Innovative Infrastructure Solutions (2021) 6:113
https://doi.org/10.1007/s41062-021-00498-w

TECHNICAL PAPER

Evaluating the influence of petrographic and textural characteristics on geotechnical properties of some carbonate rock samples by empirical equations

Reza Khajevand[1]

Received: 7 December 2020 / Accepted: 10 March 2021 / Published online: 28 March 2021

Abstract

The effect of petrographic and textural characteristics on geotechnical properties of some carbonate rock samples including limestone and travertine was investigated using Texture Coefficient (TC) and regression analyses. For this purpose, nine rock block samples were collected from quarries and road trenches in northern and northwestern parts of Damghan, northern Iran. Physical, index and mechanical properties namely specific gravity, dry and saturated unit weights, porosity, water absorption, slake-durability index, Schmidt rebound hardness, P-wave velocity, uniaxial compressive strength, point load strength index, Brazilian tensile strength and block punch strength were determined in the laboratory. Petrographic, mineralogical and textural investigations were studied by thin section and X-ray diffraction methods. Texture coefficient and required parameters were determined by JMicroVision (v1.27) software. Regression coefficient (R) was obtained between "0.10 and 0.98" by simple regression analysis. Three variable map shows that TC of the studied rocks is controlled by the presence of major minerals including quartz and calcite. Good direct linear relationships were found between TC and percent of calcite and quartz with high correlation coefficient ($R=0.79$ and 0.85). The regression analyses indicated good correlations between TC and engineering properties, especially between γ_{dry}, γ_{sat}, H_S, UCS, $I_{S(50)}$ and BPS. Also, no good relations were found between TC and n, W_a and V_P. Statistical coefficients including R, RMSE, VAF, MAPE and PI were calculated to assess performance and validity degrees of obtained equations and the regression analyses. Performance appraisal shows the model of BPS and TC has a higher performance than the other models. Experimental and calculated values of geotechnical properties that obtained from laboratory tests and predicted by statistical models were compared with 45° line ($y=x$). Based on the results, the trend lines of E, H_S, UCS, $I_{S(50)}$ and BPS models are more fit to $y=x$ line and shows high validity of experimental models. Results revealed that the texture coefficient is a useful parameter for predicting geotechnical properties of the rocks.

Keywords Geotechnical properties · Texture coefficient · Regression analysis · Limestone · Travertine

Abbreviations

TC	Texture coefficient
G_s	Specific gravity
γ_{dry}	Dry unit weight (g/cm^3)
γ_{sat}	Saturated unit weight (g/cm^3)
n	Porosity (%)
W_a	Water absorption (%)
H_S	Schmidt hardness
V_P	Primary wave velocity (Km/s)
E	Elasticity modulus (GPa)
Id	Slake-durability index (%)
$I_{S(50)}$	Point load strength (MPa)
BTS	Brazilian tensile strength (MPa)
BPS	Block Punch strength (MPa)
UCS	Uniaxial compressive strength (MPa)
XRD	X-ray diffraction
LS	Limestone sample
TS	Travertine sample
SRA	Simple regression analysis
R	Pearson regression coefficient
RMSE	Root mean square error
VAF	Coefficient values account for
MAPE	Mean absolute percentage error
PI	Performance index

✉ Reza Khajevand
r.khajevand@std.du.ac.ir

[1] School of Earth Science, Damghan University, Damghan, Semnan, Iran

Introduction

Estimating geotechnical properties of rocks is considered to be the most important components in different engineering projects such as tunnels, dams, rock foundations, rock slopes, underground structures, selection of construction materials [32] and damage to historical buildings [22]. Many researchers indicated that the mechanical and physical properties of different rocks are under the influence of their lithological and textural characteristics [1, 11, 17, 21, 23, 37, 45, 53]. So, the characteristics have particular importance for predicting mechanical and physical properties of rocks. The most important lithological and textural characteristics that may affect the physical and mechanical properties of various rocks are grain shape, grain size, grain interlocking, type of contacts, packing density, packing proximity, mineralogical composition, amount and type of cement and matrix. These properties can be easily measured in laboratory and they are commonly determined during routine thin section studies [34]. On the other hand, determining geotechnical parameters are generally difficult, destructive, expensive and requires considerable amount of time [4, 30], although can be indirectly measured using their relationships by petrographic characteristics and some index test of rocks [8, 38, 46]. Indirect methods have several advantages, including little or no specimen preparation, easy operation and low cost [33, 44].

Howarth and Rowlands [23] developed the theory of texture coefficient (TC), which made it possible to understand the variety of physical and mechanical properties of rocks with rock textural properties. In this research, they investigated the relations between the mechanical properties and TC for ten different rock types including sandstones, marbles and igneous rocks and found that there are close relationships between rock mechanical properties and TC with high correlation coefficients. Numerous researchers such as Howarth and Rowlands [24], Ulusay et al. [49], Azzoni et al. [6], Jeng et al. [28], Prikiryl [42], Tandon and Gupta [48], Ajalloeian et al. [2], Yalcinalp et al. [52], Kolay and Baser [36], Kamani and Ajalloeian [31], Garia et al. [18], Wang et al. [50], Koken [35], Cheshomi et al. [10], Cueto et al. [12] and Rahimi et al. [43] have investigated the correlations between textural characteristics, physical and mechanical properties of various rocks, by using statistical analyses and soft computing methods (e.g., Jensen et al. [29]; Singh and Verma [47]; Esamaldeen and Guang [16]; Chen et al. [9]; Germinario et al. [19]) and found strong relations between the parameters.

Dogan et al. [13] presented classifications for carbonate hardground based on petrographic characteristics and engineering geological properties including uniaxial compressive strength (UCS), triaxial compressive strength (TCS), modulus ratio and elastic constant ratio. Alber and Kahraman [3], by texture coefficient (TC) and regression analyses, predicted the elastic modulus (E) and UCS of breccia. They believed that the UCS can be easily estimated from texture coefficient. Jensen et al. [29] stated that many parameters including crystal size, porosity, cleavage planes and micro-cracks control the strength behavior of limestone. Manouchehrian et al. [39] based on textural characteristics estimated UCS by using artificial neural network (ANN) and multiple regression analysis (MRA). Ozcelic et al. [40] predicted the geotechnical properties of marble and limestone samples from microscopic data by regression analyses. Bandini and Berry [7] studied the effect of marble samples' textures on their mechanical behaviors. Pappalardo et al. [41] showed that the mechanical characteristics of migmatite are influenced by porosity and mineral composition. Ersoy and Acar [15] studied the influences of petrographic and textural properties on strength of very strong granitic rocks and concluded that the mineral size has a greater effect on strength than mineral type. Ajalloeian et al. [1] studied the impacts of petrographic properties on the ultrasonic wave velocity including dynamic elastic constants and P and S wave velocity of granitic rocks. The results showed that mineral grain size and ratio of quartz/feldspar have good accuracy for estimating the V_P and V_S.

The above-mentioned researches show that petrographic and textural characteristics have effect on the engineering properties of different rocks. Therefore, in the present research, geotechnical properties, petrography and textural characteristics of nine rock samples including limestone and travertine were determined and an attempt has been made to extract equations between textural characteristics and geotechnical properties of the rocks using regression analysis technique.

Sampling locations and geological setting

Northern and northwestern parts of Damghan are selected as the study area which has a typical continental climate and an irregular morphology that is related to its geological history, tectonics and lithology. From a geological point of view, the area is located on the Alborz-Azarbayejan structural zone and fairly complete succession of Paleozoic to Neogene rocks exist in this area. Suitable locations for sampling were selected using the 1:100,000 geological map prepared by the Geological Society of Iran [20]. The limestone samples were collected from Bahram formation of the middle Devonian outcropped in northern parts of a ballast mine in 10th Km of Cheshmeh-Ali road.

These samples have a light brown color with dolomitic and silicone veins in their texture. Atari fault were passing from near the sampling locations which put together the Bahram limestones and Karaj formation tuffs. The travertine samples were collected from Baba-Hafez quarry located near the Astaneh village in 27th Km of Cheshmeh-Ali road. The studied travertine, along the Astaneh fault, was occurred by chemical activities of springs with dolomite and limestone of Elika formation. They were deposited between the Pishsarkoh and Anbehkoh mountains. The quarry covers small area and has porous travertines with light colors namely white, gray, cream and light brown. The elevation of study area is between 1380 and 1445 m above sea level. Figure 1 depicts the geological properties of area and shows the sampling locations.

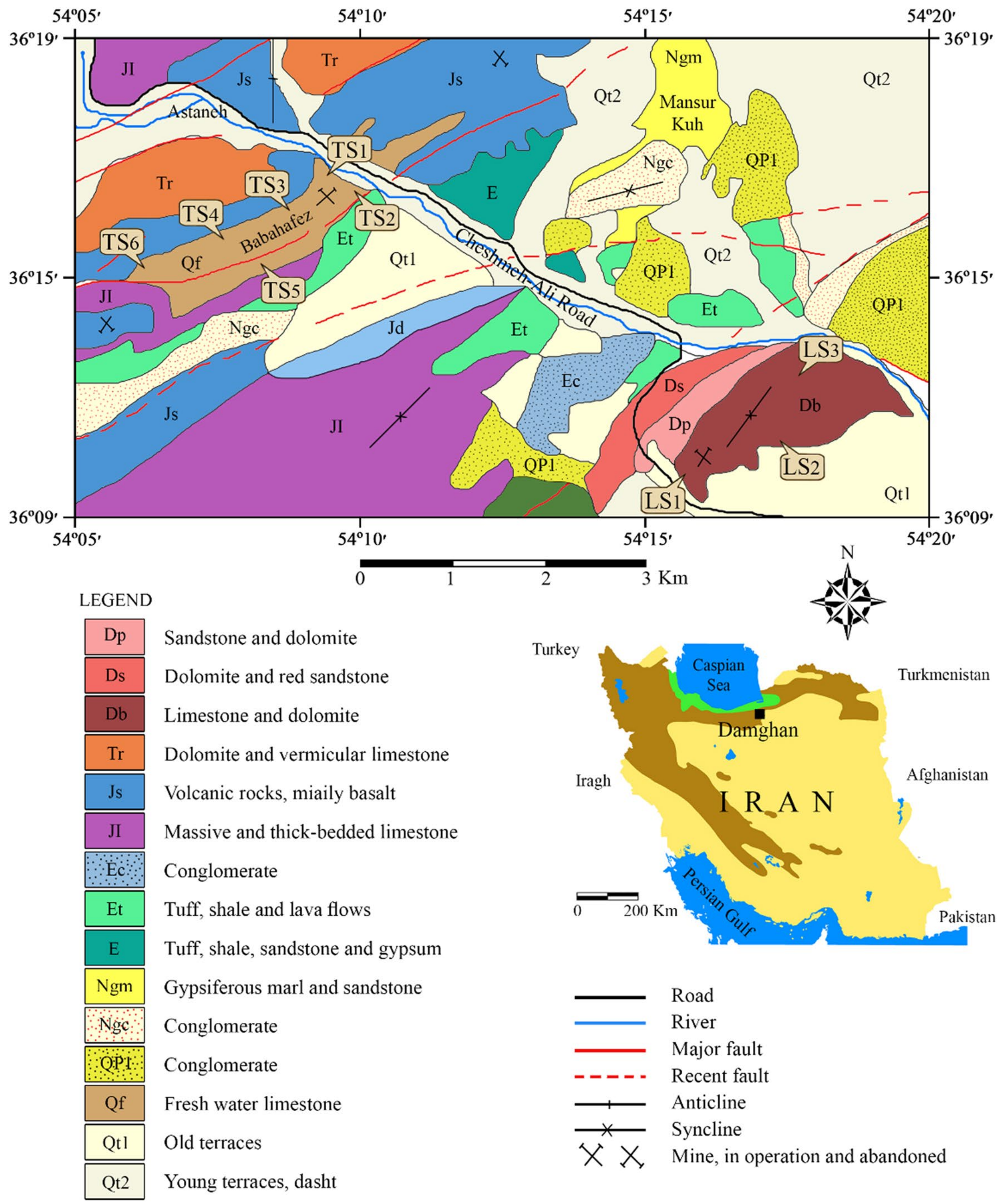


Fig. 1 Geological map of the study area indicating sampling locations and its situation on the general map of Iran [20]

Methodology

This research was based on laboratory testing and field investigations. During the field investigations, lithological characteristics of nine block samples of two rock types including travertine and limestone were determined and suitable block samples were collected from mines, quarries and road cuttings of the study region and transferred to the engineering geology laboratory. To identify mineral composition, petrographic properties, textural characteristic and texture coefficient (TC) of the rock samples, XRD analyses and optical microscopy studies on polished thin sections were performed based on ISRM [27]. A comprehensive laboratory test program was carried out on the prepared rock specimens to assess specific gravity, dry and saturated unit weights, apparent porosity, water absorption, Schmidt rebound hardness, P-wave velocity, slake-durability index, uniaxial compressive strength, point load index, Brazilian tensile strength and block punch strength based on ISRM [27]. Required specimens were prepared in three shapes: irregular or lump, disk and cylinder in the laboratory. The irregular specimens were used in the slake-durability test. The disk specimens were prepared for performing the Brazilian and punch tests. The cylindrical specimens were used for measuring physical properties, ultrasonic P wave velocity, point load index and uniaxial compressive strength. The required cores were prepared from the selected rock blocks using a radial coring machine. Finally, empirical equations between the geotechnical properties and texture coefficient (TC) were extracted using regression analyses and the results have been discussed. Figure 2 presents test plan for mineralogical, physical, index and mechanical tests in this study.

Results

Mineralogical and petrographic studies

Thin section studies and X-ray diffraction (XRD) analyses were performed to determine mineralogical, petrographic and textural characteristics of the rock samples based on ISRM [27] standard procedure. The results indicated that the limestone samples as dolomitic limestone are composed of calcite, dolomite and quartz. The presence of breccia structure and dolomitic vain with fossils fragments is textural properties of the samples. The travertine samples were commonly composed of calcite, aragonite and quartz. The samples are porous, and they have a layered texture due to succession of crystalized aragonite and calcite and micritic layers. The aragonite with especial extinction is obviously visible in the thin sections. The XRD analyses in the 2θ ranges from 4° to 72° were conducted on the rock samples which confirmed quartz, calcite and aragonite are the most important minerals of the studied rocks. The average modal abundance of minerals in the samples are presented in Table 1. Microscopic images of the samples of LS_1 and TS_1 as representative samples in normal and polarized lights are presented in Fig. 3, and XRD diffractograms are shown in Fig. 4.

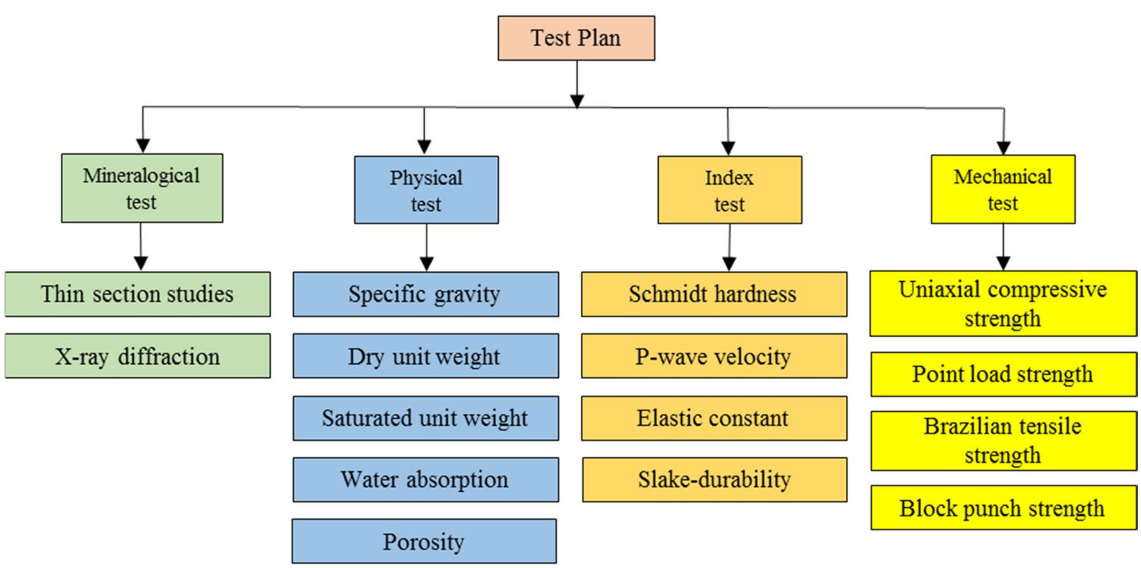


Fig. 2 Test plan for mineralogical, physical, index and mechanical test

Table 1 Type and mineral composition of the rocks

Sample	Rock type	Mineral content (%)						
		Qtz	Cal	Arg	Dol	Hem	Bor	Other minerals
LS1	Dolomitic limestone	20	55	–	21	2	1	1
LS2	Dolomitic limestone	20	55	–	20	2	1	2
LS3	Dolomitic limestone	19	55	–	19	4	1	2
TS1	Travertine	8	35	55	–	1	–	1
TS2	Travertine	10	40	45	–	–	–	5
TS3	Travertine	8	45	45	–	–	–	2
TS4	Travertine	10	40	48	–	–	1	1
TS5	Travertine	8	40	50	–	–	1	1
TS6	Travertine	9	40	49	–	–	1	1

Qtz.: Quartz (SiO_2), Cal.: Calcite ($CaCO_3$), Arg.: Aragonite ($CaCO_3$), Dol. Dolomite $Ca.Mg(CO_3)_2$, Hem.: Hematite (Fe_2O_3), Bor.: Bornite (Cu_5FeS_4)

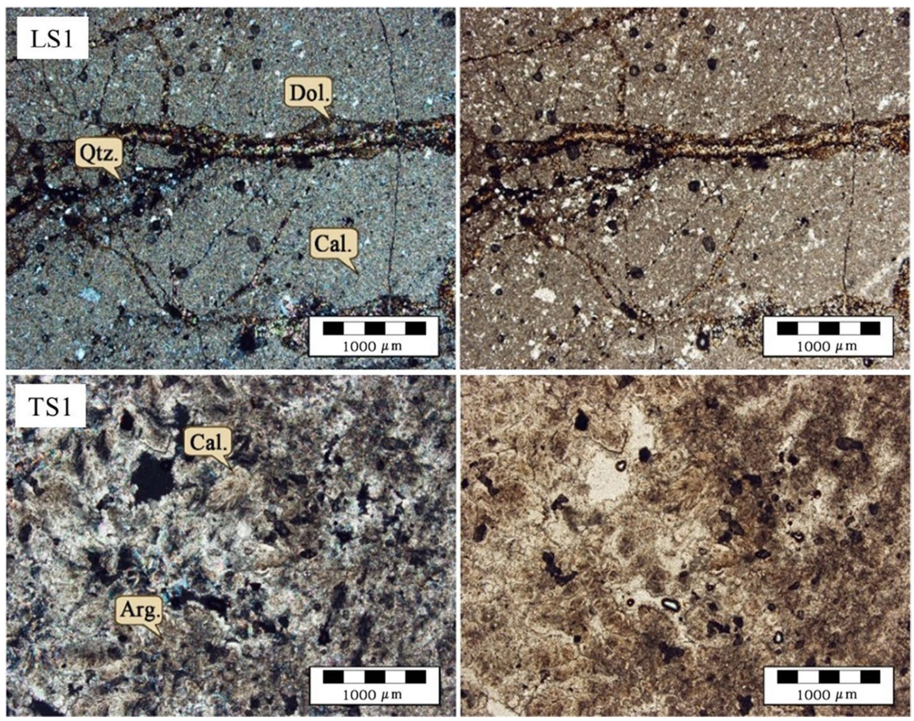


Fig. 3 Microscopic images of the representative rock samples in normal and polarized lights

Geotechnical properties

Geotechnical parameters including physical, mechanical and index properties were determined for the rocks based on ISRM [27] suggested methods. The properties including specific gravity (G_S), dry unit weight (γ_{dry}), saturated unit weight (γ_{sat}), water absorption (W_a), apparent porosity (n), Schmidt rebound hardness (H_S), P-wave velocity (V_P), elasticity modulus (E), slake-durability index (Id), uniaxial compressive strength (UCS), point load strength index ($I_{S(50)}$), Brazilian tensile strength (BTS) and block punch strength (BPS). A total of 252 core specimens were prepared and used for various destructive and nondestructive tests. The prepared NX cylindrical core specimens were tested in different length/diameter ratio to determine physical and mechanical properties that some of them are presented in Fig. 5. The number of tests or tested specimens of each sample for determining physical properties was five cylinder specimens, for Schmidt rebound hardness was twenty impacts on each rock block sample, for P-wave velocity and UCS was five cylinder specimens, for slake-durability index was ten irregular lumps and for $I_{S(50)}$, BTS and BPS was ten cylinder, ten disc and ten thin disc specimens, respectively.

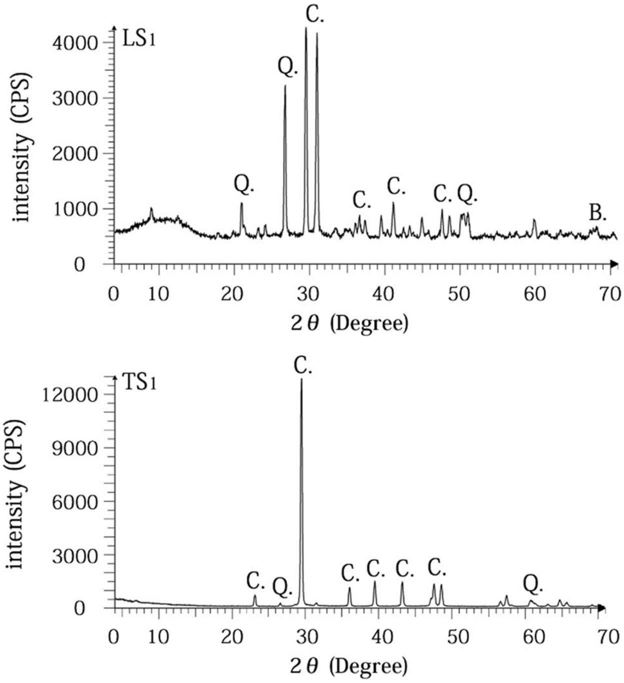


Fig. 4 Diffractograms of the representative rock samples

The slake-durability test is performed on the samples up to three cycles in natural water. The Schmidt hammer test was performed by N type Schmidt hammer with 2.207 N/m energies on rock blocks of samples. The axial point load test was applied to determine point load strength index ($I_{S(50)}$) of the rock samples. The Brazilian tensile test was carried out on rock specimens with lengths to diameter ratios from 0.5 to 0.75. In order to assess shear strength of the samples, thin disks core specimens with thicknesses ranging between 5 and 15 mm were tested under block punch. Prepared NX core specimens with a 2:2 length/diameter ratio were tested for each rock sample to determine the values of UCS. Average values of the obtained geotechnical parameters including physical, index and mechanical properties for the rock samples are outlined in Tables 2, 3 and 4, respectively.

Texture coefficient (TC)

Williams et al. [51] defined rock texture as "the degree of crystallinity, grain size or granularity, and the fabric or geometrical relationships between the constituents of a rock." Affective textural characteristics on rock strength are grain size and shape, density, degree of interlocking, porosity, grain orientation, quartz content, the nature of grain boundaries and texture model. Compositional features requiring investigations are strength properties, and percentages of component grains and cementing materials [24]. The innovation of texture coefficient by Howard and Rowlands [23] is the most exclusive technique when applying petrography techniques to quantitatively express the concept of rock texture. These researchers developed a dimensionless quantitative measure of rock texture. The procedure can be formulated as follow:

$$TC = AW\left[\left(\frac{N_0}{N_0+N_1}\times\frac{1}{FF_0}\right)+\left(\frac{N_1}{N_0+N_1}\times AR_1\times AF_1\right)\right] \tag{1}$$

where, TC is the texture coefficient, AW is the grain packing weighting, N_0 is the number of grains whose aspect ratio is below a pre-set discrimination level, N_1 is the number of grains whose aspect ratio is above a pre-set discrimination level, FF_0 is the arithmetic mean of discriminated form-factors, AR_1 is the arithmetic mean of discriminated aspect ratios, and AF_1 is the angle factor, quantifying grain orientation [3, 4]. The grain packing weighting (AW), the arithmetic mean of discriminated aspect ratios (AR) and form factor (FF) were calculated based on following formula in Eqs. 2, 3 and 4, respectively:

Fig. 5 Prepared specimens of the studied rocks **a** limestone samples, **b** travertine samples

Table 2 Physical properties of the studied rocks

Sample	Physical properties					Description of γdry (IAEG [23])	Description of n (IAEG [23])
	GS	γdry (g/cm^3)	γsat (g/cm^3)	Wa (%)	n (%)		
LS1	2.66	2.61	2.67	2.32	5.80	High	Medium
LS2	2.56	2.52	2.60	3.33	7.83	High	Medium
LS3	2.42	2.38	2.47	1.79	4.41	Moderate	Low
TS1	2.37	2.32	2.35	1.22	2.80	Moderate	Low
TS2	2.25	2.20	2.26	2.41	5.60	Moderate	Medium
TS3	2.32	2.28	2.33	1.33	4.82	Moderate	Medium
TS4	2.30	2.26	2.30	1.84	5.04	Moderate	Medium
TS5	2.32	2.37	2.39	1.15	4.71	Moderate	Low
TS6	2.13	2.09	2.14	2.31	6.69	Low	Medium
Mean	2.37	2.34	2.39	1.97	5.30	Moderate	Medium
Std. Dev	0.16	0.16	0.16	0.71	1.43	–	–

Table 3 Index properties of the studied rocks

Sample	Index properties					
	VP (Km/s)	E (GPa)	HS	Id1 (%)	Id2 (%)	Id3 (%)
LS1	5.17	38.72	36	98.71	98.28	97.98
LS2	4.67	25.91	28	98.76	98.30	97.95
LS3	5.28	30.87	36	98.60	98.28	98.01
TS1	5.98	22.81	30	99.44	98.97	98.54
TS2	4.20	10.52	20	98.34	97.85	97.49
TS3	5.40	16.82	25	99.01	98.53	98.14
TS4	4.79	20.27	29	99.04	98.55	98.16
TS5	4.71	19.88	26	99.11	98.68	98.30
TS6	3.43	8.73	20	98.53	97.90	97.39
Mean	4.85	21.62	27.78	98.84	98.37	98.00
Std. Dev	0.74	9.46	5.85	0.34	0.36	0.36

Table 4 Mechanical properties of the studied rocks

Sample	Mechanical properties			
	UCS (MPa)	$I_{S(50)}$ (MPa)	BTS (MPa)	BPS (MPa)
LS1	50.13	10.32	7.93	9.36
LS2	25.19	8.20	4.76	7.83
LS3	51.51	11.86	9.22	10.27
TS1	31.96	9.15	7.74	6.15
TS2	19.37	6.28	5.08	4.25
TS3	25.34	7.00	6.85	5.13
TS4	28.35	8.61	7.18	6.46
TS5	25.89	7.54	6.19	5.50
TS6	18.52	6.40	5.16	4.88
Mean	30.70	8.37	6.68	6.65
Std. Dev	12.13	1.85	1.51	2.08

$$\mathrm{AW} = \Sigma \frac{(\text{grain areas within the reference area boundary})}{(\text{area boundary by the reference area boundary})} \quad (2)$$

$$\mathrm{AR} = \frac{L}{W} \quad (3)$$

$$\mathrm{FF} = \frac{4\pi A}{P^2} \quad (4)$$

where, L is length, W is width, P is perimeter and A is area. The angle factor (AF) is calculated by summing the products of the class weightings and the fractions of the total number of angular differences in each class from equation below:

$$\mathrm{AF} = \sum_{i=1}^{9} \left(\frac{x_i}{\frac{N(N-1)}{2}} \right) \times i \quad (5)$$

where, N is the total number of elongated particles, X_i is the number of angular differences in each class and i is the weighting factor and class number [14].

Calculating the texture coefficient (TC) on obtained TIFF format images of thin sections was performed by JMicroVision (v1.27) software. The program, containing most of the common image processing operations, has an efficient visualization system and innovative features. This software has been developed to analyze high definition images of thin sections and is a powerful software for object analyses such as determining size, shape, orientation and texture of different rocks. After calibrating the images and drawing grains boundary, related parameters including length (L), width (W), perimeter (P), area (A) and orientation of grains were determined by the software (Fig. 6). Requirement parameters such as AW, AR, FF and AF were determined after calculations, and the texture coefficient derivations are summarized in Table 5. Also, the comparative diagrams of the values of texture coefficient for the studied rock samples are presented in Fig. 7a. According to the histograms, the average value of TC is 0.55 and standard deviation (Std. Dev.) value equal to 0.25 which is presented in Fig. 7b. The standard deviation values in all samples are very low, that shows the dispersion in the values of TC is low (Fig. 7b). As can be seen from Table 5 and Fig. 7, the values of TC for limestone samples are higher than travertine samples. The samples of LS_3 and TS_6 have maximum and minimum values of TC, equal to 0.98 and 0.30, respectively. Also, results show when AW and AR_1 increase, the values of TC will increase too.

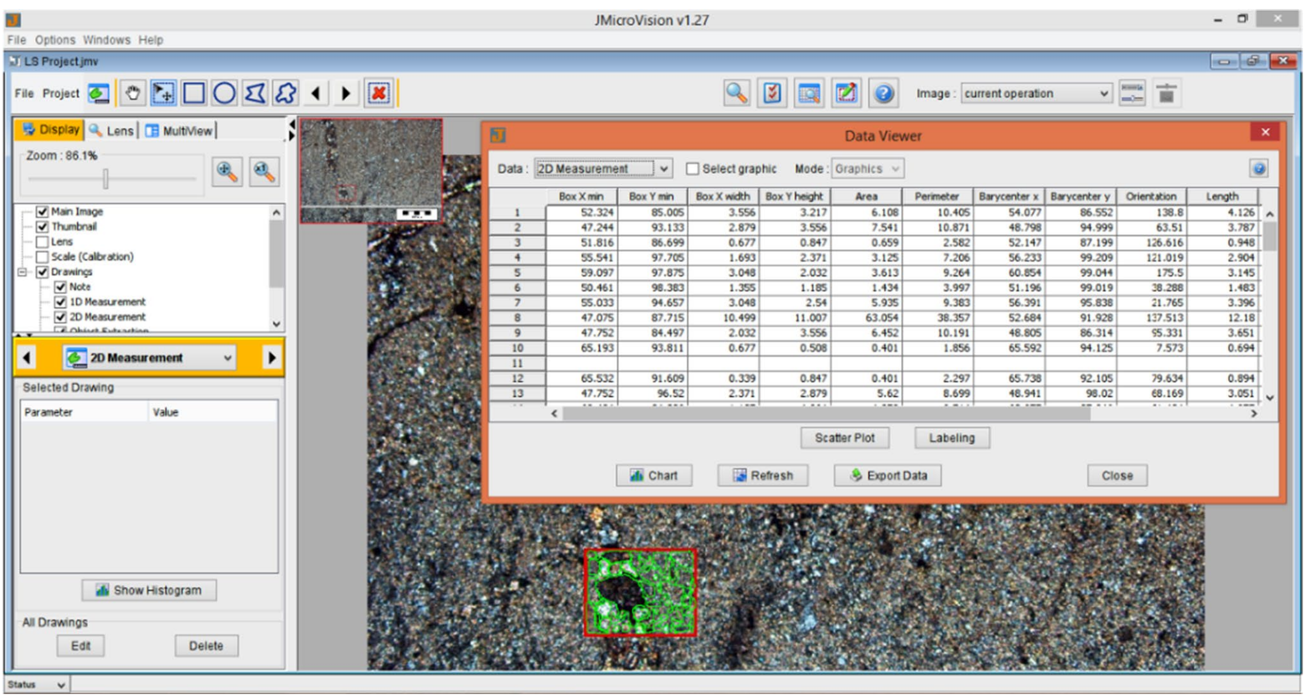


Fig. 6 Calculation procedure of TC parameter in JMicroVision (v1.27) setting

Table 5 Values of texture coefficient derivations

Sample	*AW*	$\frac{N_0}{N_0+N_1}$	$\frac{1}{FF_0}$	$\frac{N_1}{N_0+N_1}$	AR_1	AF_1	*TC*
LS1	0.68	0.68	1.35	0.32	1.90	0.75	0.94
LS2	0.64	0.86	0.90	0.14	1.74	0.75	0.62
LS3	0.87	0.77	1.04	0.23	1.86	0.75	0.98
TS1	0.39	0.83	1.32	0.17	1.78	0.50	0.49
TS2	0.31	0.91	1.07	0.09	1.50	0.50	0.33
TS3	0.32	0.88	1.18	0.12	1.54	0.50	0.36
TS4	0.49	0.95	1.07	0.05	1.41	0.50	0.51
TS5	0.36	0.83	1.22	0.17	1.76	0.50	0.42
TS6	0.27	0.76	1.20	0.24	1.75	0.50	0.30

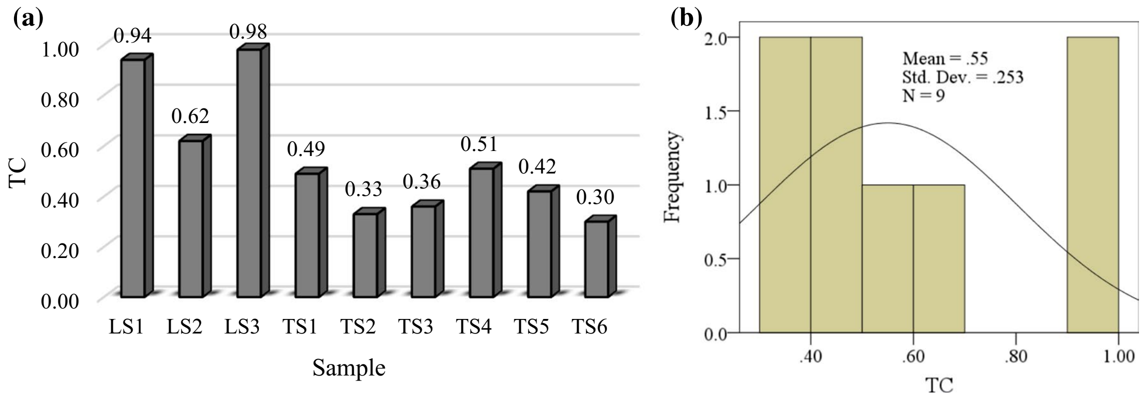


Fig. 7 **a** Comparative diagrams of texture coefficient (TC) values and **b** histogram of TC for the rocks

Statistical analysis

Statistical analyses consist of determining relationships between variables namely minerals content, texture coefficient, and geotechnical properties of the studied rocks were performed by simple regression analysis (SRA) method in statistics software IBM SPSS (V.24.0.) [26]. The values of R were calculated from the following equation:

$$R = \frac{n\Sigma X_i Y_i - (\Sigma X_i)(\Sigma Y_i)}{\sqrt{n(\Sigma X_i^2) - (\Sigma X_i)^2}\sqrt{n(\Sigma Y_i^2) - (\Sigma Y_i)^2}} \quad (6)$$

For simple regression evaluation, in the first step, main mineral constituents, namely quartz (Q.) and calcite (C.) percent, were considered as independent variable and TC was considered as the dependent variable. The diagrams of correlation between calcite and quartz content with texture coefficient are presented in Fig. 8a and b, respectively. A direct linear relationship exists between percent of calcite and texture coefficient with good correlation coefficient equal to $R=0.79$. Stronger linear relationship was found between percent of quartz and texture coefficient with high correlation coefficient ($R=0.85$). It is obviously seen that quartz content has more effect on TC than calcite content.

Equation 7 and 8 were presented in order to calculate the texture coefficient by mineralogy study and value of major minerals of rocks:

$$TC = 0.03C - 0.59 \quad (7)$$

$$TC = 0.04Q + 0.06 \quad (8)$$

The relationship between percentages of calcite and quartz versus texture coefficient is presented by a three variable map in Fig. 9. This shows the effect of minerals content on texture coefficient. This figure shows that increasing in calcite and quartz content results an increase in the texture coefficient. Therefore, the texture coefficient of studied rocks is controlled by the presence of major minerals including quartz and calcite.

In the second stage of statistical analyses, each geotechnical parameters of the rocks had been taken as a dependent variables and TC values were considered as independent variables. The correlations between texture coefficient (TC) and specific gravity (G_S), dry unit weight (γ_{dry}), saturated unit weight (γ_{sat}), water absorption ($\underline{W}_a$), porosity (n), P-wave velocity (V_P), elasticity modulus (E), Schmidt rebound hardness (H_S), second cycle of slake-durability index (Id_2),

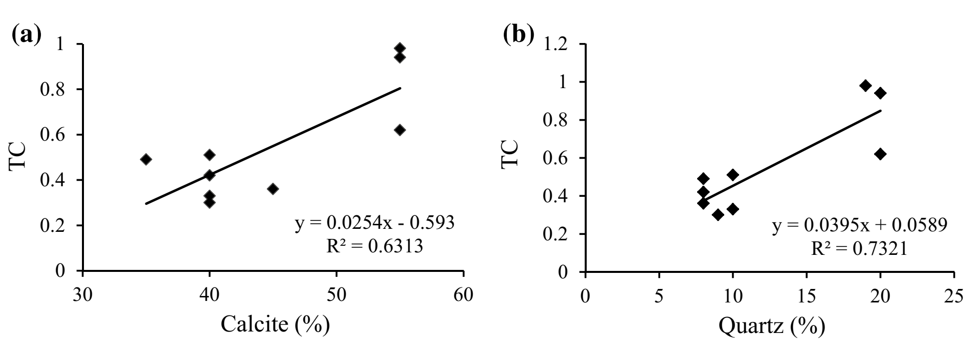
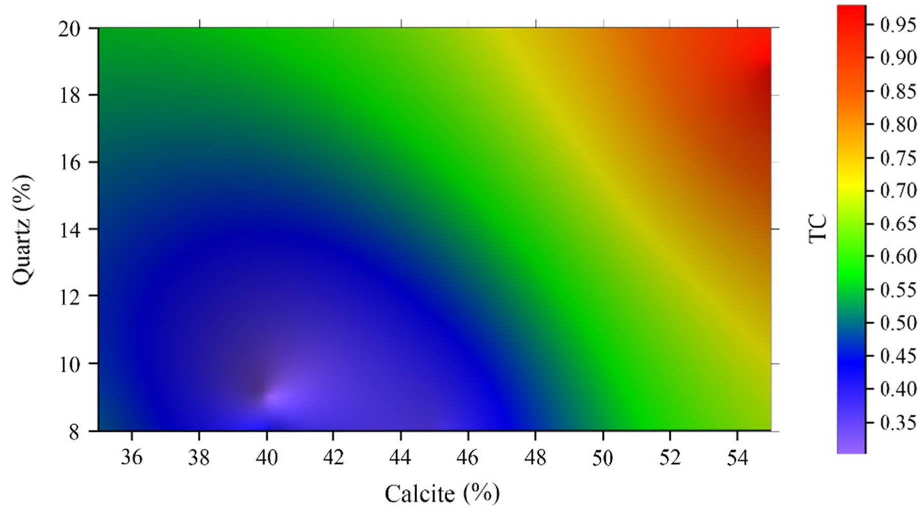


Fig. 8 **a** Correlation between calcite percent and texture coefficient and **b** Correlation between quartz percent and texture coefficient

Fig. 9 Three variable map of texture coefficient versus calcite and quartz percent



uniaxial compressive strength (UCS), point load strength index ($I_{S(50)}$), Brazilian tensile strength (BTS) and block punch strength (BPS) are presented in Fig. 10a to k, respectively. Also, obtained empirical equations and the statistical parameters including R^2, R and P-values (Sig. 2-tailed) are detailed in Table 6.

In order to assess the performance degree of regression analyses root mean square error (RMSE), coefficient values account for (VAF), mean absolute percentage error (MAPE) and performance index (PI) were calculated and their values are presented in Table 7. These statistical parameters are calculated from the following equations:

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{N}\right) \times \sum_{i=1}^{N} (y - y')^2} \tag{9}$$

$$\mathrm{VAF} = \left[1 - \frac{\mathrm{vary} - y'}{\mathrm{vary}}\right] \times 100 \tag{10}$$

$$\mathrm{MAPE} = \left[\frac{1}{N} \sum\nolimits_{i=1}^{N} \left|\frac{y - y'}{y}\right|\right] \times 100 \tag{11}$$

$$\mathrm{PI} = \left[R^2 + \left(\frac{\mathrm{VAF}}{100}\right) - \mathrm{RMSE}\right] \tag{12}$$

where, y and y' are the experimental and calculated values of the geotechnical parameters, respectively, and N is the total number of data (samples). The model will be excellent if $R = 1$, RMSE = 0, VAF = 100, MAPE = 0 and PI = 100.

Calculated values of geotechnical properties that were obtained by models of simple regression analyses are presented in Table 8. Also, the mean values and standard deviation of calculated values for all models are presented in this table. In order to compare the mean values and standard deviation of experimental and calculated values of geotechnical properties, comparative diagrams are presented in Fig. 11a and b. Based on the results, the obtained values of the mean and standard deviation in SRA models are approximately similar to experimental values or vary close to them, and have less variety than calculated values.

In order to compare the results of SRA models for predicting the geotechnical properties, experimental and calculated values; also a 45° line ($y = x$) has been plotted in diagrams and presented in Fig. 12a to f. It should be noted that the adaption rate of trend lines with 45° line shows the validity of predictive models.

The correlation between experimental and calculated values of dry and saturated unit weight that were obtained from TC is presented in Fig. 12a. Based on this graph, the trend lines partly fit to 45° line and show the moderate validity of the experimental equations. Whereas, trend lines of W_a, n and V_P intercept to 45° line (Fig. 12b). The correlation between experimental and calculated values of E and H_S is presented in Fig. 12c. It is clear that the trend lines partly overlap together and fit to 45° line and show the high validity of predictive models. Moderate validity of the experimental equations of SRA for estimating Id_2 is showed in Fig. 12d. The correlation between experimental and calculated values of uniaxial compressive strength is presented in Fig. 12e. It shows the trend line of UCS entirely fits to 45° line. The graph of relationships between experimental results and calculated values of $I_{S(50)}$, BTS and BPS is shown in Fig. 12f. It can be obviously seen from this figure that the calculated values of $I_{S(50)}$ and BPS are closer to the corresponding experimental values and completely fits to 45° line. It means that the trend line of BTS model does not completely fit to 45° line and the results of $I_{S(50)}$ and BPS are better than BTS.

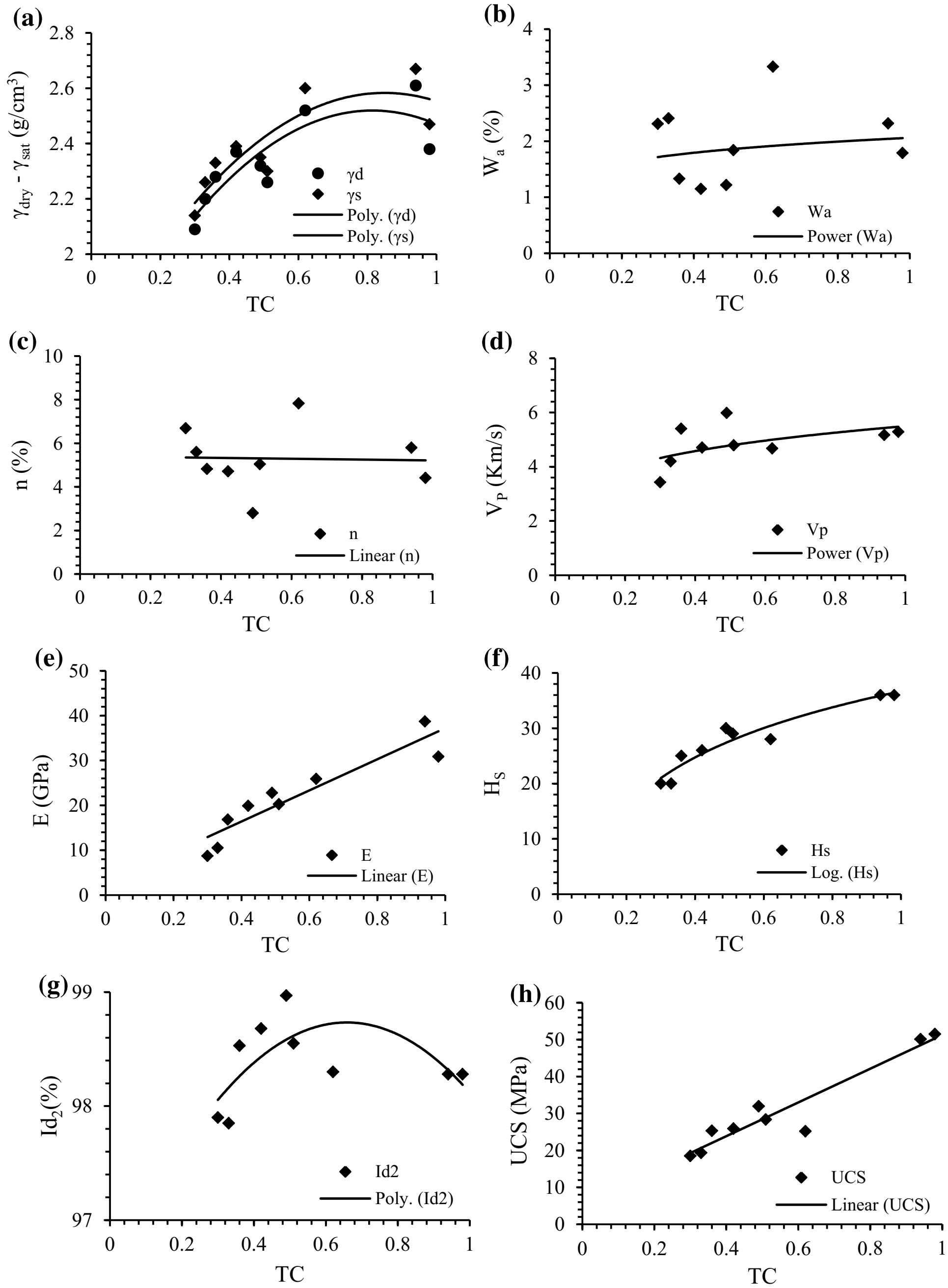


Fig. 10 Correlations between texture coefficient (TC) and **a** dry and saturated unit weights (γ_{dry}, γ_{sat}), **b** water absorption (W_a), **c** porosity (n), **d** P-wave velocity (V_P), **e** elasticity modulus (E), **f** Schmidt rebound hardness (H_S), **g** slake-durability index (Id_2), **h** uniaxial compressive strength (UCS), **i** point load strength index ($I_{S(50)}$), **j** Brazilian tensile strength (BTS) and **k** block punch strength (BPS)

Discussions

Thin section studies indicated that the rock samples were commonly composed of quartz and calcite. Based on the physical test results, the samples of TS_6 and LS_1 have the minimum and maximum values of dry unit weight and the TS_1 and LS2 samples have the minimum and maximum values of porosity, respectively. Results show the TS_6 and TS_1 samples have the minimum and maximum P-wave velocities, respectively. Based on the rock classifications by IAEG [25], most of the samples are moderate in dry unit weight, low to moderate in porosity and have low to very high values of P wave velocity. The LS_1, LS_3 and TS_2, TS_6 samples have the minimum and maximum values of Schmidt rebound hardness, respectively. The TS_6 and TS_1 samples have the maximum and minimum slake-durability index values in the third cycle (Id_3) of the test, respectively. According to the results from UCS test, the TS_6 and LS_3 samples have the minimum and maximum UCS values, equal to 18.52 and 51.51 MPa, respectively. The TS_2 and LS_3 samples have the minimum and maximum $I_{S(50)}$ values, equal to 6.28 and 11.86 MPa, respectively. On the basis of the results from Brazilian test,

Fig. 10 (continued)

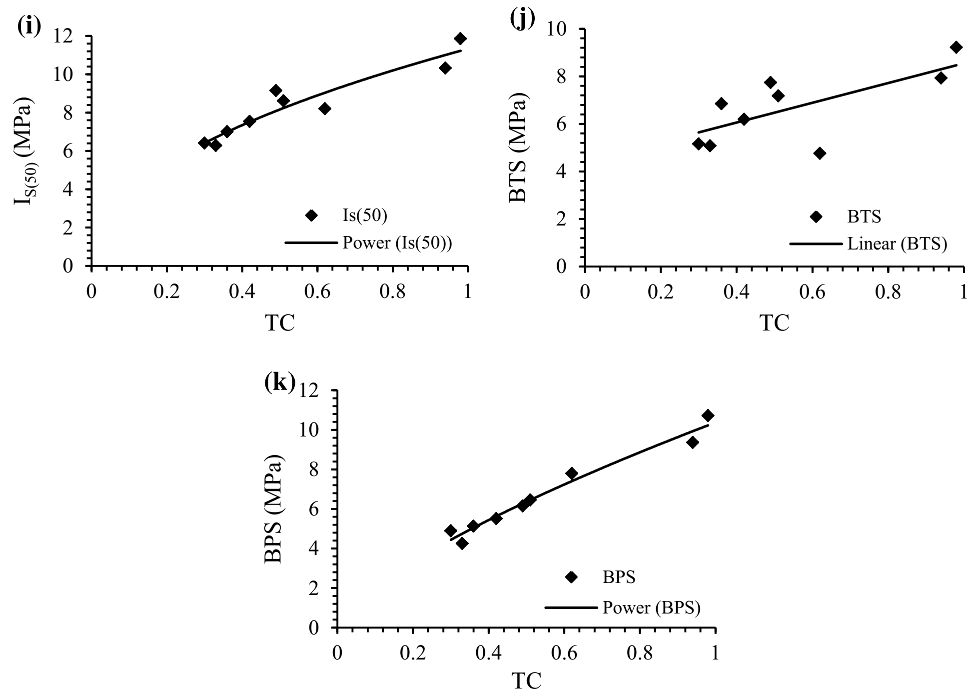


Table 6 Empirical equations and statistical parameters from regression analyses

Equation No. (Model)	Parameter	Equation	Equation type	R^2	R	Sig. (2-tailed)
1	TC—γ_{dry}	$\gamma_{dry} = -1.44TC^2 + 2.35TC + 1.56$	Polynomial	0.72	0.85	0.200
2	TC—γ_{sat}	$\gamma_{sat} = -1.32x^2 + 2.24TC + 1.63$	Polynomial	0.75	0.87	0.011
3	TC—W_a	$n = 2.06TC^{0.1518}$	Power	0.03	0.17	0.933
4	TC—n	$W_a = -0.19TC + 5.40$	Linear	0.00	0.10	0.650
5	TC—V_P	$V_P = 5.50TC^{0.2}$	Power	0.28	0.53	0.246
6	TC—E	$E = 34.70TC + 2.53$	Linear	0.86	0.93	0.000
7	TC—H_S	$H_S = 13.05\ln(TC) + 36.69$	Logarithmic	0.92	0.96	0.000
8	TC – Id_2	$Id_2 = -5.28TC^2 + 6.96TC + 96.44$	Polynomial	0.42	0.65	0.890
9	TC—UCS	$UCS = 45.68TC + 5.57$	Linear	0.91	0.95	0.000
10	TC—$I_{S(50)}$	$I_{S(50)} = 11.33TC^{0.4733}$	Power	0.90	0.95	0.000
11	TC—BTS	$BTS = 4.19TC + 4.39$	Linear	0.50	0.71	0.037
12	TC—BPS	$BPS = 10.38TC^{0.7054}$	Power	0.96	0.98	0.000

the LS_2 and LS_3 samples have minimum and maximum BTS values, equal to 4.76 and 9.22 MPa, respectively. Based on the results from block punch test, the TS_2 and LS_3 samples have the minimum and maximum BPS values, equal to 4.25 and 10.27 MPa, respectively.

The regression analyses indicated that the most of the geotechnical properties of the studied rocks are related to petrographic and textural characteristics. So, this method is an efficient technique for assessing the relationships between the parameters. Figure 10a shows direct polynomial relationships between TC and dry and saturated unit weights with acceptable correlation coefficients (R = 0.85 and 0.87). This means that the TC values are increased with increasing the unit weight in the tested rock samples. Figures 10b and 7c indicate poor reverse power and linear relations between TC and water absorption and porosity, respectively. This means that the TC values of the studied rock samples is not related to these parameters. Because, texture of rocks is defining as the shape, arrangement and size of crystals or grains of the rock. Based on this definition, porosity is not a textural factor and it is not considered in JMicroVision software. So, the TC is not related to porosity and the obtained results from the present study confirm this issue. On the other hand, the water absorption and P-wave velocity of the studied rocks

Table 7 Values of RMSE, VAF and MAPE in obtained models

Equation No	RMSE	VAF (%)	MAPE (%)	PI
1	0.08	72.22	4.34	72.64
2	0.08	74.78	3.66	75.67
3	0.66	2.78	11.98	2.37
4	1.35	0.11	9.88	– 1.35
5	0.61	23.08	4.98	27.62
6	3.33	86.05	9.23	83.53
7	1.61	91.50	0.32	91.31
8	0.26	41.61	0.04	42.06
9	3.51	90.60	3.23	88.40
10	0.58	88.98	6.65	90.31
11	1.02	48.52	4.68	49.46
12	0.37	96.83	6.11	96.60

are controlled by porosity. So, these two parameters are not related to the TC either. Based on Fig. 10f, a direct logarithmic relationship exists between H_S and TC with good correlation coefficient (R = 0.96). Whereas, moderate correlations have been found between TC and V_P, Id_2 and BTS as power, polynomial and linear with correlation coefficients of 0.53, 0.65 and 0.71, respectively (Fig. 7d, g, j). Very good direct relations were found between TC and elasticity modulus and mechanical properties including UCS, $I_{S(50)}$ and BPS as linear and power with correlation coefficients of 0.93, 0.95, 0.95 and 0.98, respectively (Fig. 10e, h, i, k). Significance level for models of E, HS, UCS, $I_{S(50)}$ and BPS calculated equal to 0.000 that indicated when TC is considered as an input the obtained predictive models can predict values of independent variable with 99% confidence limit. As a general result from the regression analyses, texture coefficient (TC) is very helpful parameter for determining geotechnical properties of the studied rocks especially dry and saturated unit weight, H_S, UCS, $I_{S(50)}$ and BPS. Statistical indexes including RMSE, VAF and MAPE show the performance degree, validity and errors values of created model and obtained empirical equations by TC values and simple regression analyses. Based on the results, Model 3, 4 and 5 has not enough validity for predicting related parameters. Whereas, Model 9, 10 and 12, which correlate UCS, $I_{S(50)}$ and BPS with TC (with VAF values of 90.60, 88.98 and 96.83, respectively) are valid and have high prediction capacity. Also, Model 1 and 2, for determining dry and saturated unit weight, have lowest values of RMSE and MAPE implying the low errors and high performance degrees of the models. Performance appraisal by PI shows model 12, that correlated BPS and TC, has a higher performance than the other models.

Conclusions

In the current study, mineralogical, petrographic and textural characteristics of nine carbonate rock samples of limestone and travertine were investigated by thin section studies and XRD analyses. Some geotechnical tests for determining physical properties, Schmidt rebound hardness, slake-durability index, ultrasonic P-wave velocity and mechanical properties namely uniaxial compressive strength, point load strength, Brazilian tensile strength and block punch strengths were performed on standard obtained core specimens. Mineralogical studies by thin section and XRD analysis show the studied samples dominantly composed of quartz and calcite. The texture investigations were performed by calculating related parameters containing length, width, perimeter, area and orientation of mineral grains composing the rocks using JMicroVision 1.27 software and microscopic images obtained from thin sections studies. Results indicated that the limestone samples have higher TC values than the travertine ones. In order to study the effect of mineralogy on TC

Table 8 Calculated values of geotechnical properties obtained from TC

Sample	Geotechnical properties											
	γdry	γsat	W_a (%)	n (%)	V_P Km/s	E (GPa)	H_S	I_{d2} (%)	UCS (MPa)	$I_{S(50)}$ (MPa)	BTS (MPa)	BPS (MPa)
LS1	2.50	2.57	2.04	5.23	5.43	35.15	35.89	98.31	48.51	11.01	8.30	9.93
LS2	2.46	2.51	1.92	5.29	4.99	24.04	30.46	98.73	33.89	9.04	6.97	7.41
LS3	2.48	2.56	2.06	5.22	5.47	36.54	36.43	98.19	50.34	11.23	8.47	10.23
TS1	2.37	2.41	1.85	5.31	4.77	19.53	27.38	98.58	27.95	8.09	6.43	4.27
TS2	2.18	2.23	1.74	5.34	4.40	13.98	22.22	98.16	20.65	6.71	5.76	4.75
TS3	2.22	2.27	1.77	5.34	4.48	15.02	23.36	98.26	22.02	6.99	5.89	5.05
TS4	2.39	2.43	1.86	5.31	4.80	20.23	27.91	98.62	28.78	8.24	6.51	6.45
TS5	2.30	2.34	1.81	5.32	4.62	17.10	25.37	98.43	24.76	7.52	6.14	5.63
TS6	2.14	2.19	1.72	5.35	4.32	12.94	20.98	98.05	19.28	6.41	5.64	4.44
Mean	2.34	2.39	1.86	5.30	4.81	21.62	27.78	98.37	30.70	8.36	6.68	6.68
SD	0.13	0.14	0.12	0.05	0.42	8.77	5.59	0.23	11.54	1.76	1.05	2.13

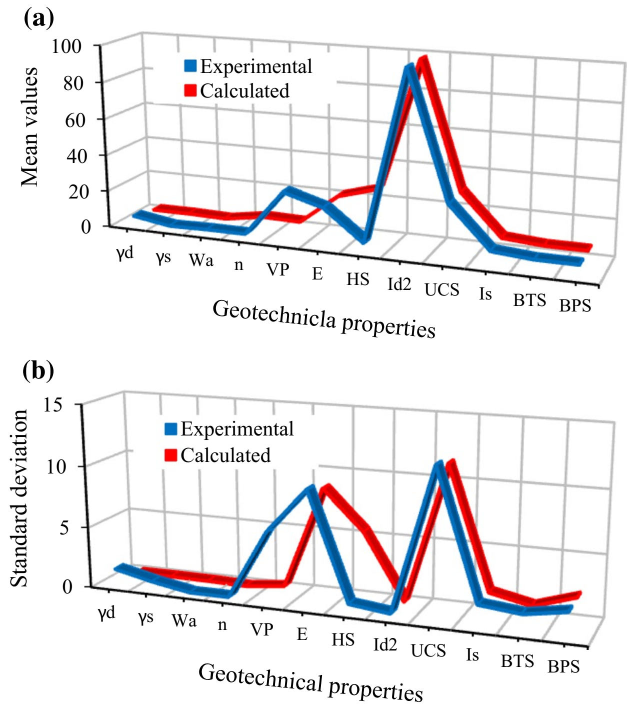


Fig. 11 Comparative diagram of **a** mean values and **b** standard deviation for experimental and calculated values of geotechnical properties

values, direct linear relationships were found between percentages of calcite, quartz and texture coefficient with high correlation coefficient. Also the three variable map shows that when calcite and quartz increase, texture coefficient increases. The relations between geotechnical properties and TC were investigated by statistical analyses. According to simple regression analysis results, the relationships between obtained parameter were direct linear, polynomial, power and logarithmic functions with correlation coefficients between 0.10 and 0.98. In fact, there was not found good relations between TC and porosity, water absorption and P-wave velocity, because the parameters are not textural factors and they are not considered in JMicroVision software. But, strong, meaningful and acceptable relations were obtained between TC and γ_{dry}, $\gamma_{sat,}$ H_S, UCS, $I_{S(50)}$ and BPS, as well as moderate correlations were found between TC and V_P, Id_2 and BTS. Also, it was found that strength of the studied rock samples increased with increasing the values of TC. Significant level values (Sig.) in the range of 0.000 to 0.933 show the engineering parameters are significantly related together. Validity and performance degrees of obtained empirical equations were investigated by statistical parameter including RMSE, VAF and MAPE which showed the errors of models are negligible and high performance capacity were detected in some models. Geotechnical properties were calculated by obtained models of simple regression analyses and mean and standard deviation of them were compared together. Based on the results, the obtained values of the mean and standard deviation of calculated values are approximately similar to experimental values. Experimental and calculated values of geotechnical properties that were obtained from laboratory tests and were predicted by the simple regression analysis models were compared with 45° line ($y = x$). The results show the trend lines of E, H_S, UCS, $I_{S(50)}$, and BPS models are more fit to $y = x$ line. This means that the predicted values are approximately equal to the experimental values. Finally, the results indicated that the geotechnical properties of the studied samples were closely related to petrographic properties and especially texture coefficient. So, the obtained empirical equations provide good predicting model for mechanical and physical properties of the rocks.

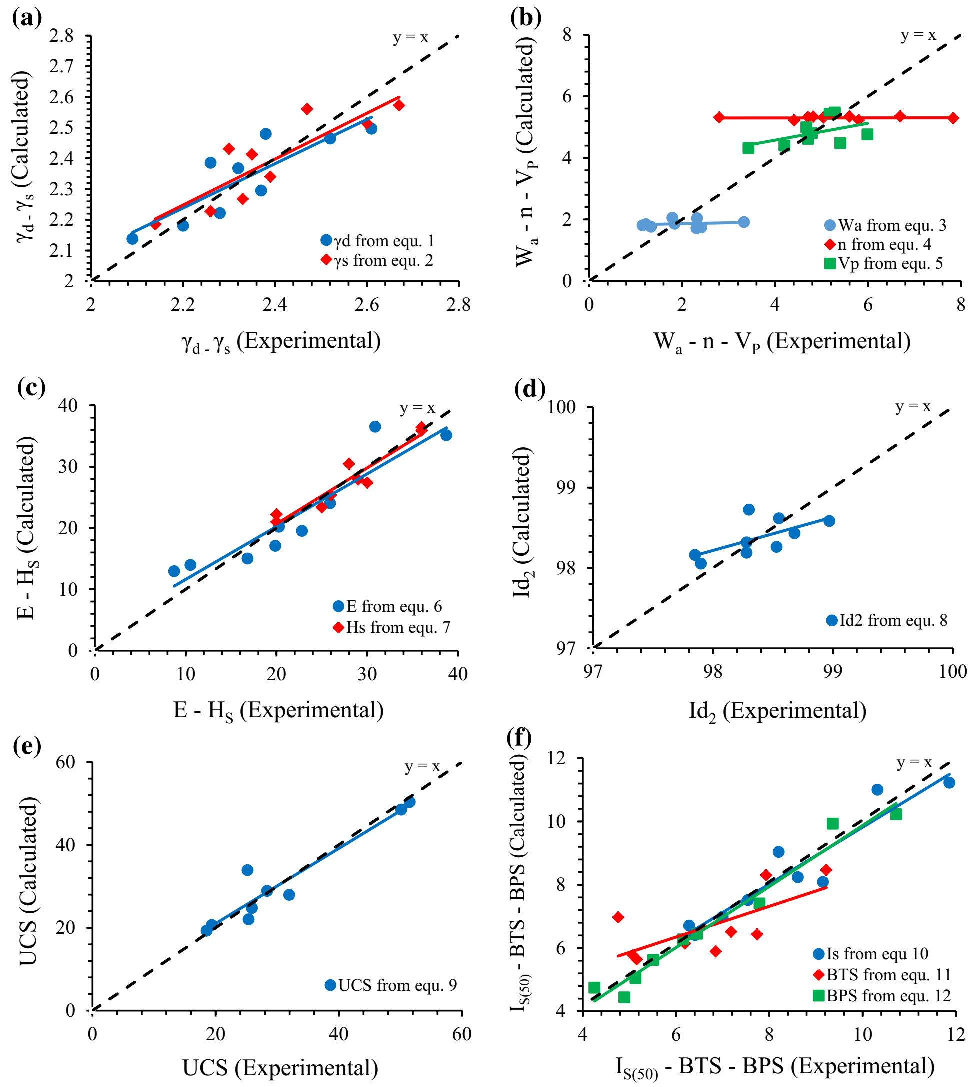


Fig. 12 Plots of experimental and calculated values of **a** dry and saturated unit weights (γ_{dry} and γ_{sat}), **b** water absorption, porosity and P-wave velocity (W_a, n and V_P), **c** elasticity modulus and Schmidt rebound hardness (E and H_S), **d** slake-durability index (Id_2), **e** uniaxial compressive strength (UCS), **f** point load strength index, Brazilian tensile strength and block punch strength ($I_{S(50)}$, BTS and BPS)

Declaration

Conflict of interest The author does not have any conflict of interest.

Ethical approval This article does not contain any studies with human participants.

References

1. Ajalloeian R, Jamshidi A, Khorasani R (2020) Assessments of ultrasonic pulse velocity and dynamic elastic constants of granitic rocks using petrographic characteristics. Geotech Geol Eng 38:2835–2844
2. Ajalloeian R, Mansouri H, Baradaran E (2016) Some carbonate rock texture effects on mechanical behavior, based on Koohrang tunnel data. Iran Bull Eng Geol Environ 76(1):295–307
3. Alber M, Kahraman S (2009) Predicting the uniaxial compressive strength and elastic modulus of a fault breccia from texture coefficient. Rock Mech Rock Eng 42:117–127
4. Asheghi R, Shahri AA, Zak MK (2019) Prediction of uniaxial compressive strength of different quarried rocks using metaheuristic algorithm. Arab j Sci and Eng 44:8645–8659
5. Atici U, Comakli R (2019) Evaluation of the physico-mechanical properties of plutonic rocks based on texture coefficient. J Sout Afr Ins Min Metal 119(1):63–69
6. Azzoni A, Bailo F, Rondena E, Zaninetti A (1996) Assessment of texture coefficient for different rock types and correlation with uniaxial compressive strength and rock weathering. Rock Mech Rock Eng 29:36–46
7. Bandini A, Berry P (2013) Influence of Marble's Texture on its Mechanical Behavior. Rock Mech Rock Eng 46:785–799
8. Barzegar R, Sattarpour M, Nikudel MR, Moghaddam A (2016) Comparative evaluation of artificial intelligence models for prediction of uniaxial compressive strength of travertine rocks, Case study: Azarshahr area, NW Iran. Model Earth Sys Environ 2:76–89

9. Chen W, Konietzky H, Abbas SM (2015) Numerical simulation of time-independent and -dependent fracturing in sandstone. Eng Geol 193(2):118–131
10. Cheshomi A, Moradizadeh M, Fizollahi S (2020) Impact of Petrography and Hardness of Sandstone Minerals on the Wear of Mini Disk Cutters through Rolling Indentation Abrasion Test (RIAT). Rock Mech Rock Eng 53:5593–5616
11. Cowie S, Walton G (2018) The effect of mineralogical parameters on the mechanical properties of granitic rocks. Eng Geol 240(5):204–225
12. Cueto M, López-Fernández C, Pando L, Arias D (2020) Engineering geological assessment using geochemical, mineralogical, and petrographic analysis along the Riyadh Metro Line 3 (Saudi Arabia). Arab J Geosci. https://doi.org/10.1007/s12517-020-5091-8
13. Dogan AU, Ozsan A, Dogan M, Karpuz C, Brenner RL (2006) Classifications of hardgrounds based upon their strength properties. Carb Evap 21(1):14–20
14. Ersoy A, Waller MD (1995) Textural characterisation of rocks. Eng Geol l39:123–136
15. Ersoy H, Acar S (2016) Influences of petrographic and textural properties on the strength of very strong granitic rocks. Environ Earth Sci 75:1461–1476
16. Esamaldeen A, Guang W (2014) Selection of influential microfabric properties of anisotropic amphibolite rocks on its uniaxial compressive strength (UCS): a comprehensive statistical study. J App Math Phyi 2:1130–1138
17. Fereidooni D (2016) Determination of the geotechnical characteristics of hornfelsic rocks with a particular emphasis on the correlation between physical and mechanical properties. Rock Mech Rock Eng 49(7):2595–2608
18. Garia S, Kumar Pal A, Ravi K, Nair AM (2019) A comprehensive analysis on the relationships between elastic wave velocities and petrophysical properties of sedimentary rocks based on laboratory measurements. J Pet Exp Prod Tech 9:1869–1881
19. Germinario L, Siegesmund S, Maritan L, Mazzoli C (2017) Petrophysical and mechanical properties of Euganean trachyte and implications for dimension stone decay and durability performance. Environ Earth Sci 76:739–760
20. GSI (Geological Society of Iran) (1975) Geological quadrangle map of Iran, No. 6862, Scale 1:100000, Printed by Offset Press Inc. Tehran
21. Hemeda S, Khalil M, Shoeb A, Abd El Aziz A (2018) The effectiveness of Nano materials and Nano-modified polymers for preservation of historic brick masonry in Rashid. Egypt Int J Cons Sci 9(4):835–846
22. Hemeda S, Pitilakis K (2010) Serapeum temple and the ancient annex daughter library in Alexandria, Egypt: Geotechnical–geophysical investigations and stability analysis under static and seismic conditions. Eng Geol 113:33–43
23. Howarth DF, Rowlands JC (1986) Development of an index to quantify rock texture for qualitative assessment of intact rock properties. Geotech Testing J 9:169–179
24. Howarth DF, Rowlands JC (1987) Quantitative assessment of rock texture and correlation with drillability and strength properties. Rock Mech Rock Eng 20:57–85
25. IAEG (1979) Classification of rocks and soils for engineering geological mapping, Part 1: rock and soil materials. Rep Comm Eng Geol Mapp Bull Int Assoc Eng Geol 19:364–371
26. IBM Corp Released (2016) IBP SPSS Statistics for Windows, version 24.0. Armonk, NY: IBM Corp
27. ISRM (2007) The Blue Book: The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring, 1974–2006," Compilation Arranged by the ISRM Turkish National Group, Ankara, Turkey, R. Ulusay and J. A. Hudson, Eds., Kazan Offset Press, Ankara
28. Jeng FS, Weng MC, Lin ML, Huang TH (2004) Influence of petrographic parameters on geotechnical properties of tertiary sandstones from Taiwan. Eng Geol 73:71–91
29. Jensen LR, Friis H, Fundal E, Moller P, Jespersen M (2010) Analysis of limestone micromechanical properties by optical microscopy. Eng Geol 110(3):43–50
30. Jing H, Nikafshan Rad H, Hasanipanah M, Jahed Armaghani D, Noman Qasem S (2020) Design and implementation of a new tuned hybrid intelligent model to predict the uniaxial compressive strength of the rock using SFS-ANFIS. Eng Comp. https://doi.org/10.1007/s00366-020-00977-1
31. Kamani M, Ajalloeian R (2018) Evaluation of engineering properties of some carbonate rocks trough corrected texture coefficient. Geotech Geol Eng 37:599–614
32. Khajevand R, Fereidooni D (2018) Assessing the empirical correlations between engineering properties and P wave velocity of some sedimentary rock samples from Damghan, northern Iran. Arab J Geos. https://doi.org/10.1007/s12517-018-3810-1
33. Khajevand R, Fereidooni D (2019) Utilization of the point load and block punch strengths to predict the mechanical properties of several rock samples using regression analysis methods. Inn Infra Sol. https://doi.org/10.1007/s41062-019-0201-8
34. Khanlari GR, Heidari M, Noori M, Momeni A (2016) The effect of petrographic characteristics on engineering properties of conglomerates from Famenin Region, Northeast of Hamedan. Iran Rock Mech Rock Eng 49(7):2609–2621
35. Koken E (2020) Investigation on fracture evolution of coal measure sandstones from mineralogical and textural points of view. Indi Geotech J 50:1024–1040
36. Kolay E, Baser T (2017) The effect of the textural characteristics on the engineering properties of the basalts from Yozgat region, Turkey. J Geo Soci Indi 90:102–110
37. Koralegedara NH, Maynard JB (2017) Chemical, mineralogical and textural properties of the Kope Formation mudstones: How they affect its durability. Eng Geol 228:312–322
38. Liang M, Tonnizam Mohamad E, Shirani Faradonbeh R, Jahed Armaghani D, Ghoraba S (2016) Rock strength assessment based on regression tree technique. Eng with Com 32(2):343–354
39. Manouchehrian A, Sharifzadeh M, Moghadam RH (2012) Application of artificial neural networks and multivariate statistics to estimate UCS using textural characteristics. Int J Min Sci Technol 22(2):229–236
40. Ozcelik Y, Bayram F, Yasitli NE (2013) Prediction of engineering properties of rocks from microscopic data. Arab J Geosci 6:3651–3668
41. Pappalardo G, Punturo R, Mineo S, Ortolano G, Castelli F (2015) Engineering geological and petrographic characterization of migmatites belonging to the Calabria-Peloritani Orogen (Southern Italy). Rock Mech Rock Eng 49:1143–1160
42. Prikiryl R (2006) Assessment of rock geomechanical quality by quantitative rock fabric coefficients: Limitations and possible source of misinterpretations. Eng Geol 87:149–162
43. Rahimi MR, Mohammadi SD, Beydokhti AT (2020) Effects of mineral composition and texture on durability of sulfate rocks in Gachsaran Formation. Iran Geotech Geol Eng 38:2619–2637
44. Salehin S, Hadavandi E, Chehreh Chelgani S (2020) Exploring relationships between mechanical properties of marl core samples by a coupling of mutual information and predictive ensemble model. Model Earth Sys Environ 6:575–583
45. Shakoor A, Bonelli RE (1991) Relationship between petrographic characteristics engineering index properties and mechanical properties of selected sandstone. Bull Assoc Eng Geol 28:55–71
46. Singh PK, Tripathy A, Kainthola A, Mahanta B, Singh V, Singh TN (2017) Indirect estimation of compressive and shear strength from simple index tests. Eng with Com 33(1):1–11

47. Singh TN, Verma AK (2012) Comparative analysis of intelligent algorithms to correlate strength and petrographic properties of some schistose rocks. Eng with Comp 28:1–12
48. Tandon RS, Gupta V (2013) The control of mineral constituents and textural characteristics on the petrophysical and mechanical (PM) properties of different rocks of the Himalaya. Eng geol 153:125–143
49. Ulusay R, Tureli K, Ider MH (1994) Prediction of engineering properties of selected litharenite sandstone from its petrographic characteristics using correlation and multivariate statistical techniques. Eng Geol 37:135–157
50. Wang Z, Li W, Wang Q, Liu S, Hu Y, Fan K (2019) Relationships between the petrographic, physical and mechanical characteristics of sedimentary rocks in Jurassic weakly cemented strata. Environ Earth Sci 78:131–143
51. Williams H, Turner FJ, Gilber CM (1982) Petrography. Freeman Company, San Francisco, W.H, p 369
52. Yalcinalp B, Aydin ZO, Ersoy H, Seren A (2017) Investigation of geological, geotechnical and geophysical properties of Kiratli (Bayburt, NE Turkey) travertine. Carbo Evapo 33:421–429
53. Zorlu K, Gokceoglu C, Ocakoglu F, Nefeslioglu HA, Acikalin S (2008) Prediction of uniaxial compressive strength of sandstones using petrography-based models. Eng Geol 96:141–158