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Effect of Freezing and Thawing on Physical and Mechanical Properties of Sedimentary Rock

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Abstract

Rocks have been used as a building material throughout the history. The Engineering Properties of rocks mainly depends on mineralogical composition and texture of the rock type. Weathering processes influence the rock porosity in cold climate area. This paper studies the effect of weathering (freezing thawing cycles) on physical and mechanical properties of specific types of rock (sedimentary rocks). Freeze–thaw cycles is one of the most important phenomena affecting the engineering properties of rocks. This study was conducted based on literature data to analyze the durability and stability of rocks throughout the physical and mechanical properties such as (density, porosity, Brazilian tensile strength, unconfined compressive strength and point load Index) of sedimentary rock specimens exposed to excessive amount freezing-thawing cycles. Key factors that affecting the strength of frozen rocks were analyzed. Results showed that porosity and the intensity of freezing-thawing cycles influenced Engineering properties of sedimentary rocks significantly. The loss in unconfined compressive strength is an important indicator for rock strength and durability However, this test is extremely expensive and tedious. Therefore, different correlations and Statistical models were developed using multiple regression analyses to predict the mechanical properties of rocks such as unconfined compressive strength and tensile strength from other physical properties and corresponding to specified number of F-T cycles. The models are very reliable with R^2= 95% and can be used to predetermination of unconfined compressive strength and tensile strength of sedimentary rocks.

Keywords Freezing-Thawing cycles, Sedimentary Rocks, UCS, Brazilian tensile strength (BTS), Point Load index ($I_{s(50)}$), Pulse velocity (Vp), Dry density (γd).

1. Introduction

In the history, natural stones were used to construct many amphitheaters, arenas, statues and monuments and nowadays rocks are used in shape of polished slabs for wall cladding of the buildings (Akin and Ozsan, 2011). Sedimentary rocks is one of the most popular types of rock used in constructions, it faces engineers as a foundation material, building stone and as face cladding material. The reason behind using Sedimentary rocks so widely in construction is their abundance in nature (Pettijohn et al., 2012). Another reason is that some sedimentary rocks have high strength and durability (Hale and Shakoor, 2003).

In literature the strength and durability of sedimentary rocks has been studied frequently and considered to be relatively proportional (Shakoor and Bonelli, 1991; and Bell, 1992). Also they reported that density is directly proportional with compressive strength, while porosity and percentage absorption are inversely proportional with compressive strength. Hale and Shakoor, (2003) have stated that the percentage of cementation material are directly proportional with compressive strength.

In general there are many physical processes that affect the strength and durability of rocks and causes disintegration of the rocks as result of the climate changes, such as wetting–drying, heating–cooling, and freezing– thawing (F-T) cycles.

According to another research heating–cooling cycles has less effect on disintegration of rocks while freezing and thawing cycles is the most detrimental physical processes that affect rock durability and disintegration (Erguler and Shakoor, 2009).

Researchers have indicated that disintegration in rocks that caused by freeze-thaw cycles has the most paramount importance on projects such as roads, building construction, railroads and pipelines (Nicholson., 2001; Zhang et al., 2004; Chen et al., 2004; Mutluturk et al., 2004; Yavuz et al., 2006; Grossi et al., 2007; Ruedrich and Siegesmund, 2007; Tan et al., 2011). Freezing-thawing action can changing the mechanical properties of rocks rapidly. Therefore, the rock's durability should be studied prior to the selection of an appropriate building stone (Zappia et al., 1998).

Water get in to the rock's pores and freezes when temperature drop to below 0 ^{o}C, as a result the volume of the water increase up to 9% and this will generate excessive pressure inside the rock pores which is greater than the tensile strength of the rock: thus the generated pressure is quite enough to disintegrate the rock and causes primarily fractures (Lienhart, 1988). Kolay, (2016) proposed that the frozen pore water can generate a pressure up to 200 MPa.

Successive freezing-thawing cycles can cause fatigue and lead to damages of the stone (Lienhart and Stransky, 1981; Lienhart, 1988).

Many parameters has been studied by researchers to investigate the physical and mechanical properties of rocks. Compressive strength is one of the most essential parameters in designing most of the geo-engineering projects (Nazir et al., 2013; Akram and Bakar, 2016).

The method for evaluating the compressive strength in laboratory is time consuming and costs a lot, nevertheless it is not easy to obtain intact samples from highly weathered rock mass (Hyam et al., 2017). Due to the mentioned reasons other indirect testy are proposed to predict the engineering properties and durability of rocks such as Point Load Index (Is(50)), indirect tensile strength (BTS) and pulse velocity (VP) (Cargill and Shakoor, 1990; Sharma and Singh, 2008).

(Topal and Sözmen, 2000) has investigated the effect of freezing-thawing cycles on compressive strength, dry density (ρd), porosity (n) and Pulse velocity (Vp), also they have reported many relationship between the freezing-thawing (F-T) cycles and the engineering parameters of rock. Accordingly many correlation and prediction equations has been developed to predict important engineering parameters of rock such as compressive strength and tensile strength (Kolay, 2016).

This study was conducted to investigate the effect of freezing-thawing cycles on physical and mechanical properties of sedimentary rocks based on data collected from literature. Various engineering parameters of rocks has been studied such as Unconfined compressive strength (UCS), Brazilian tensile strength (BTS), Point

Load index ($I_{s(50)}$), Pulse velocity (Vp) and Dry density (ρd). simple and multiple regression analysis has been developed to predict the effect of F-T cycles on the engineering properties of sedimentary rocks.

2. Modeling

In this study different correlation and relationships has been evaluated to propose models to predict the engineering properties of rock after successive amount of F-T cycles. The proposed equation presented in Table 2.

2.1 Testing the Model's Accuracy

In order to investigate the accuracy of the proposed models in this study both the coefficient of determination (R^2) and root mean square error (RMSE) has been calculated using equations Eq. 1 and Eq. 2.

$$R^2 = \left(\frac{\sum i(xi-\bar{x})\,(yi-\bar{y})}{\sqrt{\sum i\,(xi-\bar{x})^2} * \sqrt{\sum i\,(yi-\bar{y})^2}}\right)^2 \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(yi-xi)^2}{N}} \quad (2)$$

Where

yi = actual test value.

x_i = calculated value from the model.

$\bar{y}$ = mean of actual test values.

$\bar{x}$ = mean of calculated values and

N = is the number of data points.

3. Methodology

This study was conducted depending on data from literature to investigate the physical and mechanical properties of sedimentary rocks and their changes due to successive amount of freezing-thawing cycles. The tests from the literature studies was conducted according to both standards ASTM and ISRM.

3.1 Point Load Index $I_{s(50)}$

Point load test (Points load index Is(50)) has been widely used as a quick and simple method to identify the strength of rocks. The test procedure is very simple since no need regular form specimens, ether it can be done on field. Rock specimens are tested by applying concentrated point load using two steel cones end. According to the test procedure which given by ASTM (ASTM, 2002). The load should be applied in increment so that failure should occur within 1 minute. The rock specimen will fail and crack parallel to the applied load axis due to the development of tensile strength.

4.2 Pulse velocity (Vp)

Pulse velocity techniques (Vp) have been used by many researchers for many years to analyses the rock strength parameters (Vasconceloset al., 2007). Pulse velocity can be used to evaluate the porosity as well as the rock strength. It can be correlated to predict the most important engineering parameters such as uniaxial compressive strength (UCS) with a very low costs and efforts. The test procedure and specification have been given by both standards ASTM and ISRM (Vasconceloset al., 2007).

4.3 Brazilian Tensile Strength (BT)

Brazilian Tensile Strength (BTS) is an indirect method to evaluate the engineering parameters of rocks. This test can be used to predict the tensile strength of rock and also to determine the rate of damage that can be caused by successive amount of Freezing-thawing cycles. According to the test procedure which given by ASTM (ASTM, 2008) specimens in a shape of circular disk loaded and compressed across its diameter.

4.4 Unconfined compressive strength (UCS)

The Unconfined compressive strength is one of the most essential strength parameters. It has been desired by researchers to determine the engineering strength parameters. This test can be conducted according to the standard test procedure given by ISRM (Bieniawski and Bernede, 1979). Many studies has been conducted to evaluate the effect of F-T cycles on the strength and durability of stones.

5. Results and Discussion

In order to better understand the reasons that affect the strength and durability of sedimentary rocks, each parameters has been studied separately. The collected data from literature were analyzed to determine Mean, Median, Standard deviation, Variance and coefficient of variance using statistical tools. The results are presented in Table 1. The results of this study has showed that the engineering parameters of rock such as Dry density, Porosity, Tensile strength and compressive strength are mainly affected by successive amount of freezing-thawing actions. Different correlational and regression analysis has been evaluated between the index properties and the essential engineering parameters such as compression strength and tensile strength. Also different prediction equations has been developed to predict the changes in each parameters due to successive amount of freezing-thawing actions and to predict rock strength (compression and tensile) from the physical properties such as Dry density, Porosity, Pulse velocity, Point load index. The Equations are summarized in Table 2. The results and the relationships are discussed in detail as follows:

5.1 Relationship between Porosity (n%) and Freezing-Thawing Action (F-T).

Statistical analysis has been conducted for 107 data which has been collected from literature, accordingly the data has standard deviation of 6.1 % and coefficient of variation (COV) of 47.16 %, with a mean and median of 12.93 % and 12.78 %, respectively. The results are summarized in Table 2. Fig. 1 show that the porosity ratio raised up after successive amount of F-T cycles and the prediction equation Eq. 3 is highly reliable with R^2 = 91% that can be used to predict the increases in porosity ratio accurately up to 30 F-T cycles. The model parameters are summarized in Table 2.

$$n_{(\%)} = 11.022 + \frac{N}{(0.738 + 0.381N)} \qquad (3)$$

Where

N = Freezing-Thawing Number.

5.2 Relationship between compressive strength (UCS) and Freezing-Thawing Action

Statistical analysis has been conducted for 67 data which has been collected from literature, accordingly the data has standard deviation of 26.22 MPa and coefficient of variation (COV) of 71.57 %, with a mean and median of 36.64 MPa and 28.42 MPa, respectively. The results are summarized in Table 2. Fig. 2 show that the UCS dropped sharply after successive amount of F-T cycles and the prediction equation Eq. 4 is highly reliable with R^2 = 95% that can be used to predict UCS value accurately up to 30 F-T cycles. The model parameters are summarized in Table 2.

$$UCS_{\,(MPa)} = 0.027\,N^2 - 1.33\,N + 47.7 \qquad (4)$$

5.3 Relationship between Point load index ($I_{s(50)}$) and Freezing-Thawing Action.

Statistical analysis has been conducted for 45 data which has been collected from literature, accordingly the data has standard deviation of 1.74 MPa and coefficient of variation (COV) of 46.72 %, with a mean and median of 3.76 MPa and 4.1 MPa, respectively. The results are summarized in Table 2. Fig. 3 show that the point load index has affected by successive amount of F-T cycles and the prediction equation Eq. 5 is less reliable with R^2 = 43% that can be used only to have a rough idea on the point load index value up to 30 F-T cycles. The model parameters are summarized in Table 2.

$$I_{s(50)(MPa)} = 0.0015\,N^2 - 0.0514\,N + 4.06 \qquad (5)$$

5.4 Relationship between Pulse velocity (Vp) and Freezing-Thawing Action (F-T)

Statistical analysis has been conducted for 67 data which were collected from literature, accordingly the data has standard deviation of 949 m/s and coefficient of variation (COV) of 45.9%, with a mean and median of 2069 m/s and 2147 m/s, respectively. The results are summarized in Table 2. Fig. 4 show the correlation between pulse velocity and F-T cycles and the prediction equation Eq. 6 is moderately reliable with R^2 = 84 % that can be used to predict the pulse velocity value up to 30 F-T cycles. The model parameters are summarized in Table 2.

$$Pv_{m/s} = 0.015\,N^2 - 23.86\,N + 2380.6 \quad (6)$$

5.5 Relationship between Compressive strength (UCS) and Dry density (ρd)

Statistical analysis has been conducted for 44 data which has been collected from literature, accordingly the data has standard deviation of 0.37 g/cm^3 and coefficient of variation (COV) of 18.7 %, with a mean and median of 2.02 g/cm^3 and 2.04 g/cm^3, respectively. The results are summarized in Table 2. Fig. 5 show the correlation between UCS and Dry Density and the prediction equation Eq. 7 is moderately reliable with R^2 = 74 % that can be used to predict the UCS from dry density ranged between (1.41 to 2.47) g/cm^3. The model parameters are summarized in Table 2.

$$UCS = 5.53 + \frac{\rho_d}{(0.256 + 0.076\rho_d)} \quad (7)$$

5.6 Relationship between Tensile strength (BTS) and Point load Index ($I_{s(50)}$).

Statistical analysis has been conducted for 45 data which has been collected from literature, accordingly the data has standard deviation of 3.96 MPa and coefficient of variation (COV) of 63.76 %, with a mean and median of 6.22 MPa and 5 MPa, respectively. The results are summarized in Table 2. Fig. 6 show the correlation between tensile strength and point load index and the prediction equation Eq. 8 is highly reliable with R^2 = 94 % that can be used to predict the tensile strength from ($I_{s(50)}$) ranged between (1.34 to 6.7) MPa. The model parameters are summarized in Table 2.

$$BTS_{MPa} = -0.023 + \frac{I_{S(50)}}{(0.968 + 0.076\,I_{S(50)})} \quad (8)$$

5.7 Relationship between Dry density (ρd) and Pulse velocity (Vp)

Prediction equation Eq. 9, has been proposed. The model and its parameters are summarized in Table 2 and shown in Fig. 7. The accuracy of the model was tested; accordingly, the coefficient of determination (R^2) and root mean square error (RMSE) for the proposed model were 72% and 0.17, respectively.

$$\rho d_{g/cm^3} = 0.42\ (\ln Vp) - 1.27 \quad (9)$$

5.8 Relationship between Porosity (n) and Dry Density (ρd)

Prediction equation Eq. 10, has been proposed. The model and its parameters are summarized in Table 2 and shown in Fig. 8. The accuracy of the model was tested; accordingly, the coefficient of determination (R^2) and root mean square error (RMSE) for the proposed model were 50% and 4.19, respectively.

$$n = 11.8\, {\rho_d}^2 - 33.23\, \rho_d + 33.47 \qquad (10)$$

6. Conclusion

The freezing-Thawing test is the most effective test to determine the loss in strength of rocks due to Freezing-Thawing action. However, it is not easy to conduct this test as it is very laborious and costly. In this study different correlation and prediction models has been developed to predict compression and tensile strength of rock and their loss due to successive amount of freezing-thawing actions the result of this study can be summarized as:

1. In general Freezing-Thawing cycles affect porosity and increased the rock's disintegration. Especially the first 5 F-T cycles that mostly affected porosity (n) and increased it from 11% up to 13%. Also the result of the pulse velocity test confirm that the disintegration and cracks has been increased wildly after subjecting the rock specimens to successive amount of F-T actions.
2. The result of this study has shown that the F-T action affect the rock strength. The UCS of the tested specimens has dropped sharply from almost 47 MPa to less than 32 MPa after 25 successive F-T cycles.
3. Multiple regression analysis were performed and different correlation and prediction equations has been developed between the rock strength parameters (Compressive and tensile) and the index properties. This prediction equations can be used easily to predict the loss in rocks strength parameters due to the effect of F-T actions without conducting F-T test.
4. The UCS has been correlated with dry density and modeled. The developed model is moderately reliable with R^2 = 74% and can predict USC value accurately up to 30 F-T cycles.

5. The tensile strength of sedimentary rocks has been correlated with point load index. The developed model is highly reliable with R^2 = 95% that can predict tensile strength value accurately up to 30 F-T cycles.

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Appendices

Table 1. Statistical analysis of the main parameters.

Variable	Mean	St. Dev	Variance	Coef. of Var.	Minimum	Q1	Median	Q3	Maximum
[1]ρd	2.02	0.37	0.14	18.70	1.39	1.73	2.04	2.38	2.67
[2]n	12.93	6.10	37.21	47.16	1.40	7.72	12.78	17.41	23.84
[3]F-T	19.80	12.14	147.38	61.30	5.00	10.00	20.00	25.00	50.00
[4]Vp	2069	949	901430	45.90	576	1308	2147	2729	4185
[5]$I_{s(50))}$	3.76	1.74	3.03	46.27	1.25	1.97	4.10	5.25	6.700
[6]BTS	6.22	3.96	15.73	63.76	1.09	2.70	5.0	10.15	12.90
[7]UCS	36.64	26.22	687.48	71.57	8.09	18.74	28.42	42.45	127.34

[1]ρd Dry density, [2]n Porosity, [3]F-T Freezing-thawing cycles, [4]Vp Pulse velocity

[5]$I_{s(50)}$ Point load index, [6]BTS Brazilian tensile strength, [7]UCS Unconfined compressive strength

Table 2. Proposed models

Proposed Equation	Independent Parameter	Dependent Parameter	RMSE	Coefficient of determination R^2
n = 11.022 + N/(0.738+ 0.381N)	[1]F-T cycle (N)	Porosity (n)	0.26	91 %
UCS = 0.027 N2 - 1.33 N + 47.7	F-T cycle (N)	[2]UCS	1.33	95 %
Is(50) = 0.0015 N2 - 0.0514 N + 4.06	F-T cycle (N)	Point load $I_{s(50)}$	0.17	43 %
Vp = 0.01 N2 - 23.86 N + 2380.6	F-T cycle (N)	Pulse velocity Vp	104.37	84 %
UCS = 5.53 + ρd/(0.256 - 0.076 ρd)	Dry density (ρd)	UCS	4.73	74%
BTS = -0.023 + I s(50) /(0.968 - 0.076 $I_{s(50))}$	Point load $I_{s(50)}$	Tensile strength [3]BTS	0.88	95%
ρd = 0.42 lnVp- 1.27	Pulse velocity Vp	Dry density (ρd)	0.17	72 %
n = 11.8 ρd 2 -33.23 ρd +33.47	Porosity (n)	Dry density (ρd)	5.32	50 %

[1]F-T cycles: Freezing-Thawing cycles, [2]UCS: Unconfined compressive strength

[3]BTS: Brazilian tensile strength

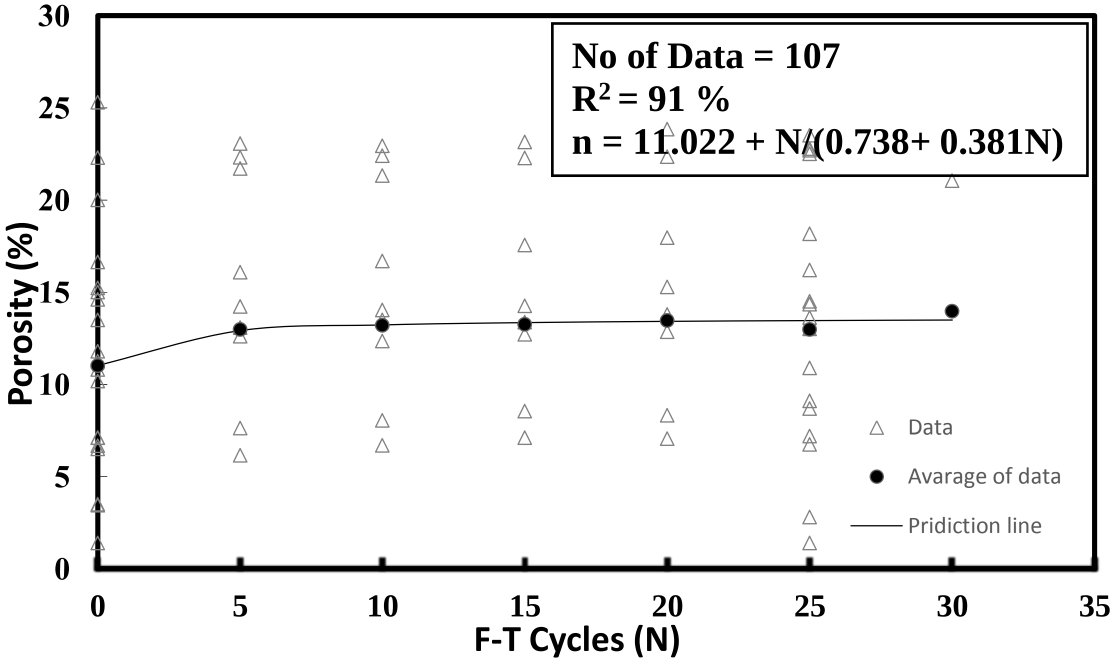

Fig1. Variation of Porosity with the number of Freezing-Thawing cycles.

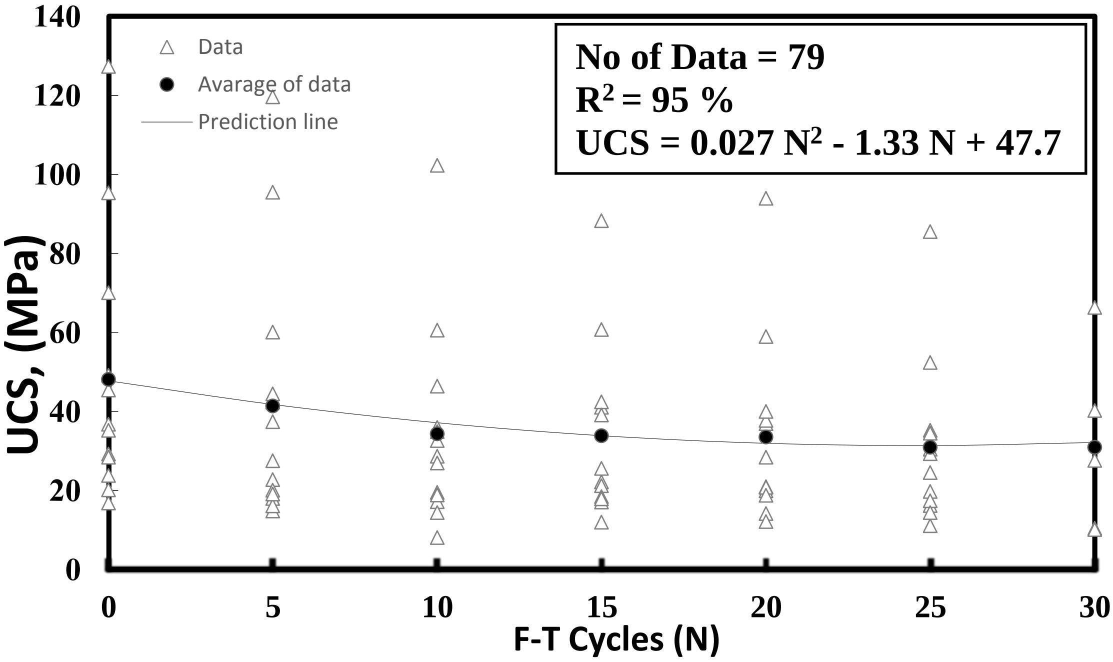

Fig 2. Variation of Unconfined compressive strength with the number of Freezing-Thawing cycles.

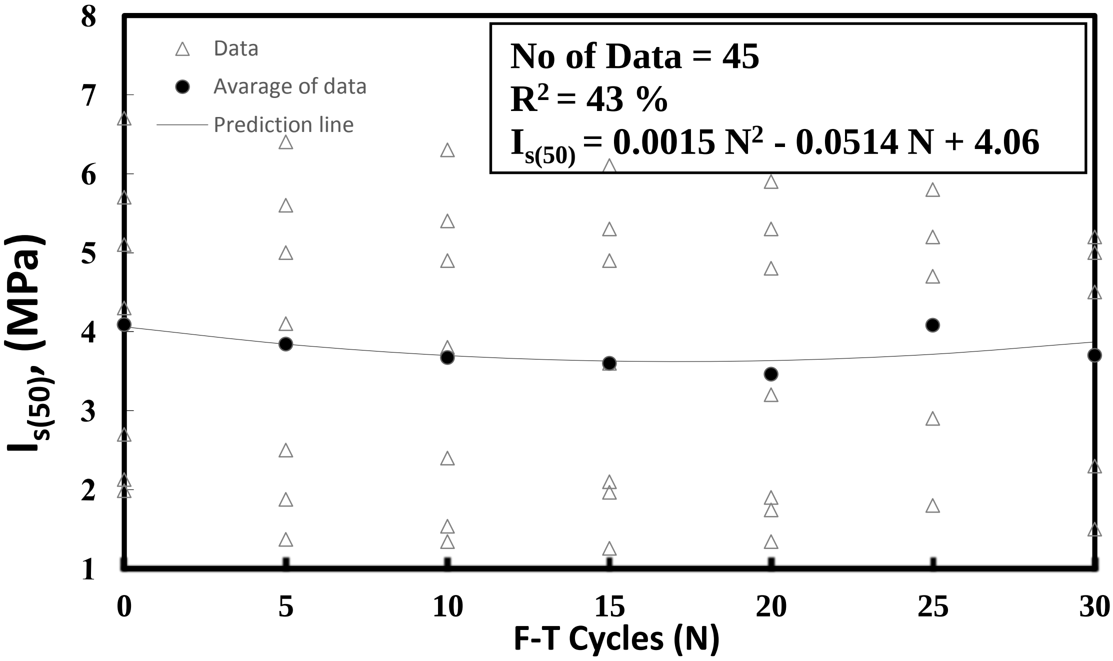

Fig 3. Variation of Point load index with the number of Freezing-Thawing cycles.

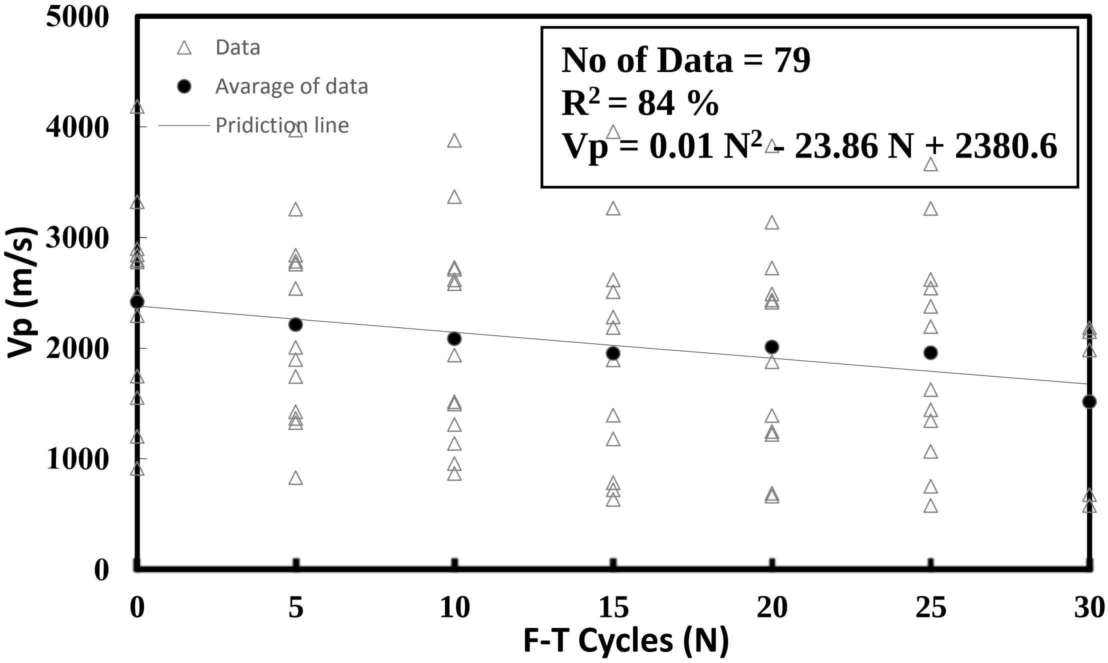

Fig 4. Variation of Pulse velocity with the number of Freezing-Thawing cycles.

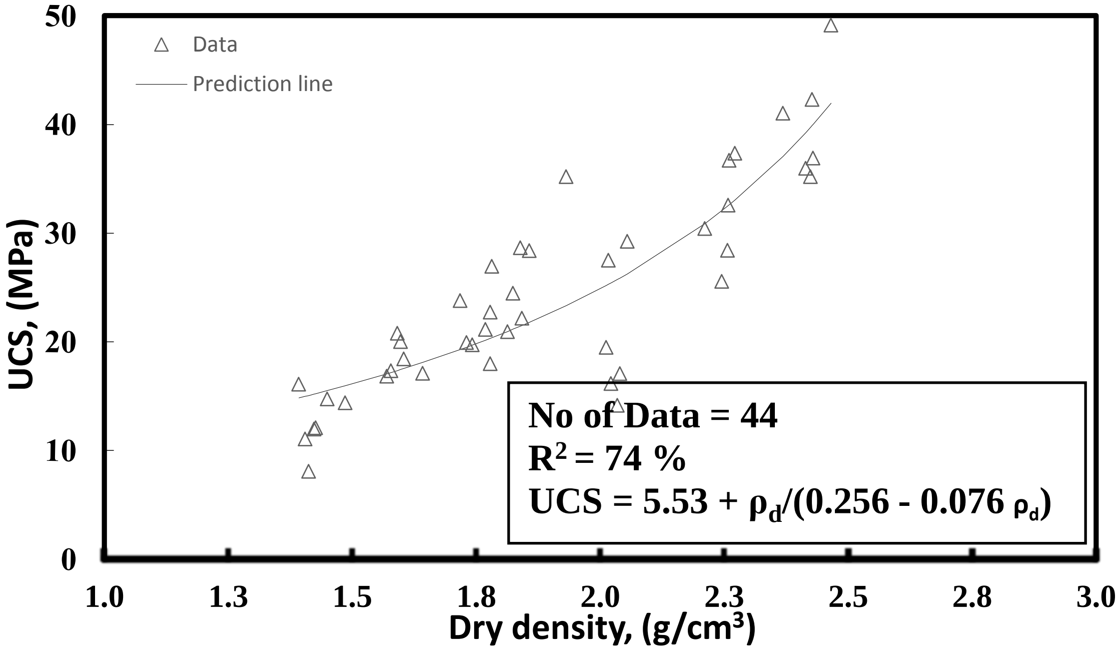

Fig 5. Relationship between Unconfined compressive strength with Dry Density.

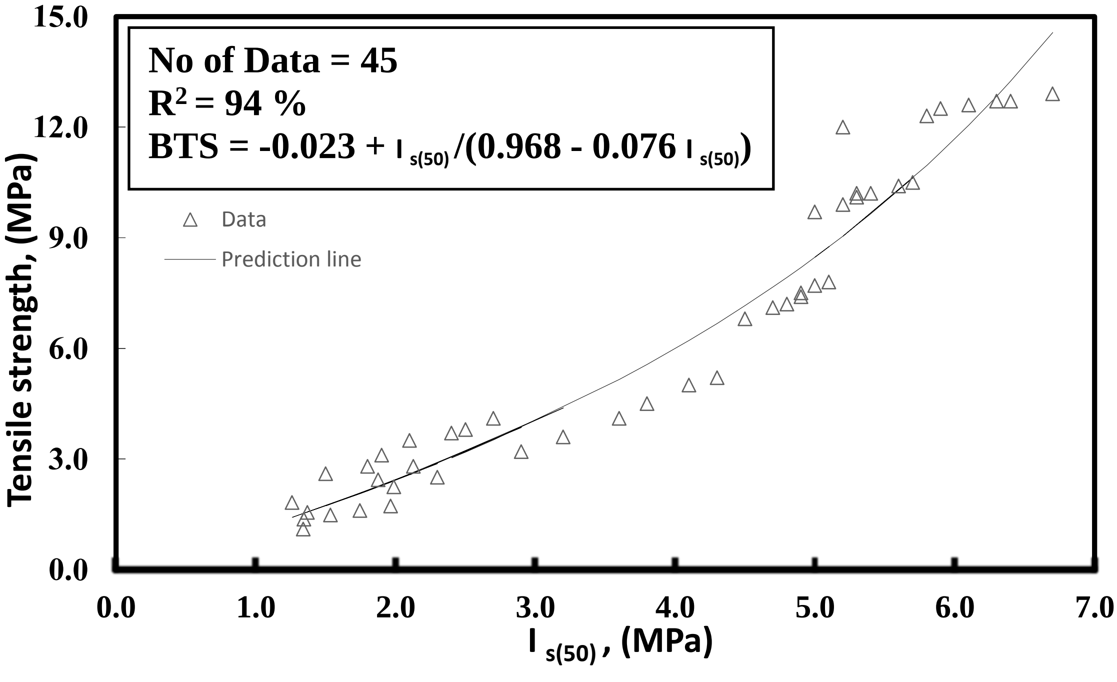

Fig 6. Relationship between Tensile strength and point load index.

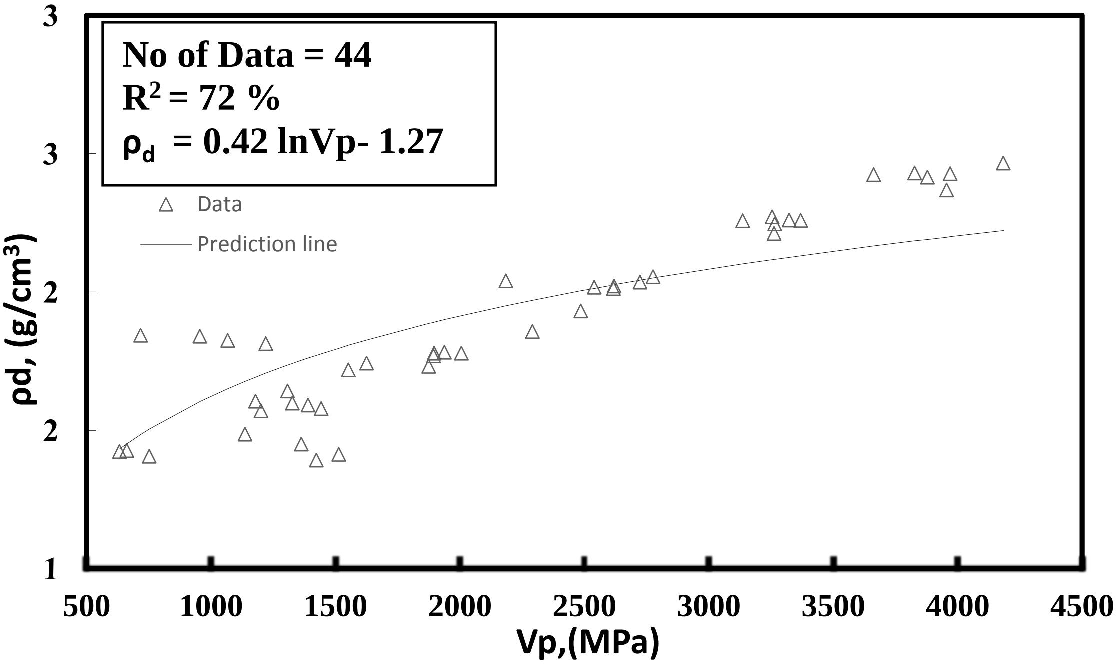

Fig 7. Relationship between Dry densities and Pulse velocity.

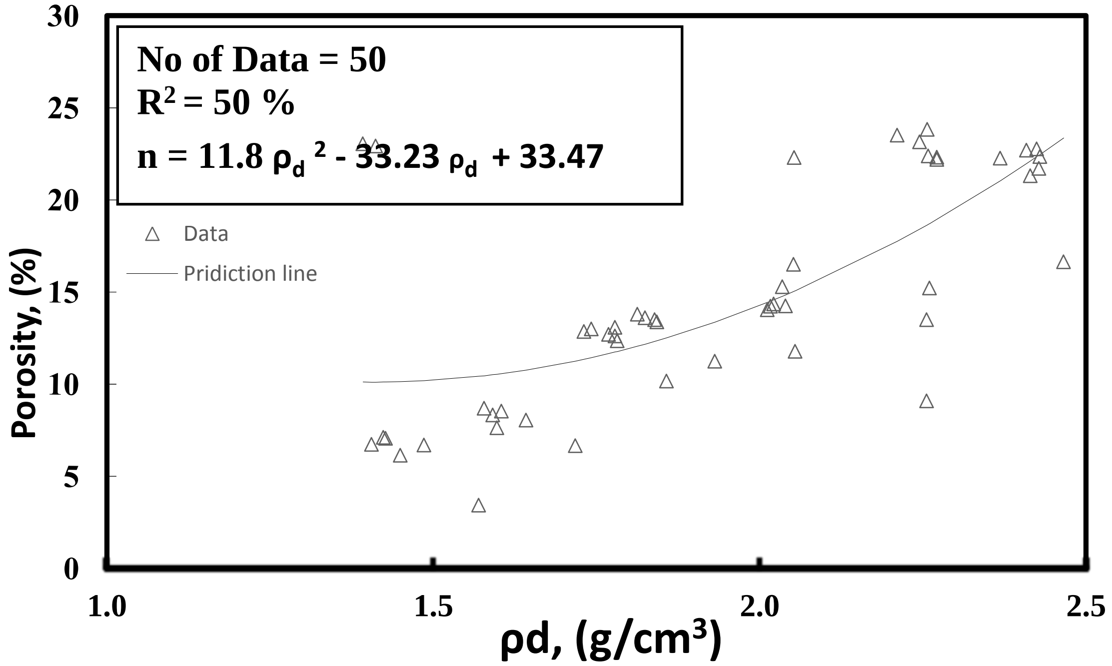

Fig 8. Relationship between Porosity and dry density.