Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi

Afyon Kocatepe University Journal of Science and Engineering

AKÜ FEMÜBİD **18** (2018) **015804** (1102-1109) AKU J. Sci. Eng. **18** (2018) **015804** (1102-1109)

DOİ: 10.5578/fmbd.67821

Araştırma Makalesi / Research Article

Predicting Strength Parameters of Igneous Rocks from Slake Durability Index

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Geliş Tarihi:24.04.2018 ; Kabul Tarihi:19.12.2018

Keywords
Slake durability index (SDI); Strength parameters; Igneous rocks; Estimation

Abstract

The aim of this study is to evaluate and develop statistical models for predicting the strength parameters (point load strength, uniaxial compressive strength and Brazilian tensile strength) of igneous rocks, using slake durability index (SDI). In this study, the index, mechanical and slake durability index parameters of the 23 rock samples collected from different locations of the Central Anatolia have been detected by testing. A very high exponential relation between the strength parameters and SDI was found out. However, it has seen that the equations developed cannot estimate the strength parameters when SDI values greater than 98%. The relationship between strength parameters and SDI was reexamined in the case of SDI values being greater and less than 98%, and very high correlations were developed for strength parameters. These developed empirical equations can be applicable for igneous rocks having similar geomechanical properties.

Suda Dağılmaya Karşı Duraylılık İndeksinden Magmatik Kayaçların Dayanım Parametrelerinin Tahmini

Anahtar kelimeler
Suda dağılmaya karşı Duraylılık indeksi(SDİ); Dayanım parametreleri; Magmatik kayaçlar; Tahmin

Özet

Bu çalışma suda dağılmaya karşı duraylılık indeksi (SDİ) kullanılarak magmatik kayaçların dayanım parametrelerini (nokta yük dayanımı, tek eksenli basma dayanımı ve Brazilian çekme dayanımı) tahmin etmek için istatistiksel modeller geliştirmek ve değerlendirmek amacıyla yapılmıştır. Orta Anadolu bölgesinden toplanan 23 farklı magmatik kaya örneği test edilerek kayaçların indeksleri, mekanik özellikleri ve suda dağılmaya karşı duraylılık indeksleri belirlenmiştir. Dayanım parametreleri ile SDİ arasında çok yüksek üssel ilişki belirlenmiş olup SDİ'nin %98'den büyük olduğu değerleri için geliştirilen denklemlerin dayanım değerlerini tahmin edemediği saptanmıştır. SDİ değerinin % 98'den büyük ve küçük olması durumları için ise dayanım parametreleri ile SDİ arasındaki ilişkiler yeniden değerlendirilmiş ve dayanım parametreleri için çok yüksek korelasyon elde edilmiştir. Geliştirilen bu deneysel eşitlikler benzer jeomekanik karakterdeki magmatik kayaçlar için de uygulanabilir özelliktedir.

1. Introduction

The strength parameters are commonly used in rock mechanics and engineering geology designs. However, in some cases, sample preparation and conducting the tests are both costly and time consuming. As a result of this, alternative tests and/or analytical and empirical relationships between mechanical-physical properties of rocks have been developed for estimating their strength parameters. Sometimes, problems may be encountered during the preparation of test samples from incompetent rocks for alternative tests. In such cases, slake durability index (SDI) testing, for which sample preparation is easy and cheap, can be conducted.

The slake durability index (SDI) test was firstly developed by Chandra (1970) and Franklin and Chandra (1972) and then standardized by ISRM (1981) and ASTM (1998). Some researchers have suggested that index values at the end of fourth cycle should be taken as a basis (Gamble 1971, Ulusay et al. 1995, Gökceoğlu et al. 2000).

By using one or more properties of rocks such as index, strength, weathering, mineralogical-petrographical properties etc., the analytical and empirical relations between SDI and different methods (simple and multiple regression analysis etc.) have been studied by many researchers (Dhakal et al, 2002, Sharma and Singh 2008, Sharma et al. 2011, Yagız 2011b, Altindag 2012, Bozkurtoğlu and Mert 2012, Sarkar et al. 2012). Additionally, some researchers studied the relation between strength parameters (uniaxial compressive strengths) and slake durability index (SDI) to develop an estimation equation for uniaxial compressive strength (UCS) (Cargill and Shakoor 1990, Koncagül and Santi 1999, Dinçer et al. 2008, Gökceoğlu et al. 2000, Yagiz 2011a, Yagiz et al. 2012, Kahraman et al. 2017). Cargill and Shakoor (1990) have also investigated the relationship between UCS and SDI values at the end of second cycle for different rock types, and developed the equations given in Table 1. Koncagül and Santi (1999) have studied the correlation between UCS and SDI for the Breathitt shale. Further, Gökceoğlu et al. (2000) have searched the correlation between UCS and SDI values at different cycles for argillaceous rocks. Dinçer et al. (2008) have developed the equations, given in Table 1, between UCS and SDI values after second and fourth cycles for Quaternary caliche sediments. Yagiz (2011a) has determined a strong correlation between UCS and SDI values obtained at the end of fourth cycle for carbonate rocks. In the study of carbonate rocks, Yagiz et al. (2012) first studied the relation between UCS and SDI by simple regression analysis and then predicted the UCS of rock materials via artificial neural networks (ANN) and nonlinear regression methods. Kahraman et al. (2017) empirically determined UCS values of pyroclastic rocks by utilizing SDI values obtained at the end of fourth cycle.

Koncagul and Santi (1999) indicated that physical parameters containing UCS and SDI tests shared similarities. Although the relations between SDI and UCS values of various rock types have been studied by most researchers, igneous rocks have not been studied until now. In this study, 23 igneous rocks samples having a wide range of strength parameters were examined. The aim of this study is to determine possible strength parameters to be predicted by an easily applicable SDI test that does not require sample preparation process.

Table 1. Equations correlating the SDI with UCS (*UCS values in the equations are revised as MPa).

Reference	Equation	r
Cargill and Shakoor 1990	$UCS = 60.338I_{d2} - 5822$	0.74
Koncagul and Santi 1999*	$UCS = 0.658I_{d2} + 9.081$	0.63
Gökceoglu et al. 2000	$UCS = 2.54I_{d4} - 202$	0.76
Dinçer et al. 2008	$UCS = 0.211I_{d2} - 13.815$	0.68
	$UCS = 16.636\ln I_{d2} - 69.552$	0.65
	$UCS = 4.9x10^{-7}I_{d2}^{3.578}$	0.74
	$UCS = 0.084e^{0.45I_{d2}}$	0.76
Yagız 2011	$UCS = 29.63I_{d4} - 28.58$	0.94
Yagız et al. 2012	$UCS = 0.7183I_{d2} - 0.0886$	0.63
	$UCS = 0.7233I_{d2} - 0.0889$	0.66
	$UCS = 0.7856I_{d2} - 0.1171$	0.71
	$UCS = 0.531I_{d4}{}^{1.454}$	0.66
	$UCS = 0.7454I_{d4} - 0.1122$	0.67
	$UCS = 0.6341I_{d4} - 0.0753$	0.60
Kahraman et al. 2017	$UCS = 0.047e^{0.065I_{d4}}$	0.92
	$UCS = 0.453I_{d4} - 26.22$	0.82
	$UCS = 7.75I_{d4} - 711.4$	0.93

2. Materials and Methods

23 igneous rock samples collected from the Central Anatolia, Turkey have been used in this study. The samples locations and their petrographic features are shown in Table 2. The categories of the rock samples are plutonic, volcanic and pyroclastic. The investigated pyroclastic rocks are composed of volcanic glass, plagioclase, quartz, rock fragments and opaque and are generally hypocrystalline and porphyritic in texture. For experimental studies, rock samples with dimensions of 20x30x30 cm were collected from the quarries. Test specimens were prepared in accordance with standards to detect their physical, mechanical and petrographic properties. In the following sections type of experiential studies will be introduced.

Table 2. The location, composition and name of the rock samples (Amp: amphibole, Ap: apatite; B: biotite, Ca: calcite, Ch: chlorite, H: hornblend, Ol: olivine, Om: opaque minerals, Ort: orthoclase, P: plagioclase, Pm: plagioclase microlite, Pyr: pyroxene, Rf: rock fragment, S: sanidine, Sp: sphene, Vg: volcanic glass, Q: quartz).

Sample	Location	Color	Composition	Texture	Rock name
1	Ortaköy-Aksaray	Grey	36% P, 34% Q, 21% Ort, 8% B, 1% Om	Hypidiomorphic	Granite
2	Hamit-Aksaray	Grey-light rose	34% Ort, 27% P, 20% Q, 14% Amp, 5% B, 2% Om	Hypidiomorphic	Granite
3	Yaylak-Aksaray	Grey	32% Q, 30% P, 23% Ort, 12% B, 2% Amp, 1% Om	Hypidiomorphic	Granite
4	Hamit-Aksaray	Light rose	32% Ort, 25% P, 20% Q, 15% Amp, 5%B, 2% Sp, 1% Ap	Hypidiomorphic	Granite
5	Erkilet-Kayseri	Black	59% Pm, 25% Pyr, 10% Ol, 1% Om	Holocrystalline porphyric	Basalt
6	Niğde	Black	54% Pm, 35% Pyr, 5% Ol, 4% P, 2% Om	Holocrystalline porphyric	Basalt
7	Niğde	Black	30% Pm, 29% Vg, 18% P, 10% Ch, 10% Ca, 3% Om	Holocrystalline porphyric	Sipilite
8	Sağlık-Konya	Grey	52%Vg, 30% P, 10% Amp, 7% Ca, 1% Om	Holocrystalline porphyric	Andesite
9	Sille-Konya	Pink	32% P, 23% Vg, 19% B, 15% Pm, 10% Q, 1% Om	Holocrystalline porphyric	Q-Andesite
10	Demirciler-Aksaray	Dark lilac-purple	45% Vg, 24% P, 10% Rf, 10% Q, 10% B, 1% Om	Vitrophyric Porphyritic	Pyroclastic
11	Kayseri	Gray	64% Vg, 15% P, 7% Q, 7% S, 4% Rf, 2% B, 1% Om	Vitrophyric Porphyritic	Pyroclastic
12	Emmiler-Kayseri	Brownish	54% Vg, 20% P, 10% Rf, 7% Pyr, 4% S, 3% Q, 2% Om	Vitrophyric Porphyritic	Pyroclastic
13	Koçağız-Kayseri	Yellow	83% Vg, 8% P, 4% Q, 4% Rf, 2% Om	Vitrophyric Porphyritic	Pyroclastic
14	Tomarza-Kayseri	Black	68% Vg, 20% Rf, 12% P	Vitrophyric Porphyritic	Pyroclastic
15	Kızılören-Konya	White	35% Vg, 35% Rf, 17% P, 10% Q, 2% B, 1% Om	Vitrophyric Porphyritic	Pyroclastic
16	Karayazı-Nevşehir	Chery	50% Vg, 20% P, 15% Ca, 5% Rf, 4% Q, 4% B, 2% Om	Vitrophyric Porphyritic	Pyroclastic
17	Karayazı-Nevşehir	Rose	46%Vg, 20%P, 15%Ca, 10%Rf, 5%Q, 4%B, 1%Om	Vitrophyric Porphyritic	Pyroclastic
18	Karayazı-Nevşehir	Rose-pink	72% Vg, 10% Q, 8% P, 8% Rf, 1% Amp, 1% Om	Vitrophyric Porphyritic	Pyroclastic
19	Selime-Aksaray	Grayish	50% Vg, 25% P, 9% Q, 8% Rf, 7% B, 1% Om	Vitrophyric Porphyritic	Pyroclastic
20	Koçağız-Kayseri	Grayish	80% Vg, 9% P, 4% Pyr, 3% B, 2% Q, 2% Om	Vitrophyric Porphyritic	Pyroclastic
21	Gümüşlü-Niğde	Light pink	69% Vg, 11% P, 9% Q, 7% Rf, 3% B, 1% Om	Vitrophyric Porphyritic	Pyroclastic
22	Ardıçlı-Konya	Grayish	40% Ca, 25% P, 15% Rf, 9% Q, 5% H, 5% B, 1% Om	Vitrophyric Porphyritic	Pyroclastic
23	Ardıçlı-Konya	Grayish	30% Ca, 25% P, 18% Rf, 13% Q, 8% H, 5% B, 1% Om	Vitrophyric Porphyritic	Pyroclastic

2.1 Index properties

The water absorption by weight and porosity values have been detected by saturation and caliper techniques. BX size core samples have been used in these tests (ISRM 2007).

2.2. ***Strength Parameters***

Strength parameters including Uniaxial compressive strength (UCS), point load test (PLT) and Brazilian tensile strength (BTS) of studied rocks have been performed on core samples having 42 mm in diameter, according to the ASTM 1995, ASTM 2005 and ISRM 2007 standards, respectively.

The UCS and PLT values have been corrected in accordance with an equivalent specimen 50 mm in diameter (Hoek and Brown 1980; ISRM, 1985).

2.3. Abrasion Parameter

Slake durability test (SDI), which is an abrasion parameter, has been conducted according to ISRM (1981) standard.

In this study, the second cycle (Id_2) of the Slake durability test has been used.

3. Results and Discussion

Determined index properties (dry density, porosity, water absorption by weight, compressional wave velocity), strength parameters (UCS, PLT, BTS) and slake durability index values of rock samples are given in Table 3. The statistical analysis of the acquired data is presented in Table 4.

Whereas dry densities of the rock samples vary between 1.25-2.69 g/cm^3, the porosity values vary between 0.46-36.83 %. Water absorption percentages by weight of these samples range between 0.18 and 28.23 %. The maximum and minimum compressional wave velocities were measured at sample 5 and 20, respectively, as 5.38 km/s and 1.39 km/s.

Igneous rock samples having strength values varying in a wide range were examined. The UCS values of the rock samples vary between 7.57-144.10 MPa.

Table 3. Some physical and mechanical properties of the rock samples.

Sample	ρ_d g/cm^3	n %	Aw %	Vp km/s	UCS MPa	PLT MPa	BTS MPa	Id_2 %
1	2.65	0.46	0.18	4.97	144.10	9.31	10.17	99.41
2	2.69	0.78	0.29	4.40	80.07	5.87	8.43	99.07
3	2.62	1.02	0.39	4.42	141.56	7.67	9.07	99.63
4	2.68	0.86	0.32	4.34	125.74	4.52	8.54	99.48
5	2.61	3.49	1.34	5.38	112.79	8.28	8.61	98.87
6	2.56	5.19	2.03	4.70	112.12	10.40	11.53	99.26
7	2.65	2.46	0.93	4.44	103.36	5.50	8.05	99.14
8	2.38	8.95	3.79	3.19	83.98	4.22	5.01	98.68
9	2.32	5.65	2.41	3.78	60.60	4.78	5.05	98.31
10	1.75	23.89	13.69	2.95	48.63	3.27	4.82	98.30
11	1.78	19.53	10.96	2.28	48.38	2.79	3.22	97.32
12	1.82	26.21	14.44	2.69	36.64	2.68	4.23	98.35
13	1.63	25.57	15.75	2.58	31.57	1.94	3.08	96.19
14	1.42	33.05	23.30	2.90	27.27	1.88	4.14	94.58
15	1.25	35.12	25.64	2.57	17.05	1.61	3.32	95.26
16	1.66	30.76	18.49	2.19	15.68	1.24	2.11	92.02
17	1.58	32.20	20.40	2.20	12.36	1.18	1.98	88.39
18	1.61	26.60	16.49	2.39	11.05	1.09	1.08	87.88
19	1.54	24.81	16.13	2.30	10.55	1.23	1.41	90.79
20	1.38	30.27	21.90	1.39	8.89	0.82	1.00	87.12
21	1.30	36.83	28.23	2.02	7.57	1.03	1.68	87.46
22	1.86	16.80	9.10	1.58	13.55	1.25	2.10	94.20
23	2.19	12.10	5.55	3.30	26.70	1.80	3.50	94.77

Table 4. Descriptive statistics of data used in the analysis.

Variables	Data	Mean	Standart deviation	Varians	Minimum	Maximum
UCS	23	55.66	46.81	2191.47	7.57	144.10
BTS	23	4.88	3.21	10.30	1.00	11.53
PLT	23	3.67	3.21	8.47	0.82	10.40
ρ_d	23	2.00	0.52	0.27	1.25	2.69
n	23	17.50	13.04	169.93	0.46	36.83
Aw	23	10.95	9.33	87.12	0.18	28.23
Vp	23	3.17	1.15	1.32	1.39	5.38
I_{d2}	23	95.41	4.36	19.01	87.12	99.63

While the UCS values of the volcanic and plutonic rocks were classified as medium to high rock class, the pyroclastic rocks vary between low and low-medium class based on Bieniawski and Bernede (1979) classification. Among the samples, the maximum and minimum BTS values were measured at sample 6 and 20, respectively, as 11.53 MPa and 1.00 MPa. The PLT values of the samples vary between 0.82 MPa and 10.40 MPa. The rock samples were classified as medium to extremely high rock according to the PLT based on ASTM (2005) classification.

The slake durability index values of the igneous rocks vary between 87.12 % and 99.63% according to the results of second cycle. The SDI values of the volcanic and plutonic rocks tested in this study fall into "very high slake durability" class according to Gamble (1971) classification. On the other hand, the SDI values of the pyroclastic rocks vary between medium high and very high slake durability class based on Gamble (1971) classification.

The relationship between strength values of the igneous rocks (UCS, PLT and BTS) and SDI (Id_2) was examined by simple regression analysis. The best approximation equations having highest correlation coefficient were generated and their relationships are depicted in Figure 1. The best relationships were determined with exponential functions and their equations are given below. A very high correlation between strength values and SDI was obtained.

$$UCS = 7x10^{-8}e^{0.2101Id_2} \qquad r=0.92 \qquad (1)$$

where UCS is the uniaxial compressive strength (MPa), Id_2 is the 2nd cycle SDI (%)

$$PLT = 6x10^{-7}e^{0.1614Id_2} \qquad r=0.88 \qquad (2)$$

where PLT is the point load test (MPa), Id_2 is the 2nd cycle SDI (%).

$$BTS = 1x10^{-6}e^{0.1551Id_2} \qquad r=0.92 \qquad (3)$$

where BTS is the Brazilian tensile strength (MPa), Id_2 is the 2nd cycle SDI (%).

When the Id_2 values were higher than 98%, it was found that the points representing the values of Id_2 versus strength parameters (UCS, PLT and BTS) deviated from the curves (Figure 1 a-c). It is obvious that strength and SDI graphics indicated different trends for the values of Id_2 greater and less than 98%. This can be clearly seen in data obtained from the equations (Equations 1-3) and compared experimental data delineated in the graphics (Figure 1d-f).

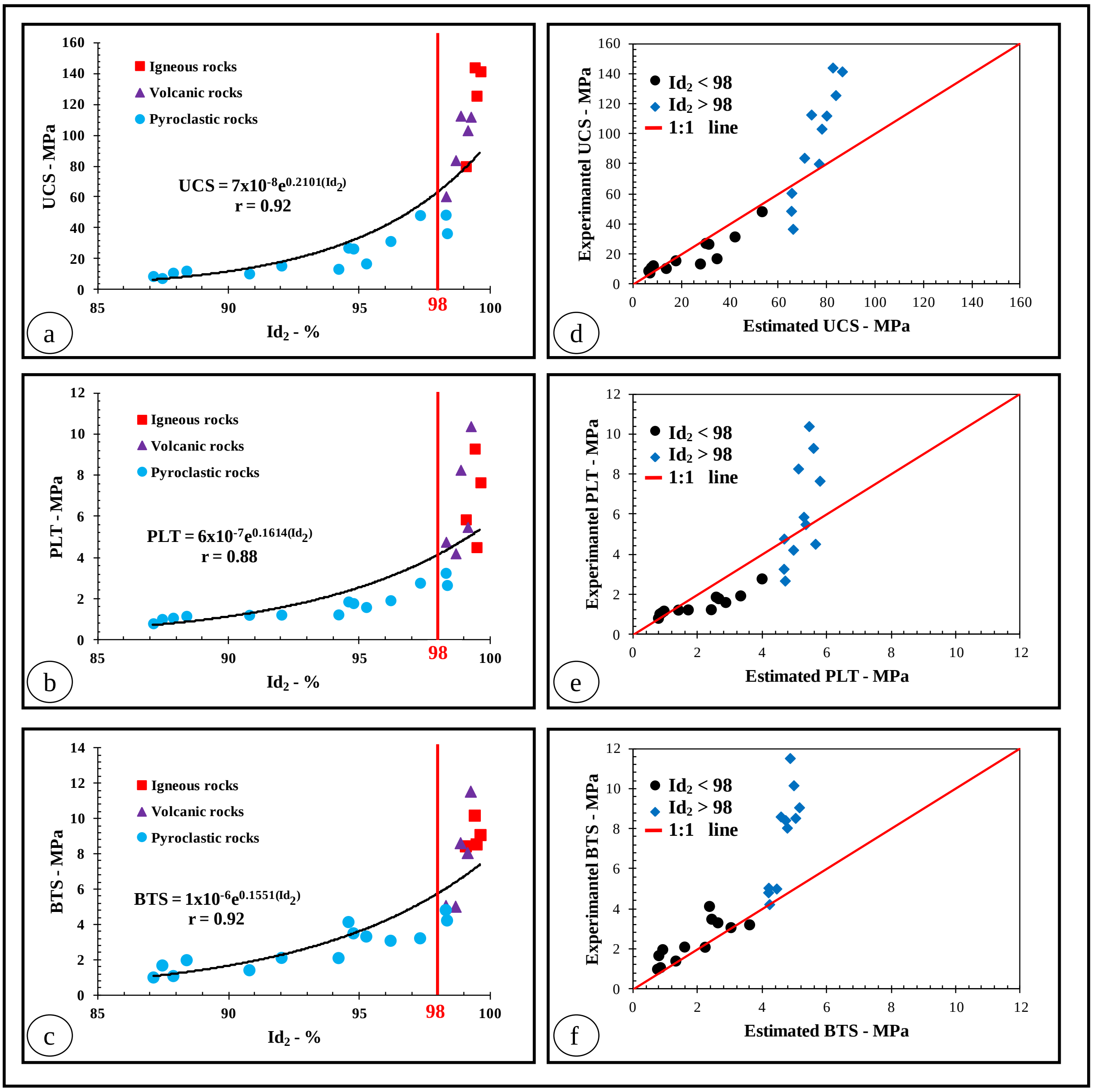

Figure 1. The relationships between SDI a) UCS and SDI, b) PLT and SDI, c) BTS and SDI; and d) estimated versus experiment UCS for Equation 1, e) estimated versus experiment PLT for Equation 2, f) estimated versus experiment BTS for Equation 3.

The relationships between strength and were reevaluated according to the situations where Id_2 value was greater and less than 98%. The validity of derived equations was checked by means of t and F test. If the computed t and F values are greater than those which were tabulated, null hypothesis is rejected. This result shows that r value is significant. If the computed t and F values are less than those of the tabulated values null hypothesis is not rejected and r value is not significant. The computed values are greater than the tabulated t and F values showing that the models in the study are valid. For a 5% significance level (α=0.05) of improved equations, the *p* value was required to be smaller than 0.05. The best approximation with the highest correlation coefficients (r) was determined among these equations. The improved equations are presented in Equations 4-9. The graphics delineated for these conditions are given in Figure 2 as well.

The analyses of variance for the validation of equations were performed and the results are given in Table 5. In this test, a 95% confidence level was chosen. The developed statistical models have shown that they are confidential to estimate the strength values for a 5% significance level (α=0.05).The correlation between values of strength parameters obtained from the experimental studies and equations developed is given in Figure 3. On the plots of UCS and BTS experiments versus estimated, the points were scattered around the 1:1 straight line (Figure 3 a and c). Whereas on the plot of PLT experiment versus estimated, the points representing the samples 1, 4 and 5 deviated from 1:1 straight line. Such deviations from 1:1 line should be caused by textural changes of the samples, as pointed out by Fener and Ince (2012).

Table 5 The variance analysis of the models belonged to the strength parameters.

Strength parameters	Eq. No	r	t test	F test	$p < 0.05$
UCS	4	0.89	6.107	37.297	0.00
	7	0.93	7.341	53.890	0.00
PLT	5	0.90	6.618	43.799	0.00
	8	0.69	2.901	8.417	0.02
BTS	6	0.86	5.302	28.114	0.00
	9	0.88	5.588	31.227	0.00

The developed equations for $Id_2 < 98$

$$UCS = 6x10^{-5}e^{0.1358(Id_2)} \quad (4)$$

$$PLT = 0.0007e^{0.0826(Id_2)} \quad (5)$$

$$BTS = 9x10^{-5}e^{0.1094(Id_2)} \quad (6)$$

The developed equations for $Id_2 > 98$

$$UCS = 69.267(Id_2) - 6758.8 \quad (7)$$

$$PLT = 4x10^{-122}(Id_2)^{61.191} \quad (8)$$

$$BTS = 1x10^{-26}e^{0.625(Id_2)} \quad (9)$$

Where UCS is the uniaxial compressive strength (MPa), PLT is the point load test (MPa), BTS is the Brazilian tensile strength (MPa), Id_2 is the 2nd cycle SDI (%).

Findings of some researchers (Cargill and Shakoor 1990, Gökceoglu et al. 2000, Yagiz et al. 2012), who studied on various rock types (sandstone, carbonate rocks, argillaceous) were compared with those of this study, and were showing in Figure 4. In the Figure 4, it is clearly seen that values of Id_2 present different curves when they are greater and smaller than 98%, except for a few points.

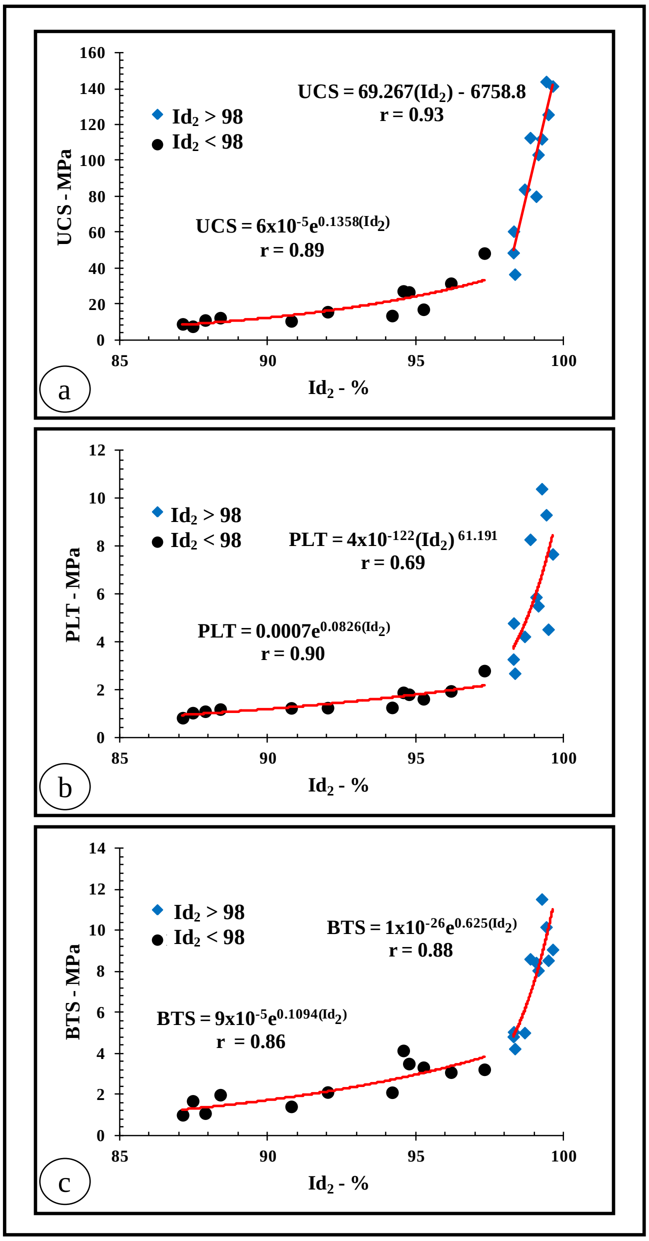

Figure 2. The correlation between strength parameters and SDI values (greater and less than 98%)

4. Conclusions

In this study, it was aimed to estimate the strength values of the igneous rocks by SDI test that is easy and non-time consuming method for sample preparation. A very high exponential relationship between SDI and the strength parameters was obtained. When this relationship was analyzed, it was determined that the equations developed for slake durability index values at the end of second cycle greater than 98% could not predict the strength values. Therefore, the relationships between SDI and strength parameters were reevaluated for the conditions that SDI values are greater and less than 98%. For these situations, a very high correlation coefficient was found between SDI and strength parameters.

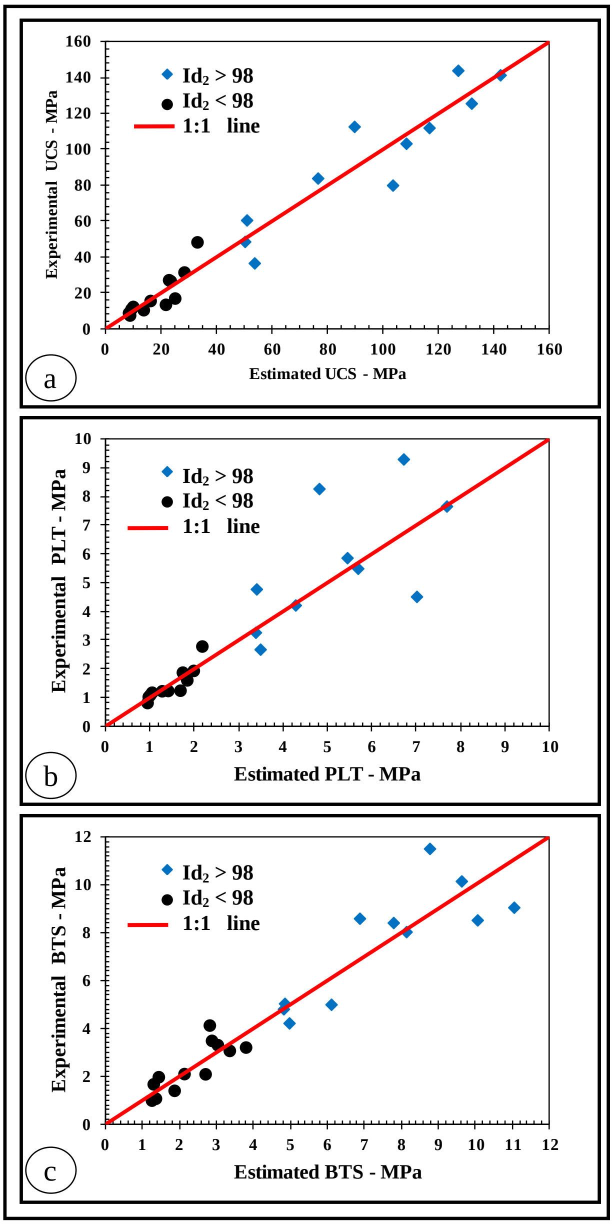

Figure 3. a) Estimated versus experiment UCS for Equation 5 and 7, b) estimated versus experiment PLT for Equation 6 and 8, c) estimated versus experiment BTS for Equation 6 and 9.

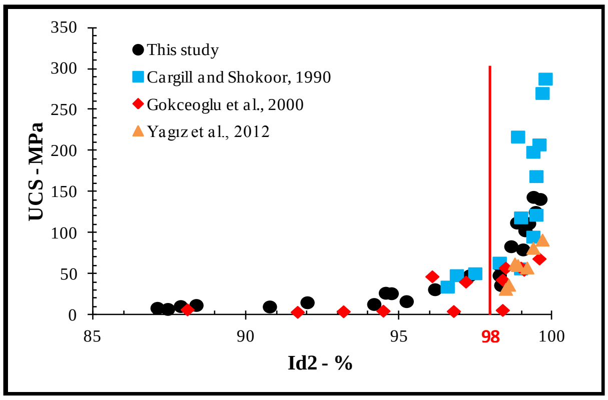

Figure 4. The comparison of the data of this study to those of other studies (Cargill and Shakoor 1990, Gökceoglu et al. 2000, Yagiz et al. 2012)

The reliability of the developed equations was verified by statistical tests (t test and F test). It was observed that in the plots of observed UCS and BTS values versus estimated values, the points were scattered uniformly around the 1:1 line suggesting that the models are reliable for the estimating of strength parameters of igneous rocks.

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