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Relationship between Texture and Uniaxial Compressive Strength of Rocks

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Abstract

Uniaxial compressive strength (UCS) is one of the most important parameters of rocks that is routinely used in rock engineering designs. This parameter is influenced greatly by textural properties of rocks; hence it is possible to estimate it from quantified texture coefficient (TC). In this paper, fourteen different types of rocks were experimentally studied to evaluate the effect of texture coefficient on UCS. Thin sections were first prepared, and then some digital photographs were taken from each section and were digitized in computer. Then, the texture coefficient for all samples were calculated. Subsequently, UCS of the samples were measured in laboratory. Finally, relationships between TC and UCS of rock samples were evaluated and related mathematical equations were presented. Results showed that the UCS has a power relationship with TC which can be utilized for future estimation purposes.

Keywords: Texture Coefficient; Uniaxial Compressive Strength; Laboratorial Study; Statistical Relationship.

1. Introduction

Processes involved in the development of igneous and metamorphic rocks include some combination of crystal growth, solution, movement and deformation which is expressed as changes in texture (microstructure). Petrographic characteristics such as grain size shape of grains, degree of interlocking, type of contacts and mineralogy composition could affect the mechanical properties of the rock [1]. Recent advances in the quantification of aspects of crystalline rock textures, such as crystal size, shape, orientation and position, have opened new avenues of research that extend and complement the more dominant chemical and isotopic studies [2]. Williams et al. defined texture as "the degree of crystallinity, grain size or granularity, and the fabric or geometrical relationships between the constituents of a rock" [3]. Rock texture generally comprises two main parts: the grain and matrix, that the grains of rocks characteristics are more effective than matrix. In rock engineering tasks, rock texture is usually classified in four groups: a) grainy, b) porphyry, c) glassy, and d) destructive such as sandstone. Common texture of this classification is the grain texture that in igneous rocks the types are classified in some subgroup according to grain size including a) very coarse grained greater than 10 mm, b) coarse grains 5 to 10 mm, c) the average of the aggregate 2-5 mm, d) fine grains with grain size of 0.25 to 2 mm, and e) very fine grains less than 0.25 [4].

The uniaxial compressive strength (UCS) is one of the most important indices in rock mechanical studies, and it is commonly used for a variety of engineering applications such as rock mass classification and rock failure criteria. However, such tests require high-quality core samples which cannot always be obtained, particularly from weak, stratified, highly fractured, and weathered rocks [5]. Thus, many researchers use conventional statistical methods to

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estimate UCS from simple index parameters such as Schmidt hammer, point load, block punch, and petrographic properties [5-14]. UCS was shown to be correlated with some mechanical properties such as point load index, Schmidt hammer rebound number, and Los Angeles degradation abrasion loss [15, 16]. Variation in rock strength is explained by a number of factors including grain size, grain shape, degree of grain interlocking, preferred orientation, quartz content, matrix content, mineral composition, density, porosity, texture, moisture content, and state of alteration [17].

There are many methods and classifications to identify and explain the texture of rocks from mineralogy and petrology points of view. However, in engineering tasks, qualitative description of texture has not become very effective so far. Hence, methods to quantify the texture properties of rock samples are of interest of engineers and engineering geologists. In this paper, an experimental practice is taking on to quantitatively investigate rock texture properties and its relationship with strength characteristic to come up with useful relationships to be utilized in the future.

2. Laboratory Studies

2.1. Determination of Uniaxial Compressive Strength of Rocks

Fourteen rock samples were taken from different sites and uniaxial compressive strength tests were conducted on them considering the standards of the International Society for Rock Mechanics (ISRM). This is a basic test in most of the engineering projects. Results of the experiments are presented in Table 1.

Table 1. The results of laboratory studies

Rock sample	UCS (MPa)	Rock sample	UCS (MPa)
Granite Maraghe	87.5	Joshan-rood	95
Limestone 17	40	Monzonite	57
Limestone 75	51	Cheshme-Haji	63.23
West sample	84.6	Red Travertine	53
East sample	98.9	Khalkhal Travertine	50.5
Sanje Mine	67	Ordud 4	87
West Ordud	82.5	Nepheline	76

2.2. Measurement and Calculation the Texture Coefficient of Rocks

Texture coefficient is the most comprehensive and most reliable index to quantify the texture of a rock that has been first presented by the Howarth and Rowlands [17]. For evaluation of texture coefficient of each type of rock a thin section from typical section of studied rocks were prepared and five digital photographs were taken under the microscope from each section. To determine the texture coefficients of studied samples the photographs were imported into AutoCAD software where closed lines were drawn around the grains in digital form. Then, perimeter and area of each grain were determined. The large and small diameters of each grain were then determined. A sample of digital format of photographs is shown in Figure 1.

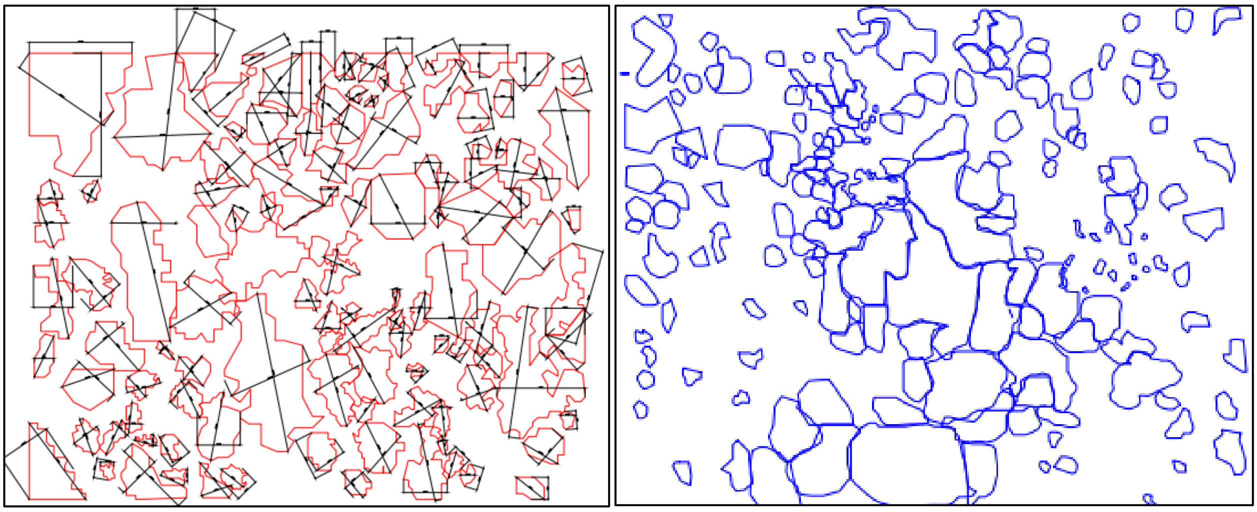

Figure 1. Two samples of digital format of photographs

After measurement of grains characteristics and texture parameters, this index is calculated with the following general equation [17]:

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

Where:

TC: Texture coefficient

AW: Area weighting (grain packing density)

N_0: Number of grains with aspect ratio (maximum Feret's diameter or length to minimum Feret's diameter or breadth) less than 2.0

N_1: Number of grains with aspect ratio greater than 2.0

FF_0: Arithmetic mean of form factor of all N_0 grains

AR_1: Arithmetic mean of aspect ratio of N_1 grains

AF_1: Angle factor orientation which were computed for all N_1 grains

The term "Area weighting" is defined as:

$$AW = \frac{Total\ grain\ areas\ within\ the\ reference\ area\ boundary}{Total\ area\ enclosed\ by\ the\ reference\ area\ boundary\ (including\ matrix\ area)} \quad (2)$$

Aspect ratio, which is the length to diameter ratio, is calculated by dividing the maximum length or diameter by minimum diameter or width of the firth. To calculate the maximum and minimum diameter, the distance between two parallel lines and tangent to each grain in several different directions is measured and finally the largest and smallest values of these intervals are considered as the maximum and minimum diameters (Figure 2).

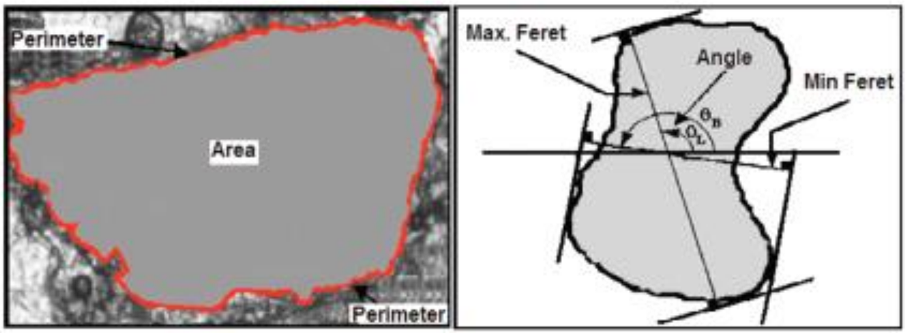

Figure 2. Demonstration of grain shape parameters [17]

The form factor illustrates shape deviates from circularity that is defined as:

$$FF = 4\pi \frac{Area}{(perimeter)^2} \quad (3)$$

Aspect ratio of grains (AR) is obtained by dividing the large diameter by small diameter of the grain. According to the geometric properties of an ellipse and definition of this indicator, it can be concluded that this index is a suitable criterion for evaluating oval of rock grains. This index is calculated by using thin sections and following equation:

$$AR = \frac{D_{max}}{D_{min}} \quad (4)$$

The last parameter in determining the texture coefficient is angle factor. Angle orientation of grains is obtained by angle factor quantification. This factor is only calculated for stretched and elongated grains for which the aspect ratio is greater than 2. Angle factor (AF_1) classified in Table 2. by weighting system. This system calculates the angular difference between all elongated grains with high accuracy. Angular difference can be classified into nine different classes which one weight is assigned to each class.

Table 2. Classes and weightings for absolute, acute angular differences

Weight (i)	Class range (β)	Number
1	$0 < \theta_{DMAX} \leq 10$	1
2	$10 < \theta_{DMAX} \leq 20$	2
3	$20 < \theta_{DMAX} \leq 30$	3
4	$30 < \theta_{DMAX} \leq 40$	4
5	$40 < \theta_{DMAX} \leq 50$	5
6	$50 < \theta_{DMAX} \leq 60$	6
7	$60 < \theta_{DMAX} \leq 70$	7
8	$70 < \theta_{DMAX} \leq 80$	8
9	$80 < \theta_{DMAX} \leq 90$	9

Therefore, for a group that have N grains, the number of unique angular difference is obtained from the following equation:

$$(N-1)+(N-2)+\cdots+2+1=(\frac{N(N-1)}{2}) \tag{5}$$

Angle factor is computed by sum of the classes and dividing by the total number of classes according to the following equation:

$$AF=\sum_{i=1}^{n}\left[\frac{X_i}{\frac{N(N-1)}{2}}\right]i \tag{6}$$

Where:

N: Total number of elongated grains;

X_i: Number of angular differences in each class;

i: Weighting factor and class number.

According to Figure 3, the context of angle factor is the angle between the horizon and the large diameter of the grain. The maximum angle is 180 degree.

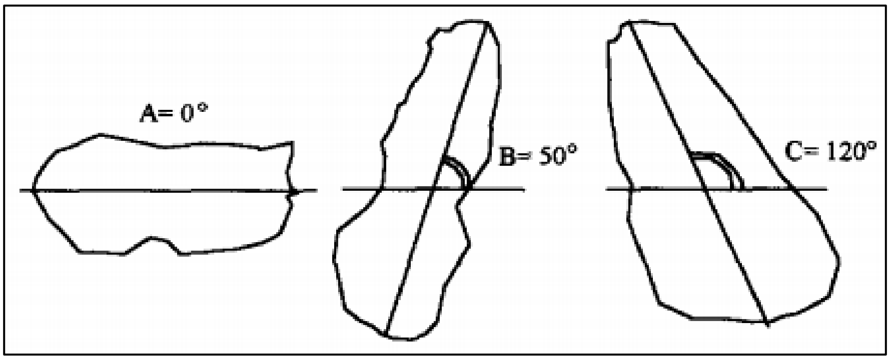

Figure 3. Illustration of deriving the angle factor

In order to better understand the context of angular factors, an example is given here. Suppose that in a rock there are 23 elongated grains, so there are so many different angles, so the number of angles difference would be 253 according to Equation 4. that is obtained from difference between the angle orientation and the horizon in different grains. To obtain the angle difference in different weights according to Table 3, the number of weights are identified and used in the equation. Angle factor has been calculated for the real data of sandstone as an example as follows.

$$\mathrm{AF}=\frac{[(28\times 1)+(29\times 2)+\cdots+(30\times 9)]}{253}=4.86 \tag{7}$$

Table 3. Angular deference in each class

Weight	Number of angular difference in each class (X_i)
1	28
2	29
3	39
4	25
5	25
6	27
7	29
8	21
9	30

Perimeter, large diameter and small diameter of grains were calculated as basic information of rock texture from sections belonging to each rock sample. Table 4. shows the textural characteristics of the studied samples.

Table.4. Determination of texture coefficient for studied samples

Sample name	AW	$\frac{N_0}{N_0+N_1}$	$\frac{N_1}{N_0+N_1}$	$\frac{1}{FF_0}$	AR_1	AF_1	TC
West sample	0.80	0.950	0.040	1.180	3.130	0.6000	0.970
East sample	0.88	0.760	0.240	1.180	2.300	0.6700	1.120
Joshan-rood	0.76	0.750	0.250	1.240	2.470	0.8800	1.120
Khalkhal Travertine	0.53	0.853	0.147	1.685	2.306	0.8713	0.913
Nepheline	0.71	0.736	0.264	1.820	2.690	0.9600	1.440
Limestone 17	0.40	0.862	0.138	1.160	2.380	0.8300	0.500
Limestone 75	0.40	0.900	0.100	1.371	2.365	0.8500	0.581
Monzonite	0.55	0.804	0.196	1.380	2.359	0.8700	0.830
Red Travertine	0.57	0.820	0.180	1.490	2.380	0.9600	0.940
Granite Maraghe	0.75	0.822	0.178	1.490	2.415	0.8214	1.183
Cheshme-Haji	0.61	0.860	0.130	1.270	2.340	0.7800	0.820
Sanje Mine	0.61	0.840	0.150	1.320	2.550	0.8900	0.890
West Ordud	0.60	0.770	0.220	1.110	2.260	0.6500	0.900
Ordud 4	0.70	0.880	0.110	1.350	2.380	0.7700	0.980

Mathematical equations should be laid out wherever possible using an equation editor and be numbered consecutively as in this example [18].

4. Statistical Analysis

According to the laboratory study on the sections, the effect of texture coefficient on the mechanical parameter of uniaxial compressive strength can be assessed. For this purpose, a simple nonlinear regression between UCS and TC is enough. The result of is presented in Figure 4.

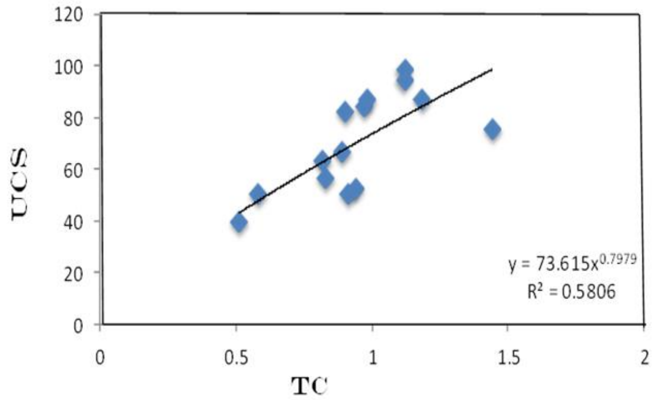

Figure 4. Relationship between texture coefficient and uniaxial compressive strength of the samples

The correlation coefficient (R^2) was used to ascertain the validity of the trend line. Figure 4. shows that there is a good positive correlation between TC and UCS. This trend suggests that with increase in TC and uniformity of grains size, the lattice and structure of rock take an isotropic mode and decreases weaknesses of rock lattice and therefore rupture of this structure is more difficult and as a result UCS increases. Also, the results show that classifying the data based on lithology can increase the reliability of the models for estimating rock strength from the TC. Increasing or decreasing values of R^2 can be explained only by differences based on lithology. Consequently, materials consisting of small, well rounded grains display a more reliable relationship between texture and UCS. This is probably the most important reason for the high values of R^2obtained for samples. The model for nine carbonate samples (West sample, East sample, Joshan-rood, Cheshme-Haji, Sanje Mine, West Ordud, Ordud 4, Limestone 17 and Limestone 75) is shown in Figure 5a. Correlation of UCS versus TC was also investigated based on grain features. Each data sample was classified according to the value of the form factors (FF0) and aspect ratios (AR1), which were used to characterize the circularity as well as elongation of grains. A regression model was applied for the TC and UCS of the data with FF0 values between 0.671 and 0.901, and AR1 between 2.26 and 3.13, and a trend line between quantified rock texture and UCS was constructed (Figure 5b), with R^2=0.75, TC is found to be an illustrative characterise to estimate properties of the rocks such as mineralogical composition, density, porosity, grain size and shape, osteoporosis and anisotropy index.

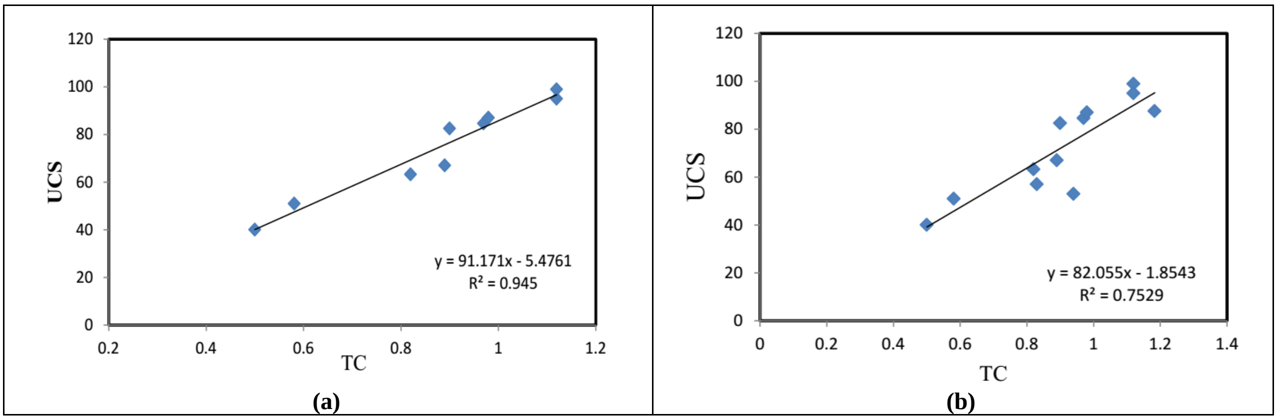

Figure 5. Relationship between texture coefficient and uniaxial compressive strength, (a) for carbonate samples (7 marble and 2 limestone samples); (b) based on grain features

3. Conclusion

This study evaluated the effects of texture coefficient on the uniaxial compressive strength of selected rock samples in the laboratory. The results showed a good correlation between TC and UCS of the samples.

Three different regression models are proposed to gain a strong relationship between UCS based on lithology and grain features. Firstly, the plot of UCS versus TC for all samples shows a rather good correlation between TC and UCS of the samples with R^2=0.58 and a power relationship. Although there is a broad trend between UCS and TC, but this result can be improved by classifying the data based on lithology and grain features. A regression model, which is UCS=91.17TC+5.48, is proposed for the materials classified as carbonate rocks (marble and limestone). Also by classifying based on grain features, using FF0 and AR1 factors. That FF0 values are between 0.671 and 0.901, and AR1 between 2.26 and 3.13. The high correlation coefficient of 0.945 and 0.75 respectively for the lithology and grain features shows that classifying the rock materials based on this features increases the reliability of the prediction models. Regardless of the simplicity of standard measurement method of UCS, more efficient alternative solutions to estimate

UCS should be explored. The new method presented in this paper uses non-destructive methods to estimate UCS by using imaging and digitization techniques. However, more extensive laboratorial study is still required to improve the prediction accuracy and present a more reliable relationship between UCS and TC in future researches.

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