engineering properties of building stones after freeze-thaw using multiple regression analysis

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Abstract

Freeze-thaw is one of the most powerful weathering agents that may cause a rapid change in the initial engineering properties of stones, and limit their durability. Freeze-thaw induces stress over the pores' surface of stones. Consequently, stone durability is closely related to its engineering and physical properties. The purpose of this study is estimating the engineering properties of deteriorated stones after freeze-thaw using multiple regression analysis. For this purpose, laboratory tests were conducted on 14 different building stones, and their petrographical characteristics, and engineering and physical properties were determined as well. Then freeze-thaw action was simulated for 30 cycles, and the engineering properties of stones including Brazilian tensile strength, point load index and P-wave velocity were determined. The statistical models for estimating the engineering properties after freeze-thaw were developed by multiple regression analysis. The models were validated by statistical tests, and the results showed that engineering properties of stones can be estimated after freeze-thaw using their initial engineering and physical properties with good accuracy.

Keywords*:* Freeze-thaw; engineering properties; physical properties; statistical models

1. Introduction

Stone failure due to freeze–thaw action occurs mainly in the environments where there is much moisture, and temperatures frequently fluctuate above and below the freezing point (Chen et al., 2004). When water turns into ice, it increases in volume by up to 9%, thus giving rise to the pressure within the pores (Bell, 2000). When the pressure reaches the tensile strength of stone, new microfractures are created and the existing ones are widened; consequently, stone durability is limited.

Linking the durability of building stones to their engineering and physical properties, including strength, P-wave velocity, hardness, porosity, water absorption, water flow and pore structure has been a long-term aim that has generated great interest in many fields such as engineering geology, material sciences, architecture and earth sciences.

Researchers have investigated different aspects of the effects of freeze–thaw on engineering and physical properties of stones (Rossi-Doria, 1985; Topal and Doyuran, 1998; Nicholson, 2001; Penttala and Al-Neshawy, 2002; Binal and Kasapoglu, 2002; Chen et al., 2004; Mutluturk et al., 2004; Yavuz et al., 2006; Ruedrich and Siegesmund, 2007; Takarli et al., 2008; Karaca et al., 2010). For instance, Topal and Sozmen (2000) investigated the changes in dry density, porosity, uniaxial compressive strength and P-wave velocity of Yazilikaya tuffs after freezing and thawing cycles. Binal and Kasapoglu (2002) studied the effect of freeze-thaw on the uniaxial compressive strength of Selime (Aksaray) ignimbrite. Mutluturk et al. (2004) proposed a decay function model for the integrity loss of rock when subjected to recurrent cycles of freeze-thawing. The model provides several meaningful parameters for rock disintegration or durability that can be used profitably for engineering evaluations. Chen et al. (2004) investigated the effect of water saturation on porous welded tuff due to freeze-thaw action, and found that both porosity and rock damage significantly increase when the degree of saturation exceeds 70%. Yavuz et al. (2006) proposed a model equation for estimating the index properties of deteriorated carbonate rocks due to freeze–thaw action. This model explains that decrease in the index property of a deteriorated rock depends on its initial engineering property and porosity.

A number of factors influence the changes of stones' engineering properties due to freeze-thaw action; 1) environmental conditions, 2) physical properties of porous materials, and 3) initial engineering properties, in particular strength, which is the material's resistance to crystallization pressure. The aim of this research is to propose

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Received: 19 June 2012 / Accepted: 30 August 2014

statistical models for estimating the stones' engineering properties after freeze-thaw action using their initial engineering and physical properties.

2. Materials and Methods

To carry out the research, 14 different building stones were selected from the stone factories around Tehran and quarries of Iran. These stones are marketed and used as building stones and are highly homogeneous in the hand specimen. During sampling, stone specimens having no bedding planes were selected to eliminate any anisotropy effects on the measurements.

3. Petrographical characteristics

Petrographical characteristics studies not only provide information on the mineralogical composition and provenance of the rock origin, but also are an important tool for assessing the rock' durability and resistance against weathering agents. Optical polarizing microscope was used to determine the mineralogical composition and textural properties of the samples. Type, class, mineralogical composition and textural properties of the samples are given in Table 1.

Table 1. Type, class, mineralogical composition and textural properties of the samples under study

Rock type	**Rock class**	**mineralogical composition and textural properties**
Rhyolite	Igneous	Fine grained texture. Fine grain quartz and Alkali-feldspar are within the vitreous groundmass. Less than 3% muscovite occur in the stone
Ignimbrite	Igneous	Composed mainly rock fragment, quartz, Alkali-feldspar, biotite. Plagioclase is partly chloritized
Granite-I	Igneous	Medium to coarse-grained (2–5 mm) and granular texture. Quartz, feldspar and muscovite are main mineral, plus less amount plagioclase and biotite. Feldspar partly altered to sericite
Granite-II	Igneous	Composed mainly of quartz, Alkali-feldspar (microcline) and muscovite. Granular texture. Plagioclase and biotite are minor
Dacite	Igneous	Main minerals observed are Alkali-feldspar and plagioclase that are more or less equidimensional. Groundmass with a high iron content
Travertine-I	Sedimentary	Essential minerals are calcite, occur in a lime mud. Calcites are mainly euhedral and subhedral. The porous are filled with iron
Travertine-II	Sedimentary	Micritic limestone. Micrite lime mud is highly porous and filled with calcite
Limestone I	Sedimentary	Micritic limestone. Essential minerals are calcite in a lime mud. Less than 4% opaque minerals occur in the stone
Dolomitic Limestone	Sedimentary	Recrystalised limestone. Essential minerals are coarse- grained calcites and medium grained dolomites
Limestone -II	Sedimentary	Essential minerals are calcite in a carbonate matrix. Calcites are fine-grained and euhedral. Less than 10% dolomite occur in the stone
Marble-I	Metamorphic	Consists mainly of fine-grained calcite crystals interlocked with each other. Slightly metamorphosed.
Marble-II	Metamorphic	Formed by entirely coarse calcite crystal that is arranged in an interlocking pattern. Slightly to medium metamorphosed
Amphibolite	Metamorphic	Amphibole and plagioclase are main minerals. Amphibole partly altered to chlorite. Garnet, sphene and epidotic can be observed in different dimensions
Vitric tuff	Pyroclastic	Perlitic texture. Composed mainly quartz, rock fragments and plagioclase that are the within the vitreous groundmass

4. Physical properties

Physical properties of the samples including dry density (ρ_d), saturated density (ρ_{sat}), effective porosity (P_e), total porosity (P_T), water absorption (W_a) and specific gravity (G_s) were determined according to ASTM-C 830 (2000). This method is suitable for the samples tested in this study because they have no friable and swelling potentials. Five samples from each stone type in cylindrical form were used and then the mean values were obtained (Table 2). According to the rocks classification based on density and porosity suggested by Anon (1979), most samples were classified as having moderate density (2.20-2.55 g/cm^3), high density (2.55-2.75 g/cm^3), and low porosity (1-5%).

Table 2. Physical properties of the samples under study

Rock type	Dry density (g/cm^3)	Saturated density (g/cm^3)	Effective porosity (%)	Total porosity (%)	Water absorption (%)	Specific gravity
Rhyolite	2.45	2.49	4.15	6.49	1.69	2.62
Ignimbrite	2.63	2.64	1.48	1.87	0.56	2.68
Granite-I	2.63	2.65	1.26	1.87	0.48	2.68
Granite-II	2.58	2.58	0.91	1.90	0.35	2.63
Dacite	2.59	2.59	0.96	1.53	0.37	2.62
Travertine-I	2.38	2.41	3.36	11.52	1.41	2.69
Travertine-II	2.41	2.44	2.93	10.07	1.22	2.68
Limestone-I	2.70	2.71	0.37	1.46	0.14	2.74
Dolomitic Limestone	2.68	2.69	0.77	1.11	0.29	2.71
Limestone-II	2.68	2.69	0.46	1.47	0.17	2.72
Marble-I	2.75	2.76	0.22	0.72	0.08	2.77
Marble-II	2.69	2.70	0.44	1.10	0.16	2.72
Amphibolite	3.06	3.07	0.35	0.97	0.12	3.09
Vitric tuff	2.18	2.30	12.21	16.15	5.61	2.60

5. Freeze-thaw test

Freeze–thaw test attempts to reproduce the stresses, which may arise inside the rock when water turns into ice. These effects are generally obtained by varying the temperature under and above 0°C on the rock samples containing a known amount of water (Rossi-Doria, 1985). For conducting the freeze-thaw test, initially the samples were saturated by submerging in domestic water and then placing in a freezer conditioned at –20°C for 12 h. Then they were thawed by placing in a water bath at 20°C for 12 h. Each complete cycle of freeze–thaw lasted for 24 h (12 h for freezing and 12 h for thawing). For each stone type, 30 freeze–thaw cycles were carried out. Two series of samples were prepared for each stone type to identify their Brazilian tensile strength, point load index and P-wave velocity before and after the treatment. The first series were utilized for determining fresh stone properties, and the second series were subjected to freeze–thaw cycles. After freeze–thaw cycles, no weight loss of the samples occurred, and no visible fractures and cracks were observed on their surface. For each engineering property, measurements were made on five samples in saturated conditions. The experimental procedure was performed according to the methods suggested by ISRM (1981).

The Brazilian tensile strength test procedure was followed in accordance with ISRM (1981). This test was conducted on the core samples having a diameter of 54.7 mm and a diameter-thickness ratio of ~2. The tensile load on the samples was applied continuously at a constant stress rate such that failure took place within 5 minutes of loading.

In this study, only axial point load test was performed on the cylindrical samples with a diameter of 54.7 mm and a thickness of 20 mm according to ISRM (1981). The results were corrected to a sample diameter of 50 mm ($I_{S(50)}$). Based on the results of point load strength tests, Travertine-II is classified as rocks with high strength (1-3 MPa), Rhyolite and Amphibolite are classified as rocks with extremely high strength (Over 10 MPa), and other samples fall into the rocks with very high strength (3-10 MPa) according to the classification suggested by Franklin and Broch (1972) (Table 3).

The P-wave velocity was determined on the cylindrical core samples with a diameter of 54.7 mm and a length 110 mm using a Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) according to the methods suggested by ISRM (1981). With the help of a polishing and lapping machine, the ends of the samples were made flat and perpendicular to the axis of the samples. Then their sides were smoothed and polished. The end surfaces of the core specimens were covered with stiffer grease to provide a good coupling between the transducer face and the samples' surface in order to maximize the accuracy of the transit time measurement. According to the rock classification based on P-wave velocity suggested by Anon (1979), most samples were classified as to have very high velocity (Over 5000 m/s), whereas Vitric tuff, and Travertine-I and Travertine-II fall into the rocks class with moderate (3500-4000 m/s) and high velocity (4000-5000 m/s), respectively (Table 3).

Table 3. Engineering properties of the fresh and deteriorated samples under study

Rock type	Brazilian tensile strength(MPa)			Point load index(MPa)			P-wave velocity(m/s)		
	Before freeze-thaw	After freeze-thaw	Percentage of decrease	Before freeze-thaw	After freeze-thaw	Percentage of decrease	Before freeze-thaw	After freeze-thaw	Percentage of decrease
Rhyolite	18.3	15.3	16.4	11.2	9.0	19.6	5390	4994	7.3
Ignimbrite	12.9	10.9	15.5	8.9	7.2	19.1	5420	5068	6.5
Granite-I	12.1	10.1	16.5	5.1	4.0	21.6	5661	5146	9.1
Granite-II	14.5	13.9	4.1	7.0	6.4	8.6	5748	5571	3.1
Dacite	18.4	17.8	3.3	12.0	11.3	5.8	5721	5556	2.9
Travertine-I	5.2	2.5	51.9	4.3	2.3	46.5	4750	4245	10.6
Travertine-II	4.1	2.6	36.6	2.7	1.5	44.4	4950	4400	11.1
Limestone-I	7.8	6.8	12.8	5.1	4.5	11.8	5921	5752	2.9
Dolomitic Limestone	10.5	9.7	7.6	5.7	5.0	12.3	6120	5939	3.0
Limestone-II	12.9	12.0	7.0	6.4	5.7	10.9	6060	5834	3.7
Marble-I	11.3	10.4	8.0	5.7	4.8	15.8	5513	5348	3.0
Marble-II	5.8	5.0	13.8	3.3	2.7	18.2	5210	5010	3.8
Amphibolite	19.2	18.4	4.2	14.9	14.1	5.4	6610	6329	4.3
Vitric tuff	11.2	8.8	21.4	7.2	5.2	27.8	3720	3265	12.2

The engineering properties of fresh and deteriorated samples are given in Table 3. As shown, the Brazilian tensile strength, point load index and P-wave velocity of all samples are decreased after the freeze–thaw action. Freeze–thaw involves deterioration and change in the engineering properties of stones.

Therefore, the engineering properties of fresh stones can be used for estimating their durability by comparison with the same properties measured after being subjected to freeze–thaw action. Hence, the percentage of decrease in the engineering properties of the samples after freeze–thaw action was calculated using the following equation:

$$\text{PDEP}\ (\%) = [(\text{FP} - \text{DP})/\text{FP}] \times 100 \qquad (1)$$

where, PDEP is the percentage of decrease in engineering properties, FP is the fresh sample properties and DP is the deteriorated sample properties.

Advantages of this Equation (1) are its simplicity and that it only needs initial engineering property (fresh engineering property) and deteriorated engineering property (after freeze-thaw test). As a result, Equation (1) can be very useful for evaluating the changes in the engineering properties due to freeze-thaw action and thus making a rapid durability assessment.

Table 3 and Fig. 1 show the percentage of decrease in the samples' engineering properties. The engineering properties measured after freeze–thaw treatment showed a decrease in their Brazilian tensile strength, point load index and P-wave velocity, changing within the range of 3.3–51.9%, 5.4–46.5% and 2.9–12.2%, respectively. The Brazilian tensile strength and point load index were found to be affected the most, whereas the P-wave velocity was affected the least. As seen from Fig. 1, the percentage of decrease in the engineering properties for Travertine-I, Travertine-II and Vitric tuff was the most, whereas it was the least for Dacite, Amphibolite and Granite-II. Fig. 1 also shows that the percentage of decrease in the engineering properties of the rock samples has no meaningful relation based on the rock type. Indeed, the rock type alone (at least for the samples used here) does not provide enough information regarding the samples' durability against freeze-thaw action.

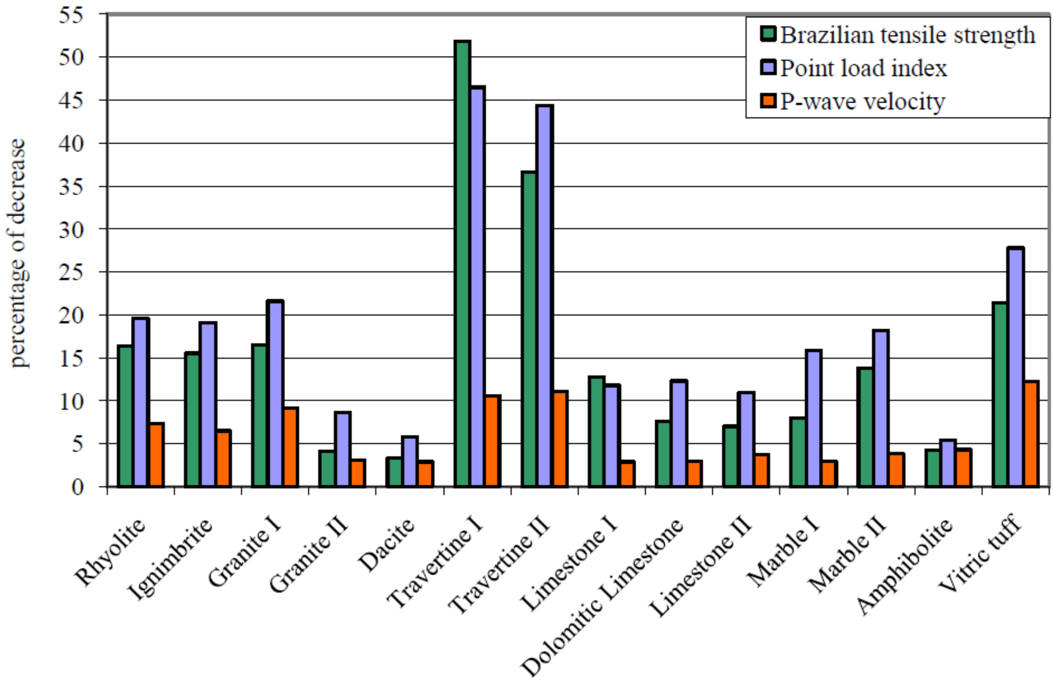


Fig. 1. The percentage of decrease in the samples' engineering properties after freeze-thaw action

6. Statistical analysis of the test results

Among the most common accepted methods of investigating empirical relationships between rock properties, such as engineering and physical properties, are simple and multiple regression analyses. In this study, we employed both the simple and multiple regression analyses for estimating the samples' engineering properties after freeze-thaw action using their initial engineering and physical properties.

6.1. Simple regression analysis

Effective porosity governs water absorption, total porosity and the magnitude of stresses generated when water turns into ice. Therefore, water absorption and total porosity can be closely related to the samples' engineering properties after freeze–thaw action. In order to investigate the relationship between the percentage of decrease in the samples' engineering properties after freeze–thaw and their initial engineering and physical properties, linear ($y = ax + b$), non-linear ($y = ax^b$), exponential ($y = ae^x$) and logarithmic ($y = a + \ln x$) regression analyses were performed. The authors attempted to develop the best correlation between different variables to attain the most reliable empirical equation. The equation of the best-fit line, the 95% confidence level, and the determination coefficient (R^2) were calculated for the above relationships. Fig. 2 shows the relationship between the percentage of decrease of the samples' engineering properties and water absorption. There are power (R^2=0.379) and logarithmic (R^2=0.415) relationships between the percentage of decrease of BTS and $I_{S(50)}$, and water absorption of the samples, respectively:

$$PDEP(BTS)=16.46\ W_a^{0.4153} \quad R^2=0.379 \qquad (2)$$

$$PDEP(Is_{(50)})=6.8428\ln(W_a)+25.004 \quad R^2=0.415 \qquad (3)$$

A good logarithmic relationship was obtained between the percentage of decrease of V_P and water absorption with R^2 of 0.728 according to the equation below:

$$PDEP(V_P)=2.4545\ln(W_a)+8.0717 \quad R^2=0.728 \qquad (4)$$

According to Equations (2) to (4), water absorption showed stronger correlation with the percentage of decrease of V_P (R^2=0.728) when compared with the correlation between the percentage of decrease of BTS and $I_{S(50)}$, and water absorption (R^2=0.379 and R^2=0.415, respectively).

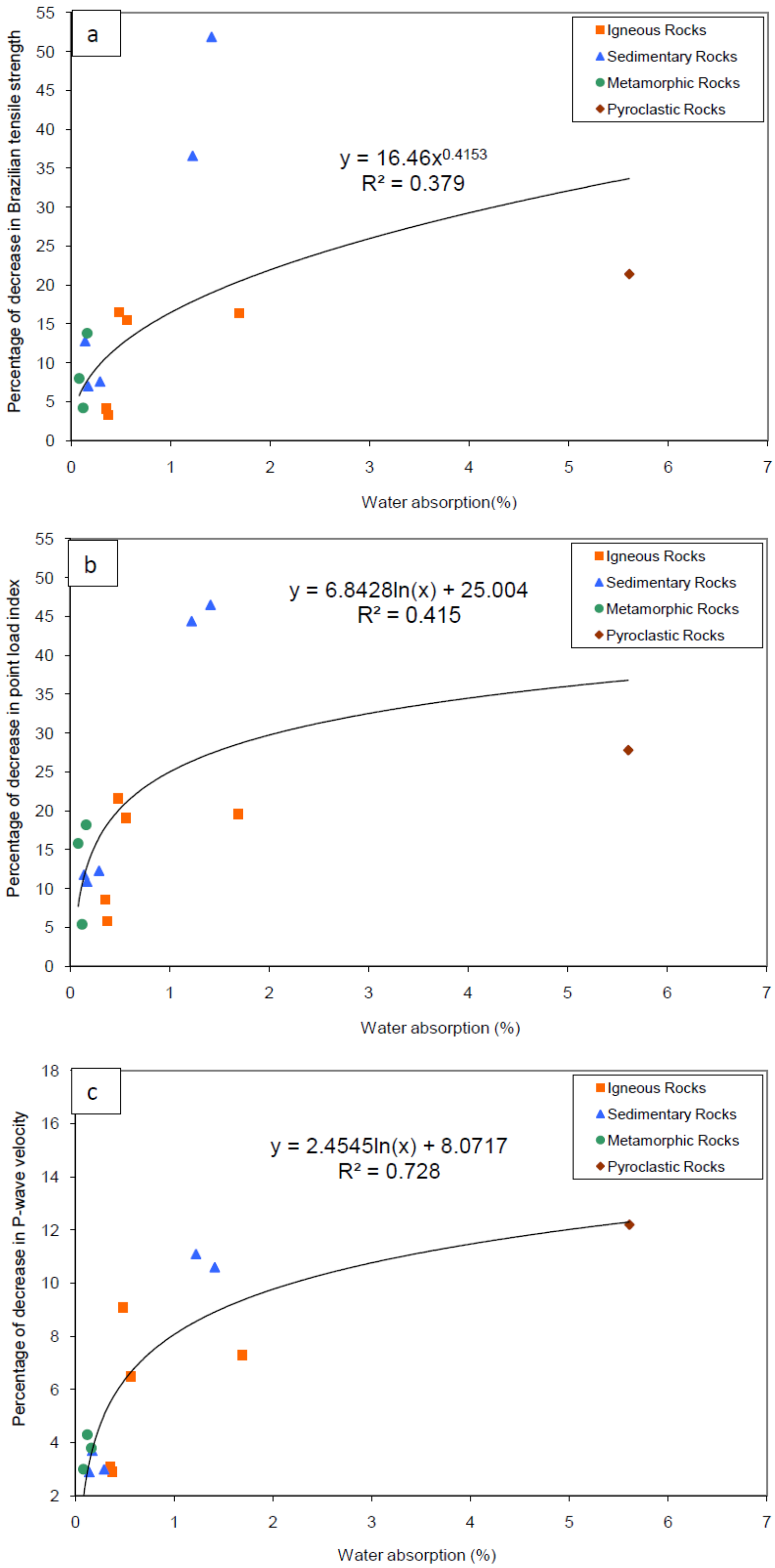


Fig. 2. The relationship between the samples' water absorption and the percentage of decrease in their (a) Brazilian tensile strength (b) point load index (c) P-wave velocity after freeze-thaw action

The relationships between the percentage of decrease of the samples' engineering properties and total porosity are presented in Fig. 3. As shown, in all cases, the best-fitted correlation is represented by logarithmic regression curves. The equations for the relationship between the percentage of decrease of BTS and $I_{S(50)}$, and total porosity of the samples are:

$$PDEP(BTS)=10.353\ln(P_T)+6.533 \quad R^2=0.599 \qquad (5)$$

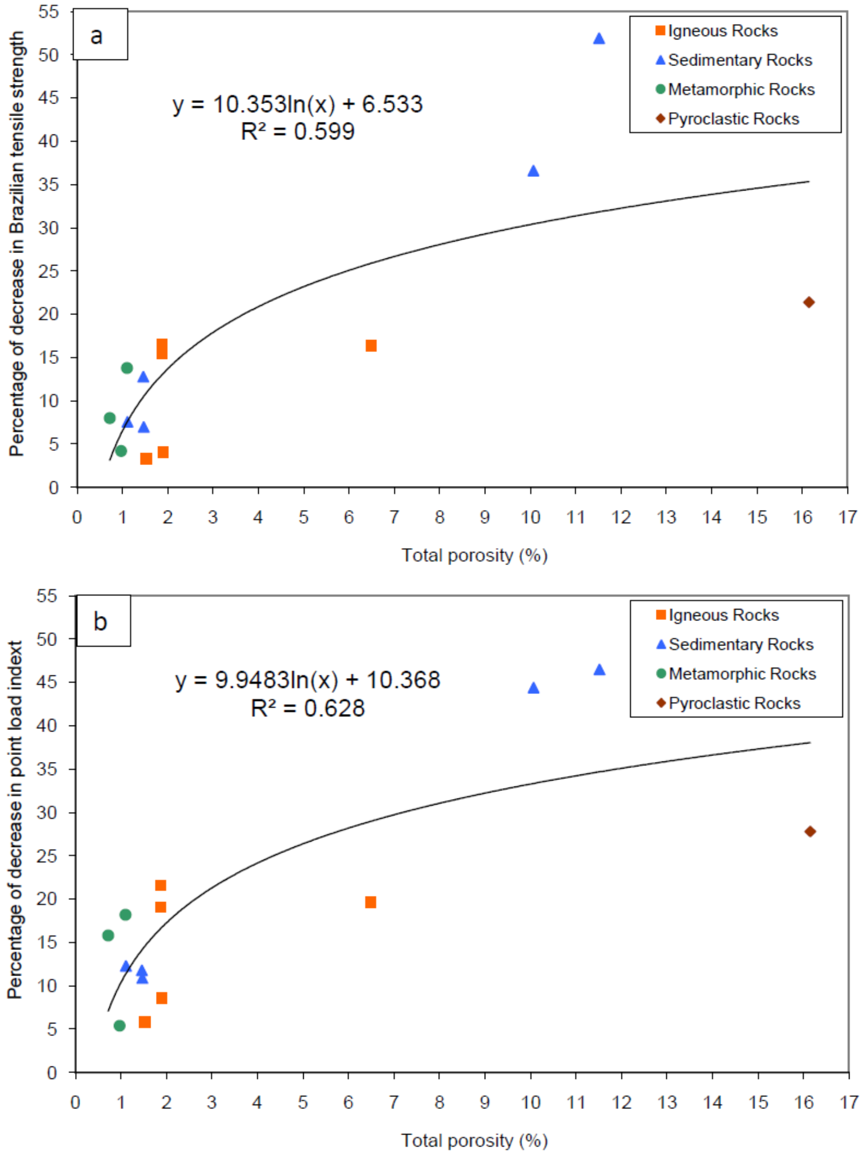
$$PDEP(Is_{(50)})=9.9483\ln(P_T)+10.368 \quad R^2=0.628 \qquad (6)$$

There is a R^2 of 0.599 between the percentage of decrease of BTS and the total porosity, and it is 0.628 between the percentage of decrease of $I_{S(50)}$ and total porosity.

Similarly, a logarithmic relationship was observed between the percentage of decrease of V_P and total porosity with higher R^2 using the equation:

$$PDEP(V_P)=3.0163\ln(P_T)+3.308 \quad R^2=0.788 \qquad (7)$$

Comparison of determination coefficient Equations (5) to (7) shows that the correlation between the percentage of decrease of V_P and total porosity is more reliable than the correlation between the percentage of decrease of BTS and $Is_{(50)}$, and total porosity.



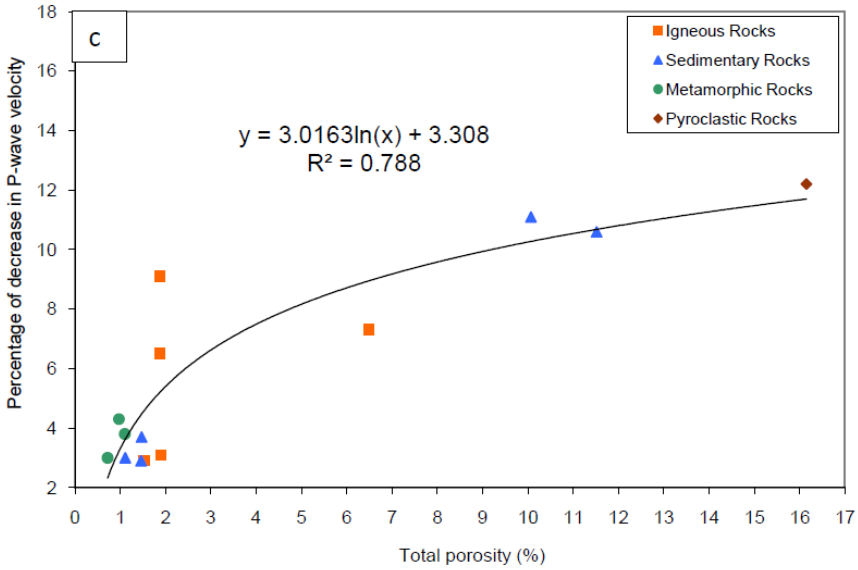


Fig. 3. The relationship between the samples' total porosity and the percentage of decrease in their (a) Brazilian tensile strength (b) point load index (c) P-wave velocity after freeze-thaw action

In general, Figs. (2) and (3) show that, although the trend of data shows very rough relationship between the percentage of decrease in the samples' engineering properties, water absorption and total porosity, due to inappropriate distribution, data scatter, and low to moderate R^2, there is no meaningful relationship between them. In fact, this implies that, in addition to water absorption and total porosity, other properties of the samples also have effect on the changes of the samples' engineering properties after freeze–thaw action.

Fig. 4 shows the relationship between initial engineering properties and the percentage of decrease in engineering properties after freeze–thaw test. The R^2 between the initial properties (Brazilian tensile strength, point load index and P-wave velocity) and the percentage of decrease in engineering properties is 0.530, 0.444 and 0.590, respectively. The equations of these correlations are as shown below:

$$PDEP(BTS)=-20.6\ln(BTS_0)+64.388 \quad R^2=0.530 \quad (8)$$

$$PDEP(Is_{(50)})=83.95\, Is_{(50)0}^{-0.903} \quad R^2=0.444 \quad (9)$$

$$PDEP(V_P)=-19.1\ln(V_{P0})+170.28 \quad R^2=0.590 \quad (10)$$

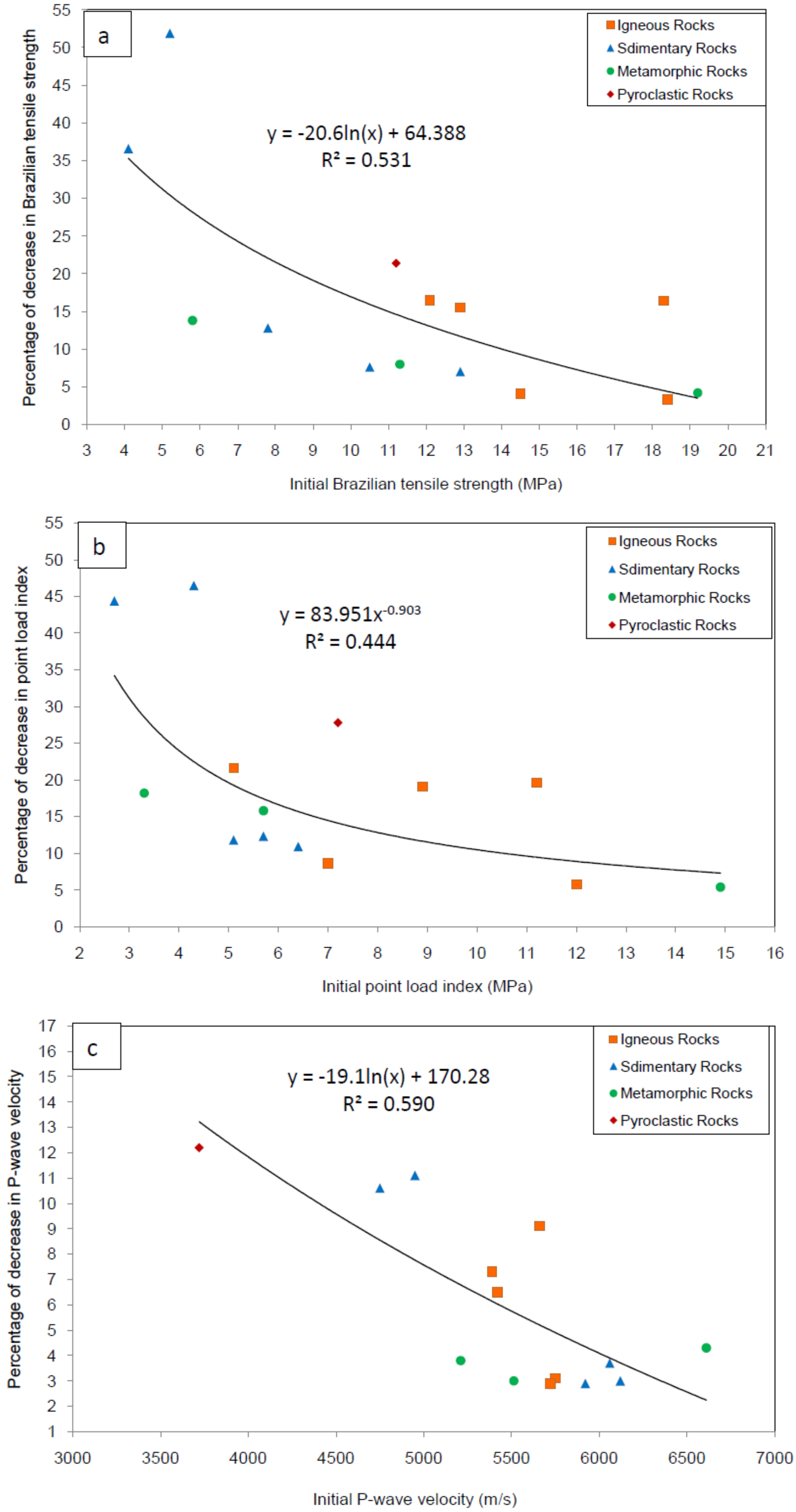


Fig. 4. The relationship between the percentage of decrease in the samples' (a) Brazilian tensile strength and their initial values (b) point load index and their initial values (c) P-wave velocity and their initial values

From this analysis, it is concluded there is not a specific meaningful difference between the initial engineering properties and the percentage of decrease in engineering properties after freeze–thaw test. With respect to the results of simple regression analysis, none of the initial engineering and physical properties alone (at least for the samples used here) can provide enough information for estimating the samples' engineering properties after freeze–thaw action. The results of simple regression analysis and the coefficients are summarized in Table 4.

Table 4. Results of the simple regression analysis tested samples

Regression equations	Determination coefficient (R^2)
$PDEP(BTS)=16.46\ W_a^{0.4153}$	0.379
$PDEP(BTS)=10.353\ln(P_T)+6.533$	0.599
$PDEP(BTS)=-20.6\ln(BTS_0)+64.388$	0.531
$PDEP(Is)=6.8428\ln(W_a)+25.004$	0.415
$PDEP(Is_{(50)})=9.9483\ln(P_T)+10.368$	0.628
$PDEP(Is_{(50)})=83.95\ Is_{(50)0}^{-0.903}$	0.444
$PDEP(Pw)=2.4545\ln(W_a)+8.0717$	0.728
$PDEP(Vp)=3.0163\ln(P_T)+3.308$	0.788
$PDEP(Vp)=-19.1\ln(Vp_{\ 0})+170.28$	0.590

PDEP(BTS): Percentage of decrease in Brazilian tensile strength after freeze-thaw; PDEP($Is_{(50)}$): Percentage of decrease in point load index after freeze-thaw; PDEP(Vp): Percentage of decrease in P-wave velocity after freeze-thaw; BTS_0: Initial Brazilian tensile strength; $Is_{(50)0}$: Initial point load index; Vp_0: Initial P-wave velocity; W_a: Water absorption; P_T: Total porosity

6.2. Multiple regression analysis

Multiple regression analysis was used for estimating the samples' engineering properties after freeze-thaw action. In this analysis, the engineering properties after freeze-thaw were considered to be variables dependent on the initial engineering and physical properties. The best-fit curves were determined using the least square method, and the fitting quality was investigated by R^2, standard error of estimate (SEE) and plots of measured versus estimated values of engineering properties after freeze-thaw. The equation of the best fit line, the 95% confidence level and R^2 was determined for each equation. The general equation for estimating the engineering properties after freeze-thaw is expressed as shown below:

$$E = \beta_0 + \beta_1 P + \beta_2 E_0 \quad (11)$$

where, E is the estimated value of the samples' engineering properties after 30 cycles of freeze–thaw action, P is the physical properties (water absorption or total porosity) of the fresh samples, E_0 is the engineering properties of the fresh samples, β_0 is a constant, and β_1 and β_2 are the regression coefficients of P and E_0, respectively.

The method of least-squares estimates the coefficients, which minimize the sum of squared deviations between the fitted and measured data. The best estimate of a coefficient is the minimum value of the residual sum of squares in the regression model to bring the curve close to the data points. The data given in Tables 2 and 3 have been analyzed and the results are shown in Table 5.

Table 5. Proposed models for estimating the samples' engineering properties after freeze-thaw test from Eq (11)

Regression equations	Tabulated F-ratio	F-ratio	Determination coefficient (R^2)	SEE
$BTS = -1.215-0.343\ W_a + 1.008\ BTS_0$	3.98	308.39	0.982	0.721
$BTS = -0.595-0.125\ P_T + 0.973\ BTS_0$	3.98	391.71	0.986	0.641
$Is_{(50)} = -0.759-0.277\ W_a + 0.983\ Is_{(50)0}$	3.98	356.05	0.985	0.468
$Is_{(50)} = -0.430-0.095\ P_T + 0.957\ Is_{(50)0}$	3.98	491.20	0.989	0.400
$Vp = -832.194-13.382\ W_a -+1.097\ Vp_0$	3.98	232.23	0.977	131.33
$Vp = 55.027+-27.28\ P_T + 0.954\ Vp_0$	3.98	333.99	0.984	109.90

BTS: Estimated Brazilian tensile strength after freeze-thaw; $Is_{(50)}$: Estimated point load index after freeze-thaw; Vp: Estimated P-wave velocity after freeze-thaw; BTS_0: Initial Brazilian tensile strength; $Is_{(50)0}$: Initial point load index; Vp_0: Initial P-wave velocity; W_a: Water absorption; P_T: Total porosity

The degree of fit to a curve can be measured by the value of R^2 (Johnson and Wichern, 1999) and the standard error of estimate (SEE). Values of R^2 and SEE for each engineering property determination of sample due to freeze-thaw action are given in Table 5.

Values of R^2 for the equations given in Table 5 show that the proposed models fit the data well and are capable of estimating the samples' engineering properties after freeze-thaw action. In addition, the SEE values for the above mentioned models are at acceptable level. These measures show that the models given in Table 5 can be accepted as a highly reliable tool for estimating the samples' engineering properties after cycles of freeze-thaw with the coefficients given in Table 5. The regression models (Table 5) were plotted in 3-D format with scattered experimental data (Figs. 5-7).

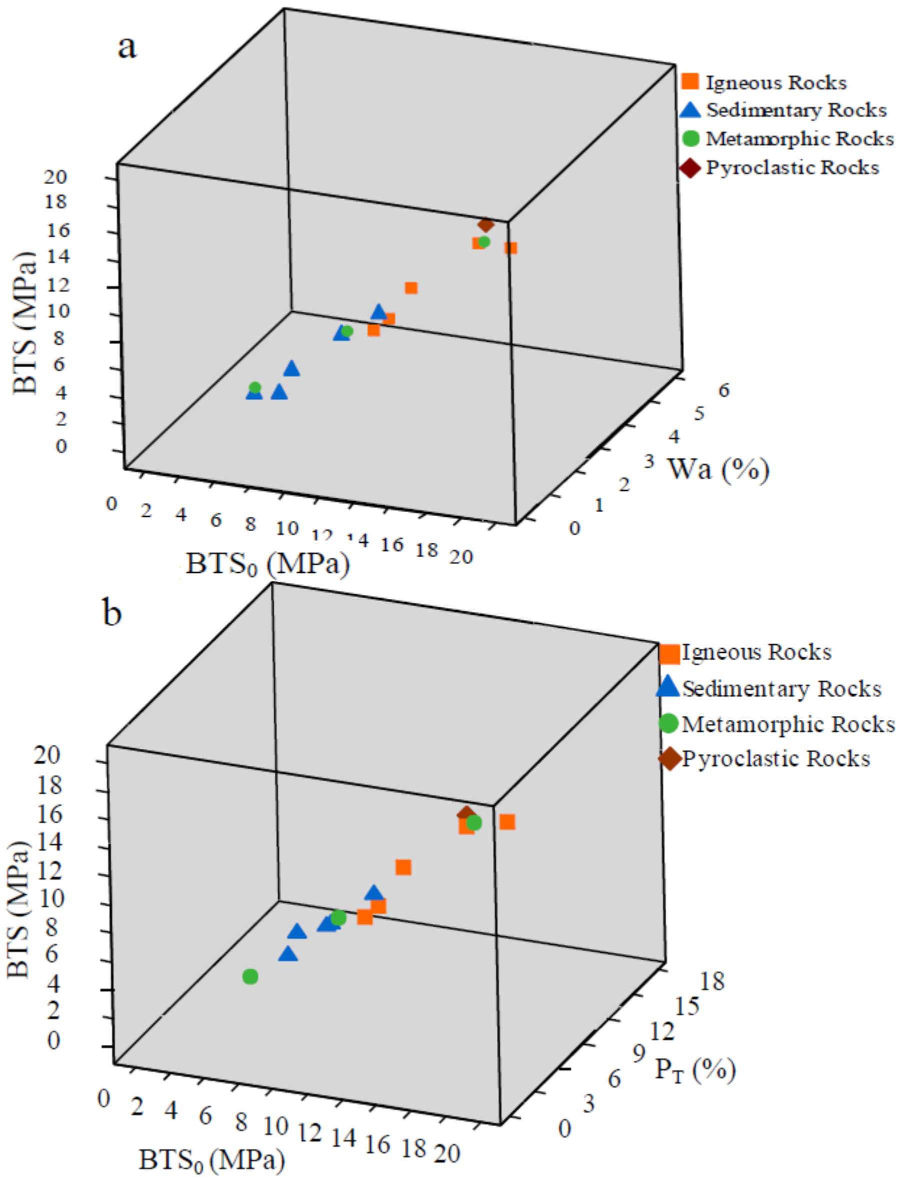
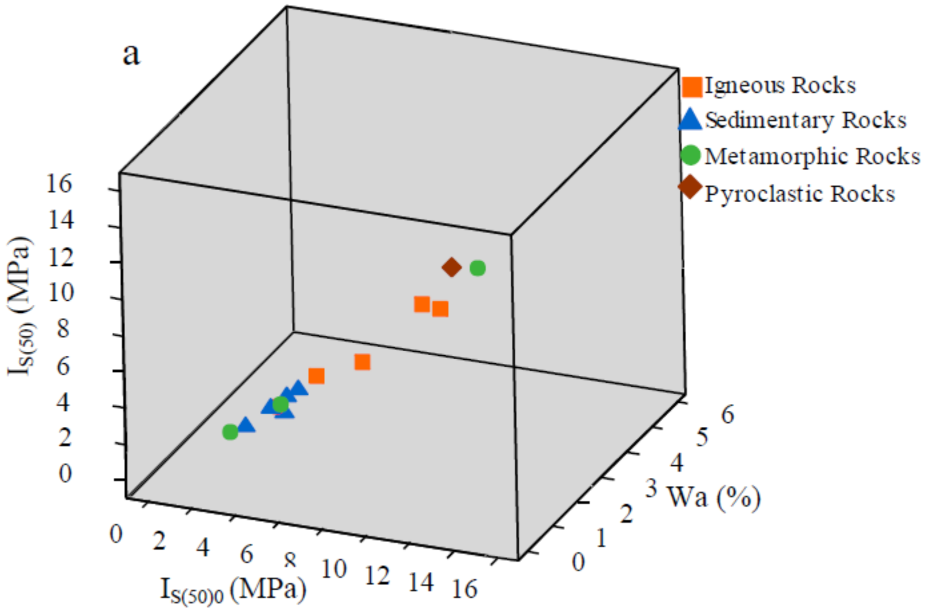


Fig. 5. The regression models after (a) BTS =-1.215-0.343 W_a +1.008 BTS_0 and (b) BTS =-0.595-0.125 P_T +0.973 BTS_0 with scattered experimental data



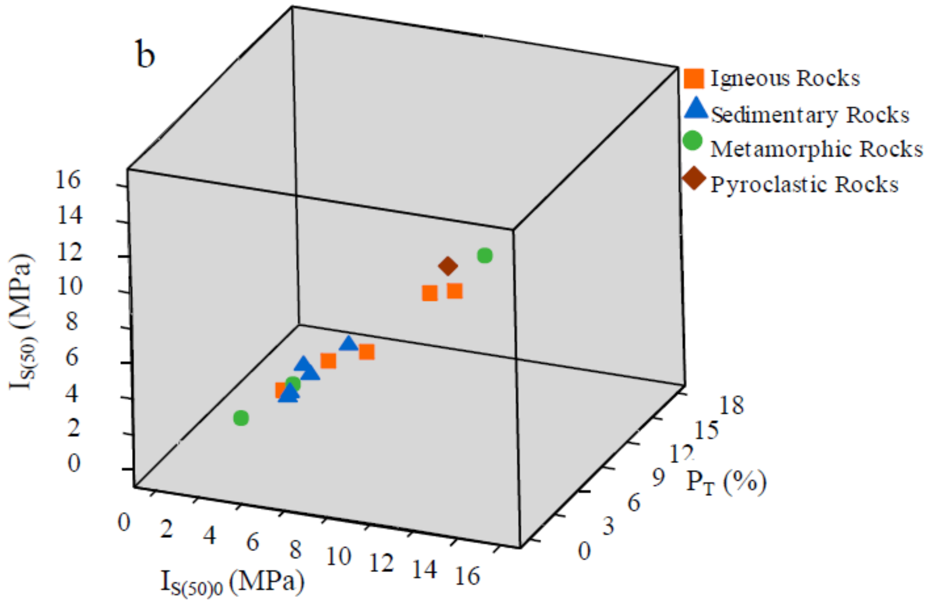


Fig. 6. The regression models after (a) $Is_{(50)}$ =-0.759-0.277 W_a +0.983 $Is_{(50)0}$ and (b) $Is_{(50)}$ =-0.430-0.095 P_T +0.957 $Is_{(50)0}$ with scattered experimental data

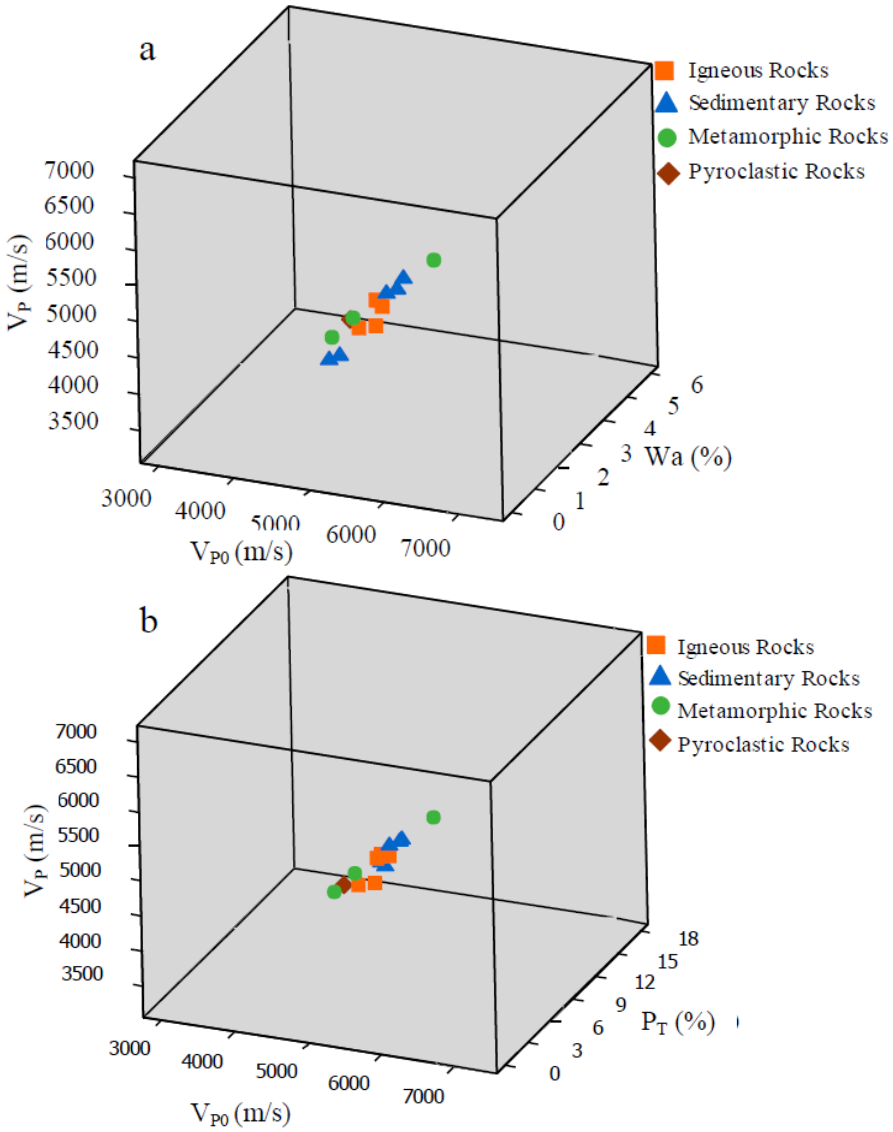


Fig. 7. The regression models after (a) $Vp = -832.194 - 13.382\ W_a - +1.097\ Vp_0$ and (b) $Vp = 55.027 + -27.28\ P_T + 0.954\ Vp_0$ with scattered experimental data

To test the global usefulness of the proposed models, analysis of variance for the regressions (ANOVA) was also performed. F-distribution test is widely used in regression and analysis of variance. The null hypothesis for this test is H_0: $\alpha_1 = \alpha_2 = 0$ against the alternative hypothesis H_1: at least one of α_1 or α_2 is not equal to zero. The results of analysis of variance for the regressions are given in Table 4. For a 95% level of confidence, the tabulated F-ratio with the degree of freedom $\upsilon_1=2$ and $\upsilon_2=11$ is 3.98. Since the computed F-ratios of the models in all cases are greater than the tabulated F-ratios, the null hypothesis is rejected. Then it is concluded that there is a clear relationship between the samples' engineering properties after freeze-thaw action and their initial engineering and physical properties, so the models are appropriate for estimating the engineering properties after freeze-thaw.

The statistical models proposed in Table 5 were evaluated by comparing their results with each other. The estimated values of engineering properties after freeze-thaw action were then plotted versus the measured values for all samples using 1:1 slope line (Figs. 8–10). A point lying on the line indicates an exact estimation. The Figs. indicate that the data points are scattered uniformly around the 1:1 slope line, suggesting that the models with the suggested coefficients are appropriate for estimating the engineering properties of the samples after freeze-thaw cycles.

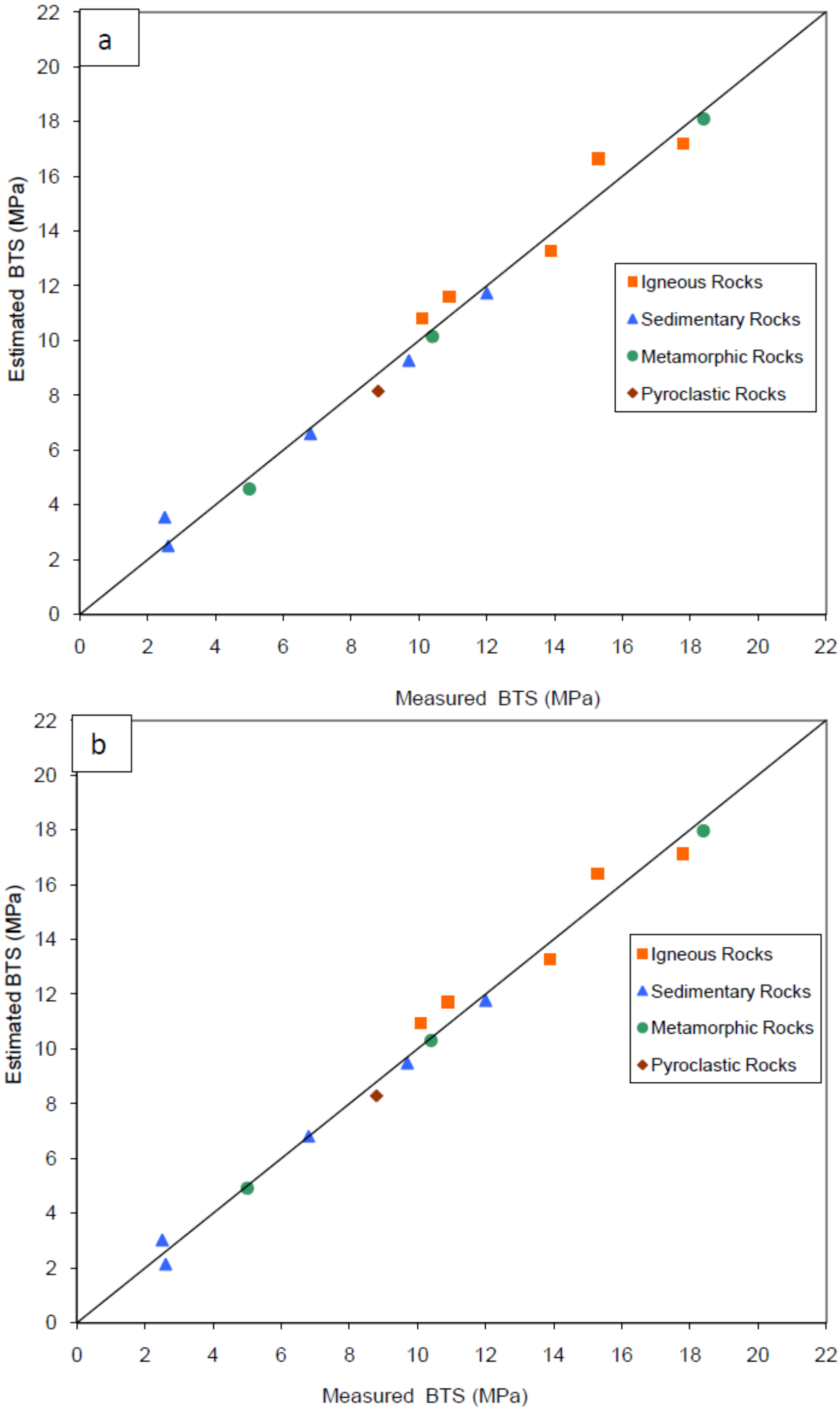


Fig. 8. Measured BTS versus estimated BTS from (a) BTS =-1.215-0.343 W_a +1.008 BTS_0 (b) BTS =-0.595-0.125 P_T +0.973 BTS_0

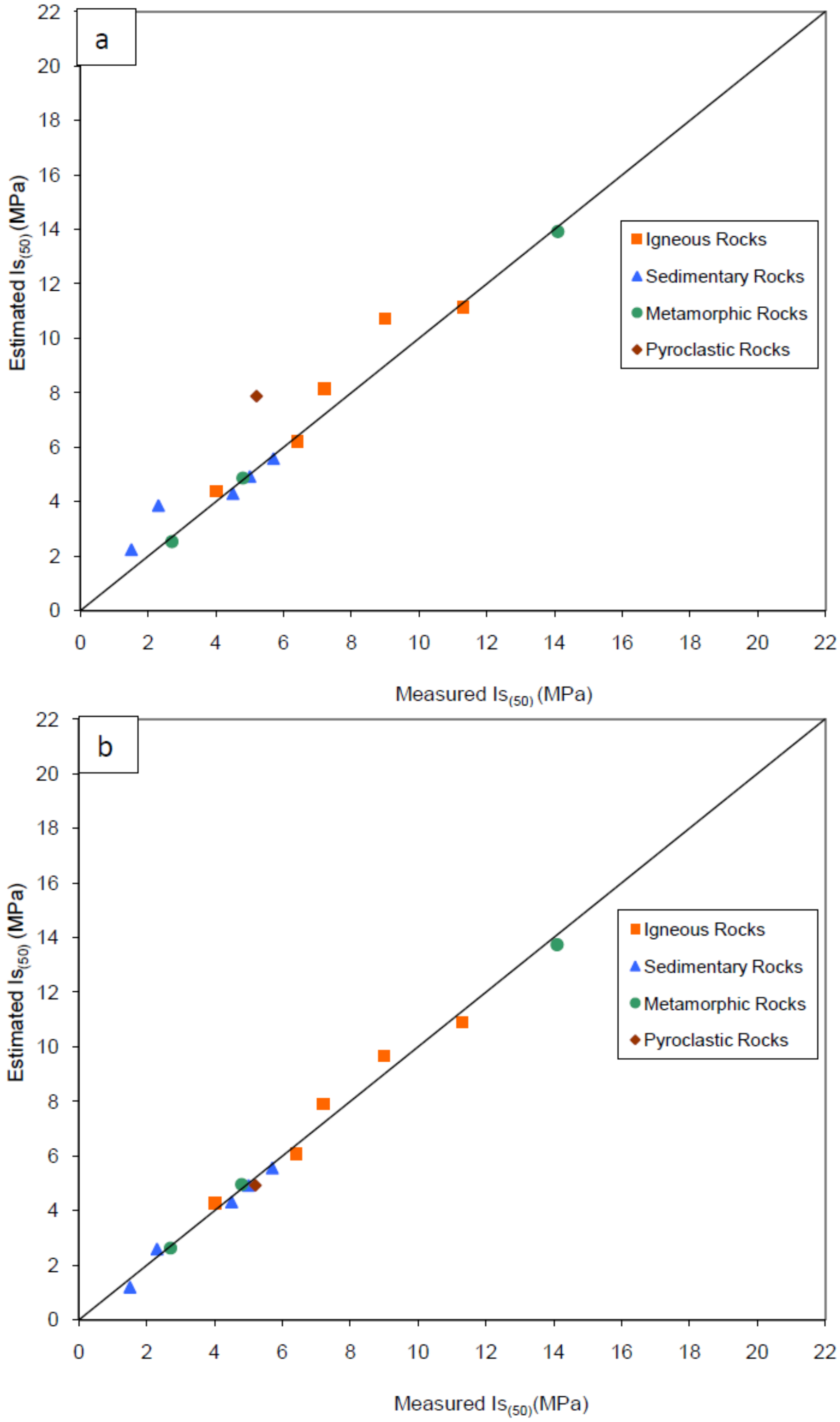
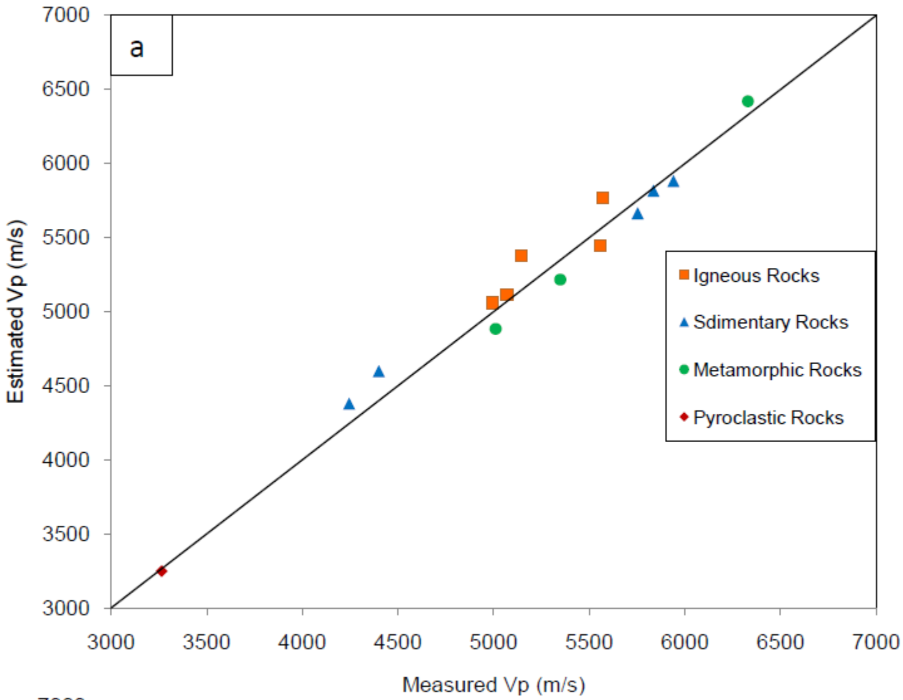


Fig. 9. Measured $Is_{(50)}$ versus estimated Is from (a) $Is_{(50)}$ =-0.759-0.277 W_a +0.983 $Is_{(50)0}$ and (b) $Is_{(50)}$ =-0.430-0.095 P_T +0.957 $Is_{(50)0}$



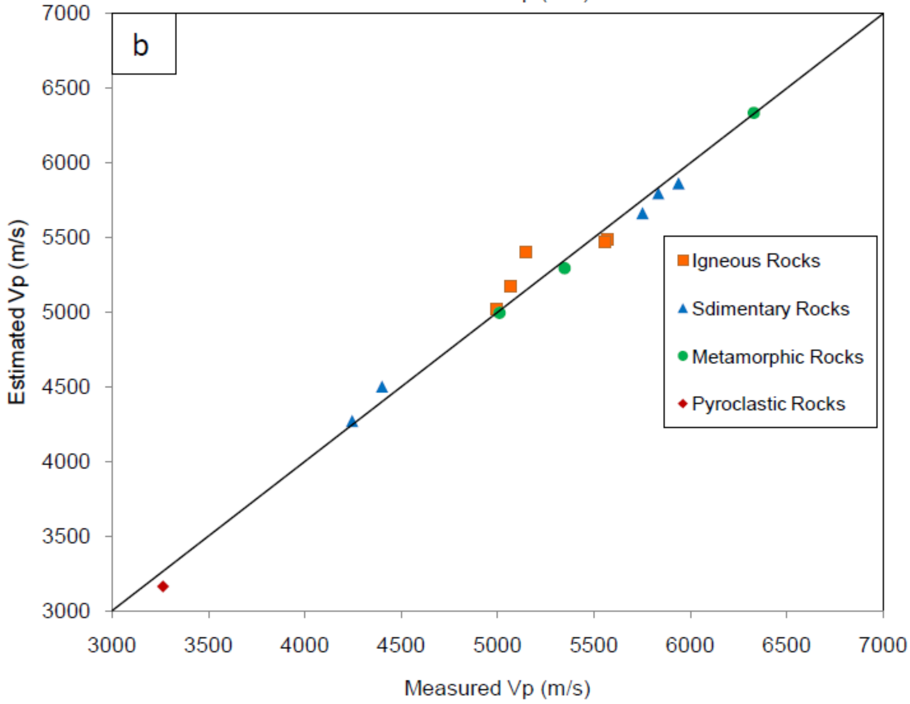


Fig. 10. Measured Vp versus estimated Pw from (a) Vp =-832.194-13.382 W_a -+1.097 Vp_0 and (b) Vp =55.027+-27.28 P_T +0.954 Vp_0

7. Conclusions

In this study laboratory testing was carried out on 14 different stones to investigate their petrographical, engineering and physical properties. Additionally, freeze-thaw action for 30 cycles was simulated and the engineering properties of the samples (including Brazilian tensile strength, point load index and P-wave velocity) were determined. The results showed that none of the rock type, and their initial engineering and physical properties alone (at least for the samples used here) could provide enough information for estimating the samples' engineering properties after freeze-thaw action, although there is a moderate correlation between them. However, there is a high correlation between the samples' engineering properties after freeze-thaw action and their initial engineering and physical properties, when both are considered. These results demonstrate the importance of both initial engineering and physical properties on the samples' durability against freeze-thaw action. The statistical models for estimating the samples' engineering properties after freeze-thaw action were developed using both the initial engineering and physical properties. The models were developed by multiple regression analysis, and verified using statistical tests. The application of the models is that by measuring one initial engineering property and one physical property of the stone, its durability can be estimated against freeze-thaw action. Consequently, these models save much time and provide significant advantages for rapid durability assessment of stones.

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