Tensile Strength Modeling of Limestone Rocks in Sulaymaniyah City, Iraq Using Simple Tests

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ABSTRACT

Tensile strength of rocks is one of the mechanical properties of intact rock that is a significant parameter for designing geotechnical structures includes dam foundations and tunnels. The tensile strength can be determined indirectly using Brazilian indirect test procedure that is mentioned in the International Society for Rock Mechanics suggested methods. The availability of rock samples is needed to perform the Brazilian indirect test so as to determine their tensile strength which is expensive, time-consuming, and cost-effective especially for weak quality rock formations. Therefore, non-destructive methods for predicting the tensile strength of the rock are crucially needed during the poor quality of rock samples. Non-destructive tests can be correlated with indirect tests to predict Brazilian tensile strength (BTS) of rocks such as ultrasonic pulse velocity and Schmidt hammer. These methods are simple and can be easily conducted in the field. This study is focused on the tensile strength of limestone rocks for three main formations of Sulaymaniyah city. The samples were obtained using a standard core barrel. Statistical analysis including minimum, maximum, mean, standard deviation, variance, and coefficient of variance for the results was conducted. Single and multiple correlations between BTS with each of ultrasonic pulse velocity and Schmidt hammer rebound number of limestone rocks were created. Reasonable empirical equations were developed to predict the tensile strength of limestone rocks. In addition, the point load strength index was correlated with BTS. The comparison between proposed equations from this study and equation from the literature was also investigated.

Keywords: Brazilian tensile strength; Limestone rocks; Point load test; Schmidt Hammer test; Ultrasonic pulse velocity

INTRODUCTION

The tensile strength of rocks is a mechanical property that is crucial in the construction of several engineering projects such as the foundation of dams and tunnels (Gokceoglu and Zorlu, 2004; Baykasoğlu et al., 2008; Gurocak et al., 2012). Brazilian tensile strength (BTS) test is an indirect method to determine the tensile strength of rocks (Garcia-Fernandez et al., 2018). The international society for rock mechanics (ISRM) suggested method can be used to find the BTS of rocks (Brown, 1981).

BTS needs the preparation of high-quality core samples and time but during the poor quality of the rocks, the samples may not be obtained; therefore, some other tests can be used to predict BTS of rocks including ultrasonic pulse velocity test (Vp), Schmidt hammer rebound number test (Rs), and point load test (PLT) (Gokceoglu and Zorlu, 2004; Kilç and Teymen, 2008; Kallu and Roghanchi, 2015; Kurtuluş et al., 2016).

Ultrasonic pulse velocity and Schmidt hammer are non-destructive tests that used to compute BTS of rocks indirectly (Kilç and Teymen, 2008; Kallu and Roghanchi, 2015). PLT is a simple and indirect test method to compute the point load strength index (Is(50)) of rocks and that can be used to predict BTS of rocks (Heidari et al., 2012). These tests consist of portable instruments that can be used in the field.

Literature review reveals that the correlation of BTS with Vp, Rs, and Is(50) for various rock types in several countries was investigated but the relationships of BTS with each of Vp, Rs, and Is(50) for core samples of limestone rocks of Sulaymaniyah city in Iraq were not investigated yet; therefore, this study focused on the tensile strength modeling of limestone rocks for three main formations of Sulaymaniyah city. Statistical analysis including minimum, maximum, mean, standard deviation, variance, and coefficient of variance for the results was conducted. Single and multiple correlations between BTS with each of Vp, Rs, and Is(50) of limestone rocks were developed. The proposed equations from this study were compared with the equations from literature.

Previous Empirical Equations

Several researchers investigated the relationship between BTS and each of Vp, Is(50), and Rs. Some of these researchers
including Kılıç and Teymen (2008); Kurtuluş et al. (2016); Khandelwal and Singh (2009); Alshkane et al. (2018); and Hama Salih and Alshkane (2018) found the correlation equation between BTS and \( V_p \) as presented in Table 1.

Some of other researchers including Gurocak et al. (2012); Kılıç and Teymen (2008); Hama Saeed and Alshkane (2018); Kallu and Roghanchi (2015); Heidari et al. (2012); Khanlır et al. (2014); Alshkane et al. (2018); and Salehin (2017) created the correlation equation between BTS and \( Is_{(50)} \) as presented in Table 2.

In addition, few researchers such as Kallu and Roghanchi (2015) carried out BTS and \( R_L \) tests for rhyolite and basalt rocks and they proposed the following power equation with the coefficient of correlation (R) of 0.91 using ASTM D3967-08 and ASTM D5873-05 for BTS and \( R_L \) tests, respectively:

\[
BTS = 0.15 * (R_L)^{1.33}
\]  

The aim of this study is to develop empirical equations to predict BTS from PLT, \( V_p \) and \( R_L \) for limestone rocks of Sulaymaniyah Province using simple and multiple regression analysis.

### Sampling Locations

Three main geological formations of Sulaymaniyah city [Figure 1] were selected so as to obtain the rock core samples. These formations with lithology, according to Numan et al., 1998; Al-Barzinji, 2008; Khanqa, 2011 are as follows:

1. Kometan Formation at Qlyasan region, lithology was white limestone
2. Pila Spy Formation at Qaradax region, lithology was dolomitic limestone
3. Sinjar Formation at Tasluja town, lithology was milky limestone.

A total of 33 limestone core samples were obtained using a standard core barrel. 10, 12, and 11 samples were obtained

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### Table 1: Empirical equations between BTS and \( V_p \) from literature

| Eq. no. | References | Equations | R  | Rock types                   | Remarks                                      |
|---------|------------|-----------|----|------------------------------|----------------------------------------------|
| 2       | Kılıç and Teymen (2008) | BTS=0.4935*(\( V_p \))^{1.8723} | 0.96 | Various rock types           | Used ISRM (1981) to perform BTS and \( V_p \) tests with 42 mm core size diameter |
| 3       | Khandelwal and Singh (2009) | BTS=14.5* \( V_p \) - 24.55 | 0.97 | Sedimentary                  | Used 54 mm core size diameter to perform BTS and \( V_p \) tests based on ISRM (1981 and 1978), respectively |
| 4       | Kurtuluş et al. (2016) | BTS=8* \( V_p \) + 3.84 | 0.88 | Sedimentary and igneous      | Performed BTS test based on ISRM (1978) and \( V_p \) test based on ISRM (2007) and ASTM (2001) with core size diameter of NX (54 mm) |
| 5       | Alshkane et al. (2018) | BTS=3.9419* \( e^{0.1587*Is_{(50)}} \) | 0.71 | Sedimentary                  | Performed splitting and \( V_p \) tests based on ISRM (1981) |
| 6       | Hama Salih and Alshkane (2018) | BTS=3.138* \( e^{0.379*Is_{(50)}} \) | 0.67 | Igneous                      | Used data from literature                     |

BTS: Brazilian tensile strength

### Table 2: Empirical equations between BTS and \( Is_{(50)} \) from literature

| Eq. no. | References | Equations | R  | Rock types | Remarks                                      |
|---------|------------|-----------|----|------------|----------------------------------------------|
| 7       | Kılıç and Teymen (2008) | BTS=7.5062*\( Ln(Is_{(50)}) \)+2.2219 | 0.96 | Various rock types           | Performed BTS test based on ISRM (1981) and diametrical PLT with core size of 50 mm diameter |
| 8       | Gurocak et al. (2012) | BTS=1.81*\( Is_{(50)} \)+4.78*10^{-6} | 0.90 | Various rock types           | Performed BTS test based on ISRM (1981) and PLT based on ISRM (1985) with core size of 50 mm |
| 9       | Heidari et al. (2012) | BTS=2.8992*\( Is_{(50)} \)-0.0723 | 0.94 | Gypsum rocks                | Performed BTS test based on ASTM (2001) and three types of PLT include axial, diametrical, and irregular lump using 56.7 mm core size diameter with ASTM D5731-01 |
| 10      | Gurocak et al. (2012) | BTS=2.9028*\( Is_{(50)} \)+1.1038 | 0.88 |                               |                                              |
| 11      |                  | BTS=3.4798*\( Is_{(50)} \)-0.523 | 0.93 |                               |                                              |
| 12      |                  | BTS=1.36*\( Is_{(50)} \)+2.06 | 0.96 |                               |                                              |
| 13      |                  | BTS=1.77*\( Is_{(50)} \)+2.57 | 0.93 |                               |                                              |
| 14      |                  | BTS=0.88*\( Is_{(50)} \)+2.7 | 0.97 |                               |                                              |
| 15      | Khanlır et al. (2014) | BTS=2.2*\( Is_{(50)} \)^{0.70} | 0.86 | Metamorphic               | Performed BTS and PLT using core size of 54 mm that prepared the samples with ISRM (1985) |
| 16      | Kallu and Roghanchi (2015) | BTS=11*\( Is_{(50)} \) | 0.90 | Rhyolite and basalt          | Performed BTS test based on ASTM D3967-08 and PLT based on ASTM D5731-08 |
| 17      | Salehin (2017) | BTS=0.617*\( Is_{(50)} \)+1.139 | 0.77 | Marlstone                   |                                              |
| 18      | Alshkane et al. (2018) | BTS=0.485*\( Is_{(50)} \)-3.0755 | 0.83 | Sedimentary                | Used ISRM (1981) and ASTM for splitting and diametrical PLT tests, respectively |
| 19      | Hama Saeed and Alshkane (2018) | BTS=[\( Is_{(50)} \]/(0.968+0.076*\( Is_{(50)} \))]-0.023 | 0.97 | Sedimentary                | Used data from literatures                  |

PLT: Point load test, BTS: Brazilian tensile strength

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**References**

Mohammed and Alshkane (2018)
from Qlyasan, Qaradax, and Tasilja regions, respectively, so as to perform BTS, \( V_p \), \( R_L \), and PLT tests.

**MATERIALS AND METHODS**

In this study, the limestone samples were taken from three site locations using drilling core machine with single-core barrel with a diameter size of NX (54.7 mm) and length of 400 mm. The samples were drilled in both lateral and vertical directions, in each site location. Half of the samples were drilled laterally and other halves were drilled vertically. These core samples were prepared according to ISRM (Brown, 1981) and cut by rock trimmer instrument. From each core sample, four pieces were prepared to perform BTS, \( V_p \), \( R_L \), and PLT tests.

BTS test was performed based on ISRM (1981) with length to diameter ratio of 0.37 using the compressive testing machine and 40 mm thick of two steel loading jaws to grip the samples during the loading that was created according to ISRM (Brown, 1981), as shown in Figure 2. \( V_p \) tests were conducted with length to diameter ratio of 2:1 and the samples ends were grinded to the flat of 0.02 mm according to ISRM (Brown, 1981). \( R_L \) test was performed according to ISRM (Ulusay, 2015) with length of 100 mm.

**Figure 1:** Sampling locations of limestone rocks

**Figure 2:** Compressive testing machine with two steel loading jaws to perform Brazilian tensile strength
Axial PLT was carried out according to ISRM (1985) with length to diameter ratio of 0.37.

RESULTS AND DISCUSSION

The results of mechanical properties for limestone rocks of Sulaymaniyah city showed that the range of BTS was from 15.132 MPa (milky limestone) to 40.041 MPa (white limestone), while the range of porosity ($n$) % was from 1.512% to 13.6% and $\gamma_n$ was from 2.061 g/cm$^3$ to 2.669 g/cm$^3$. These results showed that the tensile strength of the white limestone of Qlyasan from Komatan formation is stronger than the other two locations. Furthermore, the statistical analyses for the results of other properties for all three site locations are presented in Table 3.

The results were used to develop a single regression model between BTS and each of $V_p$, $R_l$, and $I_{s(50)}$. As well as a multiple regression model was used to predict BTS from $V_p$, $R_l$, and $I_{s(50)}$. The coefficient of correlation (R) and root mean square error (RMSE) for single and multiple regression models were computed and analyzed. According to Harris and Taylor (2003), there are several ranges of coefficient of correlation (R) for considering the degree of correlation between two parameters, as shown in Table 4.

### Single Regression Models

The relationship between BTS and $V_p$ was obtained for limestone rocks of Sulaymaniyah city that is presented in Figure 3a. It can be observed that BTS was increased by increasing $V_p$. The logarithmic model was developed to predict BTS from $V_p$. This is presented as Eq. (20) in Table 5. According to Harris and Taylor (2003), the correlation between BTS and $V_p$ is a low correlation because the R of this correlation is 0.37 which is between 0.2 and 0.4. It should be noted that the low value of R can be increased using multiple-regression model that will be presented in the next subsection.

The relationship between BTS and $R_l$ is presented in Figure 3b. It can be seen that as the value of $R_l$ increases, the value of BTS increases. The empirical equation to predict BTS from $R_l$ is presented as an exponential equation (Eq. (21)) in Table 5. According to Harris and Taylor (2003), there is a high correlation between BTS and $R_l$ since the value of R is 0.66.

Figure 3c shows the relationship between BTS and $I_{s(50)}$. It can be observed that BTS was directly proportional to $I_{s(50)}$. The empirical equation to predict BTS from $I_{s(50)}$ is presented as a power equation (Eq. (22)) in Table 5. A reasonable correlation was observed for Eq. (22) based on the value of $R$ because the value of the $R$ lies between 0.4 and 0.6 and equals to 0.42.

It can be seen that in all single correlations, the data are scattered around the trend line and according to Harris and Taylor (2003), a very high correlation was not obtained. Therefore, the multiple regressions are used for obtaining a reliable equation to predict BTS using simple tests.

### Multiple Regression Models

The multiple regression models were utilized to predict BTS from $V_p$, $R_l$, and $I_{s(50)}$. A power empirical equation was created. Eq. (23) shows this relationship, as presented in Table 5.

The multiple regression model was also developed to predict BTS from $V_p$ and $I_{s(50)}$ as a result, a logarithmic equation was created, as shown in Eq. (24) in Table 5.

The prediction of BTS from $R_l$ and $I_{s(50)}$ were created using power equation (Eq. (25)), as presented in Table 5.

In addition, three mechanical parameters of $V_p$, $R_l$, and $I_{s(50)}$ were correlated with BTS using linear equation (Eq. (26)), as presented in Table 5.

Based on the values of R and according to Harris and Taylor (2003), in all multiple equations, high correlation

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**Table 3: Statistical analysis of test results**

| Properties | No. of data | Minimum | Maximum | Mean | Stand. deviation | Variance | CoV. |
|------------|-------------|---------|---------|------|-----------------|----------|------|
| BTS (MPa)  | 33          | 15.132  | 40.041  | 26.027 | 7.450          | 55.510   | 28.63 |
| $V_p$ (km/s) | 33         | 3.224   | 5.832   | 4.674 | 0.636          | 0.405    | 13.61 |
| $R_l$      | 33          | 26.714  | 43.347  | 33.537 | 3.915          | 15.326   | 11.67 |
| $I_{s(50)}$ | 33         | 1.588   | 6.336   | 4.212 | 1.023          | 1.047    | 24.29 |
| $\gamma_n$ (g/cm$^3$) | 33       | 1.512   | 13.600  | 7.590 | 3.056          | 9.340    | 40.27 |

**Table 4: Description of R ranges after Harris and Taylor (2003)**

| Ranges of R | Descriptions       |
|-------------|--------------------|
| 0–0.2       | Very low and probably meaningless |
| 0.2–0.4     | Low correlation     |
| 0.4–0.6     | Reasonable correlation |
| 0.6–0.8     | High correlation    |
| 0.8–1       | Very high correlation |
was observed for Eq. (23) and Eq. (25), the reasonable correlation was observed for Eq. (24) and very high correlation was observed for Eq. (26).

In general, the developed models using multiple regression models were better than the produced models using single regression analysis because the multiple regression models have higher R and lower RMSE compared with equations that were developed by single regression analysis. Furthermore, in multiple regression, the value of R for the equations that include R/L is greater than the other equations that include V_p and Is_{(50)}. Furthermore, it can be observed that the Eq. (26) is better than the other multiple equations because the value of R for this equation is a maximum and equals to 0.98.

The range of RMSE of all empirical equations was from 5.13 MPa to 6.9 MPa. There was a small difference between

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**Table 5: Single and multiple equations to predict BTS**

| Equations                                      | RMSE (MPa) | R   | Eq. no. | Remarks                  |
|-----------------------------------------------|------------|-----|---------|--------------------------|
| BTS=19.0584*ln(0.8466*V_p)                   | 6.81       | 0.37| 20      | Low correlation          |
| BTS=5.3527*e^{0.0467*R_L}                     | 5.51       | 0.66| 21      | High correlation         |
| BTS=13.33*(Is_{(50)})^0.4474                 | 6.9        | 0.42| 22      | Reasonable correlation   |
| BTS=4.9204*(V_p)^0.0264+0.0004*(R_L)^0.8216   | 5.41       | 0.68| 23      | High correlation         |
| BTS=15.5981*ln (2.9*V_p)+8.8781* ln(0.048* Is_{(50)}) | 6.49 | 0.47 | 24      | Reasonable correlation   |
| BTS=0.001*(R_L)^2+4.0359*(Is_{(50)})^3.7253  | 5.13       | 0.71| 25      | High correlation         |
| BTS=1.1286*(V_p)+1.1209*(R_L)+1.6596*(Is_{(50)})−23.828 | 5.2 | 0.98 | 26      | Very high correlation    |

BTS in MPa, V_p in km/s, Is_{(50)} in MPa. RMSE: Root mean square error, BTS: Brazilian tensile strength.
them but the RMSE of Eq. (25) and Eq. (26) was 5.13 MPa and 5.2 MPa, respectively, that were low values compared with RMSE of other regression models.

Comparison with Other Expressions from the Literature

Single regression models of this study were compared with literature equations for correlation of BTS with each of the $V_p$, $R_L$, and $I_s(50)$, as shown in Figure 4a-c, respectively. RMSE was computed, as summarized in Table 6.

From Figure 4a and Table 6, it can be observed that the regression model Eq. (20) based on pulse velocity ($V_p$) of this study is more applicable to the limestone rocks to predict BTS compared with literature equations. It is interesting to see that the data from Eq. (20) of this study are closer to the equality line than the other data in the literature equations. Furthermore, the RMSE of Eq. (20) is lower than that of literature equations. It should be noted that the literature equations were developed for various rock types but the current study equations were especially developed for limestone rocks.

Concerning the Schmidt hammer rebound number, and point load strength index, it can be seen from Figure 4b and c that the Eq. (21) and Eq. (22) from this study are more reliable compared with literature equations. Based on this analysis, the equations that were developed in this study are more reliable to predict BTS using simple tests.

CONCLUSIONS

This study focused on the mechanical properties includes BTS, $V_p$, $R_L$, and PLT of intact limestone rocks for three formations of Sulaymaniyah city in Iraq. The statistical analysis of test results was conducted. The single and multiple correlations between BTS and each of $V_p$, $R_L$, and PLT were investigated using single and multiple regression models. The following conclusions are drawn:

- Based on the test of BTS on the three limestones, the tensile strength of white limestone was stronger than the tensile strength of dolomitic and milky limestone.
- Based on the $V_p$ test results, milky limestone has the highest $V_p$ which is 5.832 km/s if compared with other limestone types.

| Table 6: RMSE of the literature equations and study equations |
|---|
| **Eq. no.** | **Equations** | **RMSE (MPa)** | **Remark** |
| 1 | $BTS=0.15*(R_L)$ | 11.62 | Literature equations |
| 2 | $BTS=0.4935*(V_p)$ | 18.40 | |
| 3 | $BTS=14.5*V_p−24.55$ | 19.64 | |
| 4 | $BTS=8*V_p+3.84$ | 16.87 | |
| 5 | $BTS=3.9419*e^{0.1587*V_p}$ | 19.09 | |
| 6 | $BTS=3.138*e^{0.3*V_p}$ | 14.80 | |
| 7 | $BTS=7.5062*ln(I_s(50))+2.2219$ | 14.92 | |
| 8 | $BTS=1.81*I_s(50)+4.78*10^{-6}$ | 19.67 | |
| 9 | $BTS=2.8892*I_s(50)$−0.0723 | 15.55 | |
| 10 | $BTS=2.9028*I_s(50)+1.1038$ | 14.46 | |
| 11 | $BTS=3.4798*I_s(50)$−0.523 | 13.79 | |
| 12 | $BTS=1.36*I_s(50)+2.06$ | 19.53 | |
| 13 | $BTS=1.77*I_s(50)+2.57$ | 17.44 | |
| 14 | $BTS=0.88*I_s(50)+2.7$ | 20.86 | |
| 15 | $BTS=2.58*I_s(50)+0.79$ | 23.41 | |
| 16 | $BTS=11*I_s(50)$ | 23.11 | |
| 17 | $BTS=0.617*I_s(50)+1.139$ | 22.11 | |
| 18 | $BTS=0.485*I_s(50)+3.0755$ | 20.44 | |
| 19 | $BTS=|I_s(50)|−0.023$ | 23.91 | |
| 20 | $BTS=19.0584*ln(0.8466*V_p)$ | 6.81 | Current study |
| 21 | $BTS=5.3527*(0.0467*RL)^{0.4474}$ | 5.51 | |
| 22 | $BTS=13.33*(I_s(50)^{0.4474}$ | 6.90 | |

RMSE: Root mean square error, BTS: Brazilian tensile strength.
Based on $R_L$ results, white limestone is harder than milky, and dolomitic limestone rocks and $R_L$ of dolomitic with milky limestone rocks were approximately similar.

Test results concluded that $I_{50}$ of dolomitic limestone is stronger than $I_{50}$ of milky limestone, and approximately $I_{50}$ of white limestone was between the $I_{50}$ of other two types of limestone.

Based on $R$ and RMSE values, it can be said that the $R_L$ has a significant effect on the increasing $R$ and decreasing RMSE if compared with other parameters for single and multiple equations. Therefore, the correlation between BTS and $R_L$ is better than the correlation between BTS and other parameters.

A very strong correlation ($R$) was observed to predict BTS using three simple tests (Pulse Velocity, Schmidt Hammer, and PLT) based on a multiple linear regression model.

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