VII Brazilian Symposium on Rock Mechanics – SBMR 2016
Rock Mechanics and Rock Engineering for Innovation and Development
ISRM Specialized Conference 19-22 October, Belo Horizonte, Minas Gerais, Brazil

Correlation between Uniaxial Compressive Strength and Brazilian Tensile Strength Using Different Rock Types

Pâmmela Caroline Pinazzi da Silva Ribeiro
CEFET/MG, Araxá, Brazil, ppinazzi@gmail.com

Michel Mello Oliveira
CEFET/MG, Araxá, Brazil, michelmelo@gmail.com

Priscilla Nelson
Colorado School of Mines, Golden, United States, pnelson@mines.edu

SUMMARY: The Uniaxial Compressive Strength (UCS) is widely used by professional engineers who work in designing surface or underground structures in geologic materials. This parameter is used to determine rock properties and characteristics. Moreover, it is important not only to analyze but also to study the rock in geological and geotechnical perspectives. The UCS of intact rock is a necessary input for the estimation of rock mass strength. However, the UCS test is very expensive and demands strictly prepared high quality samples. Thus, this parameter is often determined based on the results of other tests including Brazilian Tensile Strength (BTS) and Point Load (PL). Previous scientific studies indicated that the BTS relates better with UCS than does PL. The previous studies produced somewhat inconsistent conclusions - some authors found a better linear correlation and others a better non-linear correlation between UCS and BTS. Thus, this study was carried out to figure out a better correlation between UCS and BTS for each rock type and a general equation for all types of rock. This paper analyzes previous studies about such correlations, and provides additional analyses using the database of the Earth Mechanics Institute (EMI) in the Department of Mining Engineering at the Colorado School of Mines (CSM). These data have been collected over more than 40 years of rock testing at EMI. In total, 316 tests were used for this analysis including 158 tests of BTS and 158 tests of UCS. To analyze the data, linear and non-linear correlations were used. In this study, the non-linear correlation showed a better correlation for two types of rocks (e.g., igneous and metamorphic), but this correlation was poorer for sedimentary rocks. The diversity and directionality of rocks can cause some issues in the rock strength analysis. In fact, rocks with the same mineralogy can give a different strength test value due to its porosity, weathering, or the presence of micro-fissures.

KEYWORDS: Uniaxial Compressive Strength, Brazilian Tensile Strength, and Correlation.

1 INTRODUCTION

The Uniaxial Compressive Strength (UCS) is widely used by professional engineers who work in the design of surface or underground geostructures. The UCS is used to determine rock properties and characteristics. Moreover, it is important not only to analyze but also to study the rock in geological and geotechnical perspectives. The Uniaxial Compressive Strength of intact rocks is a necessary input for the estimation of rock mass strength criterion (Brady and Brown, 2004). However, the UCS test is very expensive and requires sample preparation to high standards. Furthermore, weak, thinly bedded, or densely fractured rocks are not suitable for specimen preparation and determination of UCS (Karaman et al., 2015). For such rocks, a good correlation to determine the Uniaxial Compressive Strength is needed (Nazir et al., 2013). Thus, many studies have been developed to correlate UCS to other parameters (e.g., Kahraman, 2012; Karaman and Kesimal, 2015), for example Brazilian Tensile Strength (BTS) and Point Load (PL). Farah (2011) concluded that UCS better correlates with BTS than PL.

According to Sheorey (1997), the UCS is typically 10 times larger than the BTS for many rock types. However, this value can vary according to the rock orientations. Kahraman et al. (2012) conducted experiments for different rock types, and proposed a linear correlation between the UCS and BTS with a correlation coefficient (R^2) of 0.50 (Table 1). Altindag and Guney (2010) studied rocks with a larger range of UCS and BTS and found a non-linear correlation that better correlates UCS and BTS having an R^2 of 0.81 (Table 1). Karaman et al (2015) found a better linear correlation with an R^2 of 0.90 (Table 1). Another way to correlate BTS and UCS is determining the ratio UCS/BTS. Din and Rafigh (1997) found the ratio between UCS and BTS as being 7.5. However, Vutukuri at al. (1974) found it in a range of 10 and 50 for most rocks.

The purpose of the present study is to correlate UCS and BTS, to develop equations to determine UCS based on the BTS test, and to compare previous studies developed by other researchers.

Table 1. Previous Correlations between UCS and BTS.

References	Correlation	R^2	Rock Type
Kahraman et al. (2012)	$UCS_{(MPa)} = 10.61*BTS$	0.54	Different Types
Altindag and Guney	$UCS_{(MPa)} = 12.38*BTS^{1.0725}$	0.81	Different Types
Karaman et al. (2015)	$UCS_{(MPa)} = 24.30+4.87*BTS$	0.90	Different Types

2 LABORATORY STRENGTH TESTS

Strength testing of rock is conducted to verify the resistance of the rock against load. Strength is defined as the maximum average stress that the rock can sustain under a given set of conditions (Brady and Brown, 2004). In this study, two types of strength tests were investigated: direct and indirect. This study compares Uniaxial Compressive Strength and Brazilian Tensile Strength test results, with tests conducted using the standard procedures specified by the American Society for Testing and Materials (ASTM).

3 MATERIALS AND METHODOLOGY

This study was developed based on bibliography reviewing and analyzing the database of the Earth Mechanics Institute (EMI) at Colorado School of Mines (CSM). These data were collected over the last few years from experiments made for different companies and university projects.

Thus, the data analyzed is based on laboratory experiments conducted using different rock types. In total, 158 tests of UCS and BTS being 42 different rocks (5 types of igneous rock, 17 types of metamorphic rock, and 19 types of sedimentary rock). The data used is represented in Table 2, which is showing the number of samples used, rock type, the UCS and BTS average of the samples, and the standard deviation.

4 RESULTS AND DISCUSSIONS

This study was developed to figure out a better correlation for UCS and BTS. Thus, a linear and a non-linear correlation were analyzed for considerations. The following items are presenting analysis for each rock type, a general analysis considering the three rock types, and a particular analysis for sandstone.

Table 2. Samples used, average of tests, and standard deviation of the tests.

Number of Samples	Rock	Rock Type	UCS (MPa) Average	Standard Deviation of UCS Tests	BTS (MPa) Average	Standard Deviation of BTS Tests
1	Barre Granite	Igneous	164.6	0.0	8.9	0.0
4	Diabase	Igneous	176.3	25.4	17.4	1.9
3	Granite	Igneous	146.5	47.6	12.9	4.7
2	Granite / Granodiorite	Igneous	103.7	56.7	10.8	5.8
1	Granodiorite	Igneous	159.8	0.0	18.8	0.0
1	Quartz Monzonite	Igneous	134.7	0.0	10.2	0.0
3	Amphibolite	Metamorphic	95.1	12.6	12.5	2.2
17	Black Mylonite	Metamorphic	133.3	55.6	15	4.1
5	Black Mylonite	Metamorphic	99.8	8.3	14.7	3.2
2	Blastomylonite	Metamorphic	215.5	0.0	14.1	0.0
1	C. Argilite	Metamorphic	47.8	0.0	14.9	0.0
1	Dundee	Metamorphic	156.2	0.0	7.1	0.0
4	f-c grained schistose gneiss	Metamorphic	140.7	38.3	12.9	3.8
5	Gneiss	Metamorphic	189.2	2.9	13	2.8
3	Green Phyllite	Metamorphic	134.1	22.2	12.3	2.3
1	Meta-Andesite	Metamorphic	118.4	0.0	13.2	0.0
4	Mylonitic Granite	Metamorphic	223.0	31.7	15.3	5.6
2	Quartz Phyllite	Metamorphic	158.9	0.0	14.932	0.0
1	Quartzite	Metamorphic	181.7	0.0	11.2	0.0
2	Schist	Metamorphic	100.7	11.1	15.5	1.7
1	Silica	Metamorphic	138.6	0.0	8.2	0.0
5	White Mylonitic	Metamorphic	202.7	52.2	14.2	2.2
2	White Quartz Mylonite	Metamorphic	87.1	0.0	12.2	0.0
1	Silty Shale	Sedimentary	56.8	0.0	5.1	0.0
5	Conglomerate	Sedimentary	113.0	21.8	10.2	3.3
12	Coral Limestone	Sedimentary	9.0	6.6	1.9	0.7
3	Dark Gray Limestone	Sedimentary	149.0	21.9	8.1	0.7
1	Gypsum	Sedimentary	23.6	0.0	3	0.0
11	Limestone	Sedimentary	98.6	46.0	7.1	3.1
6	Mudstone	Sedimentary	84.0	43.7	5.3	2.3
2	Mudstone with Clast	Sedimentary	98.9	7.8	3.4	1.2
4	Reddish Sandstone	Sedimentary	118.8	3.6	7.5	0.5
12	Sandstone	Sedimentary	61.6	61.1	4.6	4.1
8	Shale	Sedimentary	115.0	13.9	6.2	1.0
3	Siltstone	Sedimentary	83.3	43.3	8.1	3.2
2	Silty Sandstone	Sedimentary	53.0	0.0	4.1	0.0
3	Tar Sands	Sedimentary	5.2	2.1	0.3	0.1

1	Trona	Sedimentary	42.1	0.0	4	0.0
5	Sandstone, course	Sedimentary	147.7	21.8	8.8	2.0
1	Sandy shale	Sedimentary	84.6	0.0	10.7	0.0
1	Weathered Limestone	Sedimentary	80.0	0.0	9.1	0.0
6	Oil Shale	Sedimentary	41.3	14.8	3.4	1.2

4.1 Rock Analysis: Sedimentary, Metamorphic, and Igneous Rock

A linear correlation of UCS and BTS was found for sedimentary (Figure 1) and igneous rock (Figure 3). The metamorphic analysis did not show a correlation between UCS and BTS (Figure 2). The equations of the straight lines are respectively:

$$UCS = 13.703 * BTS, \; R^2 = 0.67 \qquad (1)$$

$$UCS = 10.051 * BTS, \; R^2 = -0.29 \qquad (2)$$

$$UCS = 10.435 * BTS, \; R^2 = 0.53 \qquad (3)$$

where UCS is the uniaxial compressive strength (MPa) and BTS is the Brazilian tensile strength (MPa).

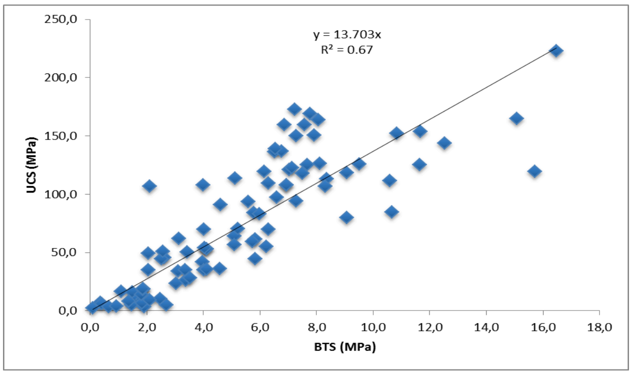

Figure 1. Linear correlation between UCS and BTS for Sedimentary Rocks.

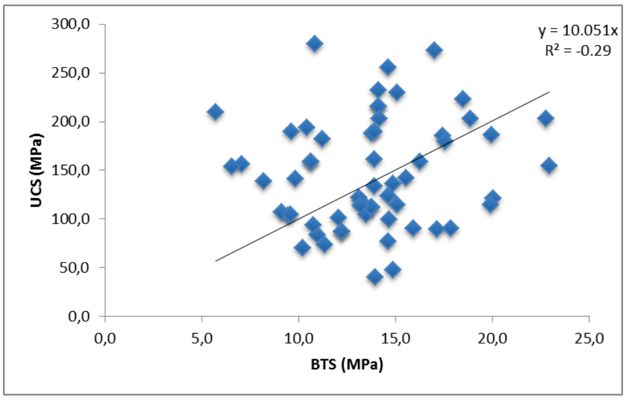

Figure 2. Linear correlation between UCS and BTS for Metamorphic Rocks.

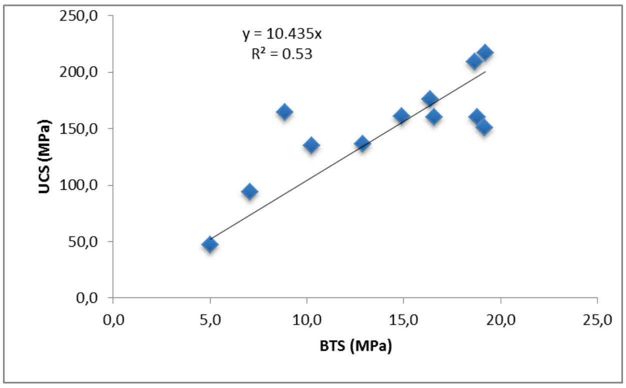

Figure 3. Linear correlation between UCS and BTS for Igneous Rocks.

A better correlation for UCS and BTS was found by using a non-linear correlation for sedimentary (Figure 4), metamorphic (Figure 5) and igneous (Figure 6) rocks. The equations representing the non-linear correlations for each rock type are respectively:

$$UCS = 9.944 * BTS^{1.1349} \qquad R^2 = 0.76 \qquad (4)$$

$$UCS = 107.04 * BTS^{0.0907} \qquad R^2 = 0.003 \qquad (5)$$

$$UCS = 18{,}656 * BTS^{0.793} \qquad R^2 = 0.74 \qquad (6)$$

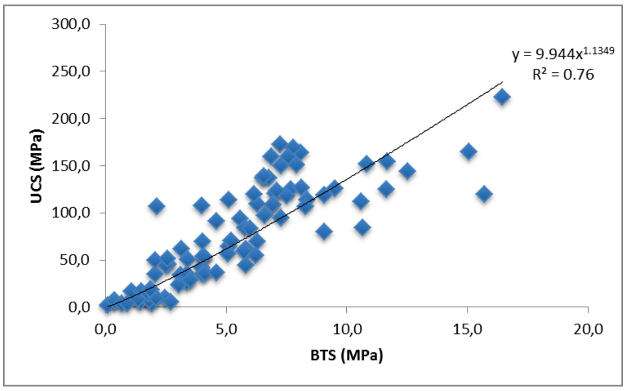

Figure 4. Non-linear correlation between UCS and BTS for Sedimentary Rocks.

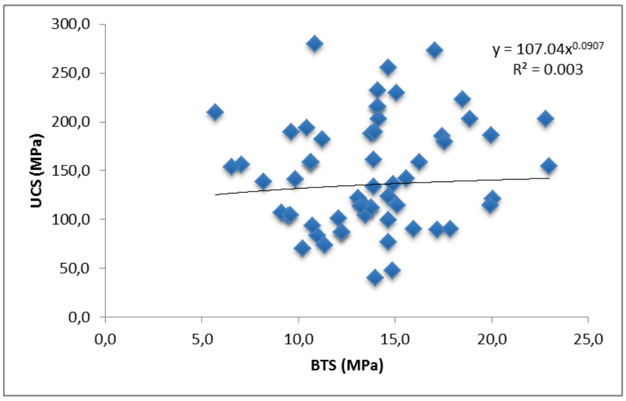

Figure 5. Non-linear correlation between UCS and BTS for Metamorphic Rocks.

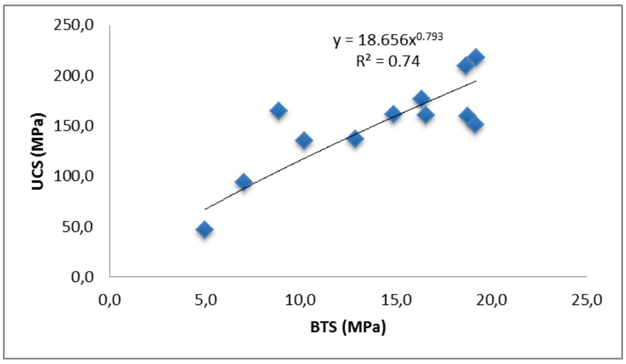

Figure 6. Non-linear correlation between UCS and BTS for Igneous Rocks.

4.2 General Analysis

A general linear correlation between UCS and BTS was found for the three rock types (Figure 7). The equation of the line is:

$$UCS = 8.315*BTS+31.592 \qquad R^2 = 0.51 \qquad (7)$$

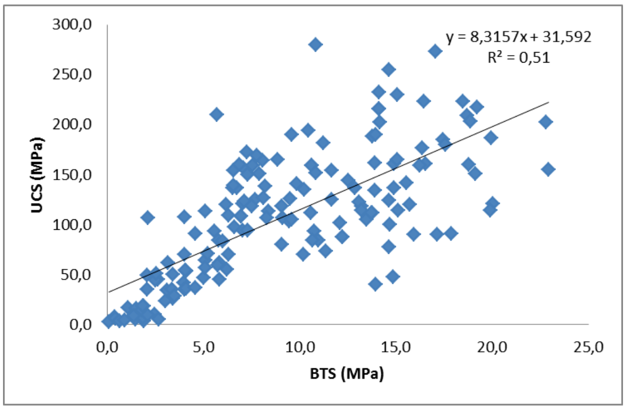

Figure 7. General linear correlation between UCS and BTS for sedimentary, metamorphic and igneous rock.

A better general non-linear correlation between UCS and BTS was found for the three rock types (Figure 8). The equation of the correlation is:

$$UCS = 11.751*BTS^{0,9777} \qquad R^2 = 0.74 \qquad (8)$$

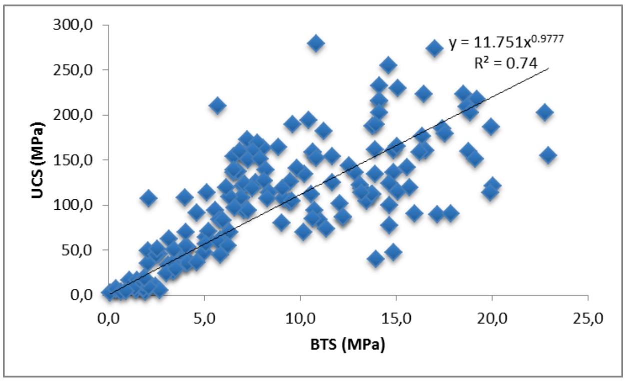

Figure 8. General non- linear correlation between UCS and BTS for sedimentary, metamorphic and igneous rock.

4.3 A Particular Analysis: Sandstone

The previous analysis showed a better non-linear than linear correlation between UCS and BTS. Differently from that, the sandstone plot showed that the correlation between UCS and BTS is better linearly, as represented in Figure 9 and Figure 10. The equations are respectively:

$$UCS = 14.035*BTS \qquad R^2 = 0.93 \qquad (9)$$

$$UCS = 11.42*BTS^{1.091} \qquad R^2 = 0.82 \qquad (10)$$

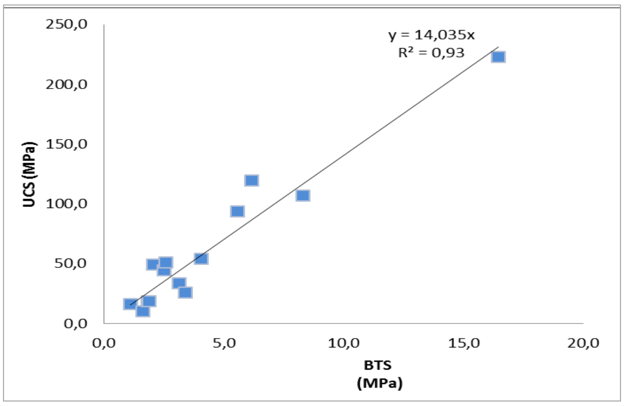

Figure 9. Linear correlation between UCS and BTS for Sandstone.

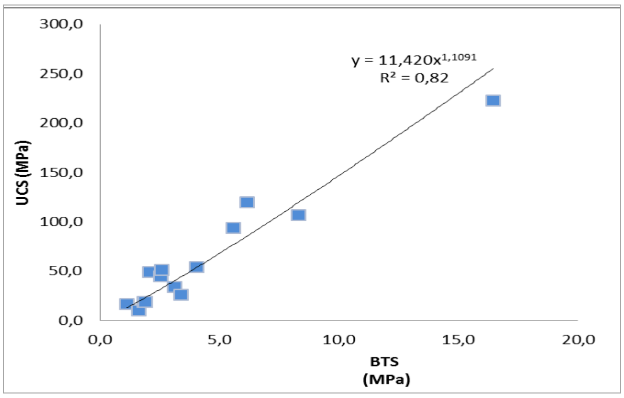

Figure 10. Non-linear correlation between UCS and BTS for Sandstone.

In addition, the correlation found between UCS and BTS for sandstone is a very representative correlation considering that the samples used in the analysis are from different core samples. This individual analysis was justified due to the representative number of sandstone core samples in the database.

4.4 Analysis of Previous Studies

Aiming to compare previous studies, the difference between the UCS tested and UCS predicted was analyzed based on the average and the standard deviation for each rock type and for the general correlation, i.e. considering all rock types. The equations used in this comparison are represented in table 1 and it was retrieved from different previous studies [Kahraman et al. (2012), Altindag and Guney (2001), and Karaman et al. (2015)].

The comparisons are represented in Table 3 for Igneous Rocks, Table 4 for Metamorphic Rocks, Table 5 for Sedimentary Rocks and Table 6 for the general equation. The UCS predicted using the equations found in this study showed to be close to the UCS found in the laboratory tests because the last was base for this study. Furthermore, a specific equation for each rock type was used in this study. On the other hand, other authors have used a general equation in their studies.

Analyzing the data (Table 3), the correlation found for Igneous and Metamorphic rocks and for the general correlation showed to be better represented using a non-linear correlation. However, the correlation found for sedimentary rocks showed to be better represented using a linear correlation even having a lower coefficient of determination.

The same happens when comparing the correlation found for Kahraman (2012). The UCS predicted using his equation resulted in closer values to the UCS found at the Rock Mechanics laboratory at CSM than other authors, even having an equation with lower coefficient of determination.

5 CONCLUSIONS

The UCS is an important parameter to determine the rock characteristics. However, the determination of UCS demands high-quality samples, and it is a very expensive method. Thus, other methods are used to predict the UCS.

Although there are many studies developed that relate UCS and BTS, or UCS with other parameters, it is very hard to find a representative correlation between UCS and other parameters. One reason is that even testing rocks with the same mineralogy, the strength tests present different results. It occurs due to the rock's porosity, weathering, and the presence of micro-fissures.

Table 3. The Critical Analysis of UCS Test Conducted and UCS Predicted for Igneous Rocks

	Kahraman et al. (2012)	Altindag and Guney (2001)	Karaman et al. (2015)	Linear Correlation of this study	Non-linear Correlation of this study
AVERAGE	21,552	64,513	58,794	22,252	20,201
STANDARD DEVIATION	21,075	39,979	27,904	20,171	16,460

Table 4. The Critical Analysis of UCS Test Conducted and UCS Predicted for Metamorphic Rocks

	Kahraman et al. (2012)	Altindag and Guney (2012)	Karaman et al. (2015)	Linear Correlation	Non-linear Correlation
AVERAGE	51,787	78,463	60,898	50,961	46,500
STANDARD DEVIATION	36,435	54,011	48,940	36,959	31,556

Table 5. The Critical Analysis of UCS Test Conducted and UCS Predicted for Sedimentary Rocks

	Kahraman et al. (2012)	Altindag and Guney (2012)	Karaman et al. (2015)	Linear Correlation	Non-linear Correlation
AVERAGE	25,315	22,528	36,895	21,664	22,307
STANDARD DEVIATION	24,651	20,857	29,696	19,788	22,064

Table 6. - The Critical Analysis of UCS Test Conducted and UCS Predicted for General Rocks

	Kahraman et al. (2012)	Altindag and Guney (2012)	Karaman et al. (2015)	Linear Correlation	Non-linear Correlation
AVERAGE	35,219	47,087	42,723	35,485	34,988
STANDARD DEVIATION	32,080	46,622	39,952	26,899	31,454

Analyzing this data and previous studies, it was determined that the UCS and BTS have a better non-linear than linear correlation, when analyzing the rocks as a group except for sedimentary rocks. Also, the correlation found in this study showed to be closer to the UCS tested in laboratory than the correlation found in previous study.

In summary, the equation found in this study is similar to the equation found by Kahraman et al. (2012).

ACKOWLEGMENTS

The authors would like to thank the Earth Mechanics Institute (EMI) and the Department of Mining Engineering at Colorado School of Mines for authorizing the use of the database, and also for technical support. They also thank CAPES for the financial support.

REFERENCES

Altindag, R., and Guney, A. (2010). Predicting the Relationship between Brittleness and Mechanical Properties (UCS, TS, and SH) of Rocks, *Scientific Research and Essays* , p. 2107-2118.

Brady, B. H. G., and Brown, E. T., (2004). *Rock Mechanics for Underground Mining*, 3rd ed., Kluwer Academic Publishers, New York.

Din , F., and Rafiq, M. (1997). Compressive Strength and Tensile Strength/ Index Strength od Some Rocks of North-west Frontier Province (Limestone and Granite), *Geological Bulletin*, University of Peshawar, p. 183.

Farah, R. (2011). Correlations Between Index Properties and Unconfined Compressive Strength of Weathered Ocala Limestone, *UNF Theses and Dissertations*, p.142.

Kahraman, S. and Fener, M., Kozman, E. (2012). Predicting the Compressive and Tensile Strength of Rocks from Indentation Hardness Index, *Southern Africa Institute of Mining and Metallurgy*, p. 331-339.

Karaman, K., Cihangir, F., Ercikdi, B., Kesimal, A., and Demirel, S. (2015). Utilization of the Brazilian Test For Estimating the Uniaxial Compressive Strength and Shear Strength Parameters. *The Journal of The Southern African Institute of Mining and Metallurgy,* Vol. 115, p. 185-115.

Karaman, K. and Kesimal, A. (2015). Evaluation of the influence of porosity on the engineering properties of rocks from the Eastern Black Sea Region: NE Turkey. *Arabian Journal of Geosciences,* Vol 8. p. 557-564.

Nazir, R., Momeni, E., Armaghani, D., and Amin, M. (2013). Correlation Between Uncinfined Compressive Strength and Indirect Tensile Strength of Limestone Rock Samples, *EJGE* , p.1737-1746.

Sheorey, P. R. (1997). Empirical Rock Failure Criteria, *A.A. Balkema* , p. 176.

Vutukuri, V. S., Lama, R. D., and Saluja, S. S. (1974). Handbook on Mechanical Properties of Rocks, *Testing Techniques and Results*.