Trends of Differentiation of Igneous Rocks using Unconfined Compressive Strength

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Abstract: Igneous rock is one of the three main rock types, other being sedimentary rocks and metamorphic rocks. Igneous and metamorphic rocks make up 90–95% of the top 16 km of the Earth's crust by volume. The engineering properties of these rock types essentially depend on physical properties of minerals and thus show varied characteristics. Hence in broader sense, these rocks can also be differentiated on the basis of their engineering characters. It is widely accepted that strength, deformation and permeability are the key engineering parameters that define the suitability of any rock type in general. Many researchers so far have tried to derive relationships between different physical properties and engineering properties of Igneous rocks. In Civil engineering precise knowledge of Unconfined Compressive Strength (UCS) of different rocks in various regions is considered to be of crucial importance. Unconfined compressive strength (uniaxial compressive strength) is the strength of rock or soil sample when crushed in one direction (uniaxial) without lateral restrain. It was found that unconfined compressive strength (UCS) of intact rock is a key parameter required for the design of various geo-mechanical problems ranging from wellbore instabilities during drilling, evaluation of sand production potential and quantitatively constraining stress magnitudes using observations of wellbore failure. In this review paper thus the emphasis is placed on trends of differentiation of Igneous rocks based on UCS tests and analysis. A brief overview of classification of Igneous rocks and a summary on different methodologies for determining the UCS of Igneous rocks has been discussed in this paper.

Keywords: Uniaxial compressive strength (UCS), Igneous Rocks, Differentiation, Field test, unconfined compressive strength.

Introduction

It is well known fact that Igneous and Metamorphic rocks make up 90–95% of the top 16 km of the Earth's crust by volume. About 64.7% of the Earth's crust by volume consists of Igneous rocks; making it the most plentiful category. Of these, 66% are basalts and gabbros, 16% are granite, and 17% granodiorites and diorites. Only 0.6% are syenites and 0.3% peridotites and dunites. The oceanic crust is 99% basalt, which is an Igneous rock of mafic composition. Hence the core theme of this review paper is Igneous rocks.

Igneous rocks are the natural products of cooling, crystallization and solidification of extremely hot mobile molten material (magma) originated from the deepest parts of the Earth. The mode of formation can be either intrusive (plutonic) or extrusive (volcanic). Each of the major genetic groups of Igneous rocks is characterized by a particular shape, appearance and characteristic structures and textures by which geologists, especially Petrologists, can recognize and identify their mode of origin. It can also be differentiated on the basis of its complex chemical composition. Slight changes in the chemical properties can lead to major changes in the engineering properties of these rocks. Strength of rocks highly depends upon these different and small properties of rocks. Hence in broader sense, these rocks can also be differentiated on the basis of their strengths.

It is well understood that for construction of many civil engineering projects, it is necessary to get detail properties of the rock on site otherwise, it may lead to huge loss of cost and project failure if proper measures are not taken. Many researchers so far have tried to derive relationships between different physical properties and engineering properties of Igneous rocks. The focus of this paper is thus strength characteristics of Igneous rocks and accordingly the discussion is primarily based on UCS which is a major property using which the Igneous rock can be further differentiated. The paper thus discusses significance of UCS and a comparison of different methods for calculating UCS in subsequent sections. A generalized classification of Igneous rocks is first briefed followed by a review on trends in UCS.

Classification of Igneous Rocks

Igneous rocks are classified according to mode of occurrence, texture, mineralogy, chemical composition, and the geometry of the Igneous body as given in Table 1 and 2;

Table 1: Chemical Classification of Igneous rocks

Type of Igneous rock	Silica present
Felsic Igneous Rocks	Greater Than 63% Sio_2
Intermediate Igneous Rocks	Between 52 – 63% Sio_2
Mafic Igneous Rocks	Low Silica 45 – 52%
Ultramafic_ Igneous Rocks	Less Than 45% Silica
Alkalic Igneous Rocks	Molar Ratio Of Alkali To Silica Greater Than 1:6

Table 2: Mineralogical Classification of Igneous rocks

	Composition			
Mode Of Occurrence	**Felsic**	**Intermediate**	**Mafic**	**Ultramafic**
Intrusive	Granite	Diorite	Gabbro	Peridotite
Extrusive	Rhyolite	Andesite	Basalt	Komatite

Table 1 summarizes the chemical classification based on % of SiO2 whereas Table 2 illustrates the classification based on mode of occurrence and composition of minerals. Table 2 depicts the differentiation of Igneous ricks according to both their composition and mode of occurrence. Literature reveals that mineralogical classification can be done based on Aeromagnetic surveys. In earlier studies, it was determined that mafic-ultramafic rocks commonly have a high magnetic susceptibility and cause linear and strong positive aeromagnetic anomalies. Intermediate-felsic rocks have a stable and low magnetic susceptibility and show a flat gradient variation and regular shape. Volcanic rocks have large variability in regard to magnetic susceptibility and romance; therefore, the aeromagnetic anomalies are always random or show variation within a planar area and decrease rapidly when an upward continuation is applied [4].

Physical classification

Igneous rocks can be classified on the basis of their physical properties such as texture, specific gravity, compressive strength, hardness, crystallinity, shapes, luster, microstructure including: minerals cleavage, grain boundaries, and micro-fractures[2], etc.

Chemical classification

Chemical classification is based upon the type and amount of chemical present in the rocks. One of the major chemical element present in the rocks is silica. Igneous rocks can be classified based upon the amount of silica present in the rocks. Table 1 shows some types of Igneous rocks and the amount of silica present in them.

Mineralogical classification

Felsic rock - highest content of silicon, with predominance of quartz, alkali feldspar and/or feldspathoids: the felsic minerals; these rocks (e.g., granite, rhyolite) are usually light coloured, and have low density.

Mafic rock – lesser content of silicon relative to felsic rocks, with predominance of mafic minerals pyroxenes, olivines and calcic plagioclase; these rocks (example, basalt, gabbro) are usually dark coloured and have higher density than felsic rock.

Ultramafic rock - lowest content of silicon, with more than 90% of mafic minerals (e.g., dunite).

Above discussion forms the basis for generalized differentiation of rocks. However it is known that for precise classification a thorough understanding of physical properties and corresponding engineering properties is certainly beneficial. The engineering properties essentially depend on physical properties of minerals and thus show varied characteristics. Hence in broader sense, rocks can also be differentiated on the basis of their engineering characters. The compressive strength plays a huge role in construction. Small errors in calculation of compressive strength can lead to measure changes in designing.

Hence it becomes important to calculate compressive strength as precisely as possible. It is a well known fact that the strength of rocks, is dependent upon different parameters such as cohesion, friction and existing fractures. Literature review reveals that Unconfined compressive strength (UCS) of intact rock is a key parameter required for the design of various geo-mechanical problems ranging from wellbore instabilities during drilling, evaluation of sand production potential and quantitatively constraining stress magnitudes using observations of wellbore failure. The UCS of formation has very important influence in well drilling rather than factors such as azimuth, slope, exposure time and even the mud weight [3]. In literature, many researchers have formulated different relationship between the UCS and physical properties of Igneous rocks. The next section thus briefs the recent literature describing various methodologies for UCS determination and their results.

Literature Review

The core perception of this paper is to bring about an overview of literature pertaining to relate compressive strength of Igneous rocks with their physical properties. Following are some of the methodology which were followed for determining and relating the compressive strengths (UCS) of the Igneous rocks.

UCS Methodology

Different indirect testing methods have been developed so far and are being used to interpret the engineering properties of rock. Many studies had been carried out to correlate the engineering properties of rock with its physical index properties. Researchers [2] correlated the unconfined compressive strength of different rock types (sedimentary, Igneous, and metamorphic rocks) with shore scleroscope hardness according to the equation:

$$UCS = 300X(1 \pm 0.1)Sh \qquad \ldots\ldots 1$$

where UCS is the unconfined compressive strength in psi, and $_{Sh}$ is the shore scleroscope rebound hardness. Based on tested rock samples, correlated the unconfined compressive strength of rock with the shore scleroscope hardness using very simple linear equation:

$$UCS = 400.Sh \qquad \ldots\ldots 2$$

Deere and Miller (1996) performed an extensive study on large number of rock samples representing different types of rocks (Basalt, Diabase, Dolomite, Gneiss, Granite, Limestone, Marble, Quartzite, Rock Salt, Sandstone, Schist, Siltstone, And Tuff) to develop an engineering classification system for the intact rock. The researchers found that the classification is strongly affected by rock mineralogy, texture, and anisotropy. They also concluded that rock strength and modulus properties are correlated better with Schmidt hardness than Shore hardness when the effect of unit weight of the rock is included. Furthermore, they found that sonic velocity as an index property for rock modulus is not as good as Schmidt or shore hardness [2]. Following table 3, provides the important correlations that were developed by Deere and Miller (1966).

Table 3: Correlations of UCS with engineering properties[2]

Correlations between rock hardness and both unconfined compressive strength and tangent modulus of rock Equation	R^2
UCS=461γ–52586	0.604
UCS=514Sh–6213	0.897
UCS=1246HR–34890	0.880
Et=(0.15γ–16.74)×106	0.784
Et=107165Sh+1.67×106	0.746
Et=(0.259HR–4.29)×106	0.731
UCS=10(0.00014γHR + 3.16)	0.943
UCS=10(0.000066γSh + 3.62)	0.921
Et=1395γHR–2.94×106	0.847
Et=622γSh+1.83×106	0.80

Table 3 thus summarizes the various correlations between engineering properties of the intact rock with its index properties signifying the relevance of understanding the trends of differentiation of Igneous rocks.

IS method (1979)

This standard covers the method for determination of unconfined compressive strength of a rock sample in the form of specimens of regular geometry. In this method, specimens of required dimension, shape are taken. A load is applied on the specimen gradually in such a way that failure will take place in about 5 to 15 minutes of loading. Alternatively, the stress rate shall be within the limits of 0.5 MPa/s to 1 MPa/s. The maximum load on the specimen shall be within 1 Percent accuracy. The unconfined compressive strength of the specimen shall be calculated by dividing the maximum load carried by the specimen during the test, by the average original cross-sectional area[5].

Recent Advancement (2012)

It is understood that uniaxial compressive strength of intact rock is an important mechanical parameter required for the design of geotechnical, mining engineering and petroleum reservoir projects. In geotechnical and mining projects, rock cores are usually available to be tested for such purposes. In the petroleum reservoirs, however, the extreme high cost and time-consuming of coring operation is a main issue and thus, rock core for mechanical destructive testing are rarely available. Usually, for determining UCS of reservoir rocks, i) the uniaxial compression test is carried out on intact rock cores and ii) geophysical logs are run in the borehole. These methods have some limitation as:

1. Preparation of standard cylindrical samples from the jointed rock mass is not possible,
2. Appropriate geophysical logs are not always available for the reservoir interval.
3. Well logs are run after drilling, thus are affected by the reservoir status and do not provide geo-mechanical understanding of rock properties being drilled in real time.

A new method was thus presented for measuring the unconfined compressive strength which followed following procedure-

i. Preparation of rock cuttings and rock cores.
ii. Determination of the appropriate size of cuttings, optimum water content and maximum density of cuttings for reconstructing cylindrical specimens,
iii. Building artificial cores and conducting uniaxial compression tests on reconstructed cores as well as on intact rock cores.

For this purpose, a total of 23 blocks of limestone having different densities including Asmari and Sarvak Formations from Western part of Iran and also Cretaceous limestone from Northern part of the country were used. After preparing appropriate cores from the blocks, uniaxial compressive strength test was performed on rock cores. Next, rock cuttings were produced from the same blocks and were reconstructed into artificial cylindrical specimens. The size of the rock cuttings varied between 0.075 mm and 0.4 mm, since it proved promising in preparing specimens with a maximum density of about 80% of the intact rock. Thus, cylindrical specimens with the diameter of 38mm and the length of 76 mm were built from the cuttings using standard compaction test. Cores with the same dimensions were taken from the same rock blocks. The two sets of samples were next subjected to the uniaxial compression test. The results obtained are as shown in figure 1.

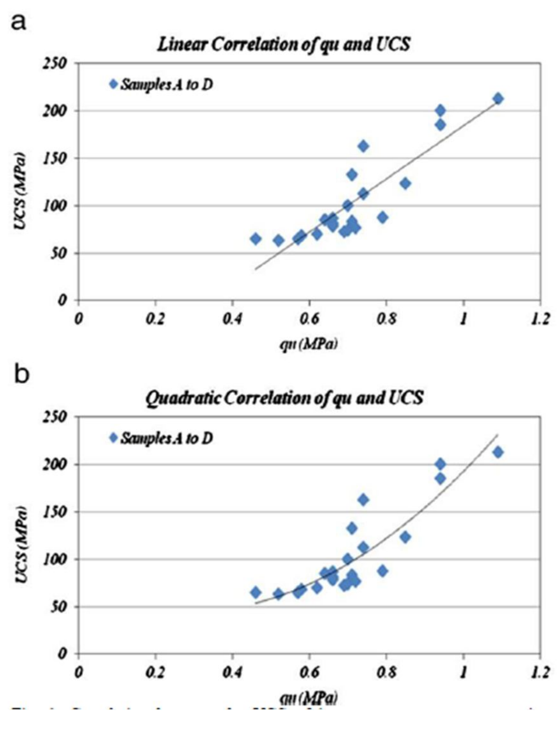

Figure 1 Linear and Quadratic variation of UCS with Compressive Strength [3]

Figure 1 indicates the linear and quadratic variation of UCS(MPa) with Compressive strength(q_u, MPa). The best linear relation from Fig. 1a gives the following equation with a correlation coefficient of 0.87:

$$UCS = 279.8(q_u) - 95.89 \qquad R=0.87 \qquad \ldots\ldots 3$$

The best quadratic curve from Fig. 1b relating UCS to qu is given below with a correlation coefficient of 0.89:

$$UCS = 280(q_u)^2 - 152(q_u) + 64.25 \qquad R=0.89 \qquad \ldots\ldots 4$$

Correlation between the two sets of data was strong; with a correlation coefficient higher than 0.85. Accordingly, two empirical equations for linear and quadratic relation were derived to estimate UCS from q_u. To verify the prediction of UCS from rock cuttings, the UCS of another type of limestone was estimated based on its q_u. Results showed that the estimated values are close enough to the measured UCS with an error of about 7% and thus the suggested method seems promising in the geo-mechanical evaluation of the reservoir rock[3].

Nail gun test (2015)

The penetration depth is one of the major index parameters for indirect determination of the unconfined compressive strength (UCS) of rock. The major tools used in this investigation included a series of gasnailers at different energy levels and nail diameters. Nail guns operate with a gas cartridge exerting high powers on different diameter pointy nails. The energy levels of the nail guns range from 80 to 105 J-power. The weaker the rock, the deeper the nail penetration should be, and vice versa. The penetration depth depends on the strength of material, the impact energy and nail diameters of nail guns. A relation was derived between the penetration depth and the compressive strength after testing 65 different samples**.** The results of laboratory conducted unconfined compressive test were correlated with nail penetration depth (h), nail gun energy (e) and nail diameter (d) and an empirical equation was established using multiple regression analysis. The UCS values of the intact rocks were converted to nail penetration depths (h) using the following empirical relationship.

$$\sigma_c = 154\exp(-0.064h) \qquad \ldots\ldots 5$$

The proposed equation can be used to estimate the UCS of intact rocks [1].

Using Triaxial and Brazilian test (2016)

Previously many researchers have performed triaxial test and Brazilian test on different rock specimens. The results in form of σ_t(Brazilian strength), σ_c (UCS strength) and E(modulus of elasticity) with different signatures for the studied rock types were plotted as function of the bulk density in water saturated surface dry condition being saturated as part of the preparation of the test specimens. Project investigations related to preliminary plans for a hydro-electric power station at Núpur and Þórsá, Iceland were carried out and included 12 km headrace tunnels. The main subject of this project was to obtain rock parameters for the different rock in the region based on laboratory tests on rock samples from drilling cores made available.

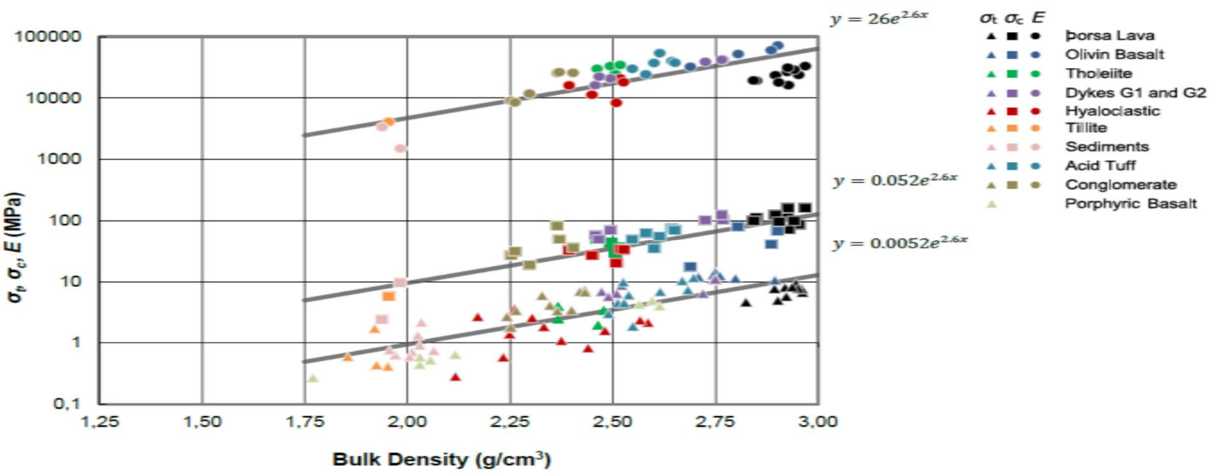

Figure 2 Rock mechanical properties from volcanic rock types in the Núpur – Þórsá region [7]

Figure 2 shows the variation in the mechanical properties volcanic rocks in the Núpur – Þórsá region. 12 different volcanic and sedimentary rock types were selected from 12 boreholes in the area which contributed to 48 test specimens used for 82 Brazilian tests, 46 unconfined compression tests and 5 triaxial tests. The results in form of σ_t, σ_c and E with different signatures for the studied rock types are plotted as function of the bulk density in water saturated surface dry condition being saturated as part of the preparation of the test specimens. Figure 2 shows the main results grouped in selected rock types together with a regression analysis of the trend lines for the 3 set of results with great variation depending on bulk density and lowest values for the Móberg formations. The triaxial tests thus confirm the level of friction angle and cohesion for Tillite, Porphyritic Basalt, and Hyaloclastic[7].

Porosity, Density and UCS relationship (2012)

A total of 49 samples were collected as blocks of carbonate rocks from 26 active quarries in Iran. According to the geological settings and rock classes in a quarry, different blocks were sampled to encompass small variations. Weights and volumes of blocks were 600–1,000 kg and 0.2–4 m^3, respectively. Testing samples were prepared (or cored) from central and homogeneous parts of the blocks, far from visible fractures. Different tests such as porosity test, density test, UCS test, uniaxial deformability test, indirect tensile strength were performed according to ASTM. Using the results, data showing the correlation between tested parameters were tabulated [9].

Strength estimation using rock texture: (2014)

Texture, which is defined as the degree of crystallinity (Williams et al., 1982), is the combination of mineral grains and matrix that includes the smallest particles of rock material. Nearly all mechanical and physical properties of interest to rock engineers depend on how the grains and matrix relate to the texture. The relationship between texture and strength of intact rock material was investigated by image analysis of thin sections of rock samples studied previously by different researchers. Firstly the quantitative assessment of rock texture was performed to get the texture coefficient (TC). Further these TC were used to estimate the UCS of tested rock samples. One such representative graph that were plotted between UCS and TC for different types of rocks is as shown in Figure 3 below [6];

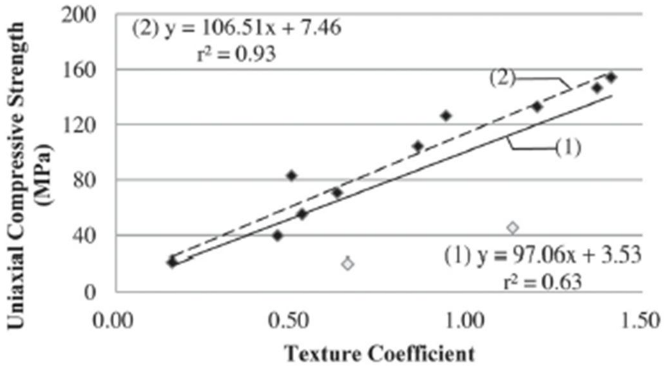

Figure 3. Variation of UCS with Texture [6]

Figure 3 shows the correlation between σ_c and TC for sandstone, siltstone, marl, and shale. The correlation coefficient of the dotted line (r2=0.93) is quite acceptable due to higher correlation coefficient.

Use of Artificial Intelligence: (2015)

In the recent years, the application of artificial intelligence (AI) in solving geotechnical problems has drawn considerable attention. AI, which is a mathematical algorithm, can be employed in civil or geotechnical problems when the contact natures between some input(s) and output(s) parameters are unknown. In general, it incorporates several techniques such as artificial neural network (ANN), adaptive neuro-fuzzy inference system (ANFIS), particle swarm optimization (PSO), genetic algorithm (GA), a few of them are mentioned. Readers are referred to classic AI books for more information e.g. Englebrecht. Nevertheless, for the problem of interest, there are several factors that can affect the UCS of rocks such as rock minerals, porosity, and water content to name a few. Hence, the use of AI in predicting UCS is advantageous[8].

In an attempt to overview trends of differentiation of Igneous rocks, based on above review a summary with remarks focusing the relevance of present work and future scope has been discussed in next section.

Summary And Remarks

Based on literature review following inferences are drawn:

The summarized remarks are discussed herein based on literature review.

Based on the coefficient of correlation (r), equation 5 provides a strong relationship between the UCS of intact rocks and variables (h, e and d) of the gasnailers. A simple power relationship between the UCS and the variables (h, e, and d) of nail guns was established in the form of the equation, [σ_c =f (h, e, d)] [1].

In the new method introduced for computing the UCS, the q_u was obtained for several samples of a few types of limestones and was correlated to the UCS of intact cores of the same rock type The correlations proposed are applicable to the sampled area only (Iran). Presenting a general correlation between UCS and q_u requires further work on other types of rocks as well as on samples from other geographical locations [3].

The trends established for compression strength, tensional strength and elasticity modulus must be carefully considered. Different rock types and the local variability should be included in an overall evaluation. Beside the influence of porosity and variation in mineralogy, there is an effect of weathering and age of the volcanic formations [7].

Different rock classes and porosity have major effects on the relation between uniaxial compressive strength (UCS) and other rock properties. A strong significant positive correlation was observed between UCS and in sedimentary limestone and marbles. In diagenetic dolomitic limestones, utilizing porosity did not yield any significant improvement of correlation coefficients between different variables and UCS [9].

The results of experimental analysis showed that there is an effect on rock strength due to increasing variance in TC. This trend can be used to classify the rock samples based on relative strength [6].

Use of Artificial Intelligence can provide a huge set of data of different properties of rocks. Using these parameters, many relationships between different parameters of rocks and UCS can be found through which different trends of classification of igneous rocks can be determined [8].

Methods for estimating engineering relationships between the physical and chemical properties of igneous rocks should be found. A summarized review thus suggests the following:

1. Precise classification of Igneous rocks is possible.
2. UCS is an important engineering parameter
3. UCS can be determined by using laboratory testing e.g.: nail gun test
4. UCS determination using analytical tools such as ANN is also feasible.
5. UCS depends on mineralogical factors e.g.: texture, hardness and physical factors such as density, porosity, etc.

It is clear that the effect of physical, mineralogical and chemical factors influences the UCS, these factors are interdependent. Hence it is necessary to perform an integrated analysis for more precise understanding of differentiation of Igneous rocks. Such an attempt of integrating these factors has not been reported so far and thus differentiation of Igneous rock by integrating physical, chemical and mineralogical aspects can be done which can be further validated by laboratory and /or analytical tools.

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References

[1] Levent Selçuk, Kamil Kayabali, "Evaluation of the unconfined compressive strength of rocks using nail guns", Engineering Geology 195, June 2015, 164–171.

[2] Faisal I. Shalabi, Edward J. Cording , Omar H. Al-Hattamleh,"Estimation of rock engineering properties using hardness tests", Engineering Geology 90, January 2007, 138–147.

[3] Saber Mehrabi Mazidi, Mohammad Haftani,Bahman Bohloli, Akbar Cheshomi,"Measurement of uniaxial compressive strength of rocks using reconstructed cores from rock cuttings",Journal of Petroleum Science and Engineering 86–87,March 2012, 39–43.

[4] Shengqing Xiong, Hai Yang, Yanyun Ding, Zhankui Li, Wei Li, "Distribution of igneous rocks in China revealed by aeromagnetic data", Journal of Asian Earth Sciences 129, August 2016, 231–242.

[5] IS : 9143 – 1979: Method for the determination of unconfined compressive strength of rock materials.

[6] C.A. Ozturk, E. Nasuf, and S. Kahraman, "Estimation of rock strength from quantitative assessment of rock texture", The Journal of The Southern African Institute of Mining and Metallurgy volume 114, June 2014, 471-480.

[7] N. N. Foged, K. A. Andreassen, "Strength and deformation properties of volcanic rocks in Iceland", Proceedings of the 17th Nordic Geotechnical Meeting Challenges in Nordic Geotechnic, 25th– 28th of May 2016, 347-356.

[8] Ehsan Momeni, Ramli Nazir, Danial Jahed Armaghani, Mohd For Mohd Amin, Edy Tonnizam Mohamad, "Prediction of Unconfined Compressive Strength of Rocks: A Review Paper", Jurnal Teknologi (Sciences & Engineering) 77:11, September 2015, 43-50.

[9] G. Rakhshandehroo, Mohommad Ali Rajabzadeh, Zohreh Moosavinasab, " Effects of Rock Classes and Porosity on the Relation between Uniaxial Compressive Strength and Some Rock Properties for Carbonate Rocks.", Rock Mechanics and Rock Engineering 45(1), January 2012, 113-122.