Research article

Statistical models for estimating the uniaxial compressive strength and elastic modulus of rocks from different hardness test methods

Ahmet Teymen*

Department of Mining Engineering, Niğde Omer Halisdemir University, 51240 Niğde, Turkey

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ABSTRACT

In engineering projects (dams, tunnels, slope stability) the strength characteristics of the rocks affect the construction operations. It is sometimes difficult, time-consuming, and expensive to evaluate the engineering properties of solid rocks by performing direct tests. For this reason, various laboratory studies have been carried out by many researchers to predict important engineering properties such as uniaxial compressive strength (UCS) and elastic modulus (E) of rocks in a practical way. One of the engineering properties used to estimate UCS-E practically is the hardness of rocks. Hardness tests are easy to apply and non-destructive, and in many of these tests very small specimens are needed. The main objective of this study is to analyze the relations between the UCS-E of the rocks and the various hardness methods (Schmidt hammer hardness, SHH; Shore Scleroscope hardness, SSH; Vickers hardness, HV; Brinell hardness, HB; and Indentation hardness index, IHI). For this purpose, the most appropriate and meaningful relations between hardness tests and UCS-E were determined by simple regression (SR) techniques. Relationships between main engineering properties (UCS, E) and physicomechanical properties were analyzed by multiple regression (MR) techniques using SPSS software. The statistical analyses made revealed the existence of strong correlations between UCS-E and hardness properties of rocks.

1. Introduction

Determination of the physicomechanical properties of intact rocks is very important to the classification of rocks for engineering applications such as foundations, underground structures, slope stability, and dam projects. The most widely used parameters for rock engineering are the UCS and E. Satisfactory results can be obtained from standard UCS and E tests with the use of samples with no micro cracks, discontinuity, and weakness. The need for precise sample preparation, the need for a heavy testing device, and the fact that it is a time-consuming test are disadvantaged sides of the UCS and E test. For these reasons, many predictive models were developed by many researchers for estimating UCS and E using some index or physical properties (Schmidt hammer hardness-SHH, Brazilian tensile strength-BTS, P-wave velocity-Vp, porosity-P, and point load index-I50). These tests require a shorter test time and less sophisticated equipment. On the other hand, many of these equipment can be used in the field. Until now, many researchers have presented many relationships to determine the physicomechanical properties of rocks and their relationship to UCS and E. In these studies, one or more parameters were investigated and significant results were obtained.

Diamantis et al. (2009) used parameters such as Is and Vp to predict the UCS of serpentines and developed some empirical equations. Minaeian and Abangari (2013) used SR and MR techniques in their work to determine the characteristics of the conglomerates. They identified relations between Vp, SHH, and UCS in their work. Jamshidi et al. (2016) conducted a correlation study using Iran travertines. The purpose of their study is to verify the correlation between Vp and SHR with some of the mechanical properties (UCS, BTS, Is) by empirical equations. Their results show that Vp appears to be more reliable than the SHR for estimating the mechanical properties.

Some researchers were worked to determine correlations between IHI and UCS (Atkinson et al., 1986; Pang et al., 1989; Szwedzicki 1998; Copur et al., 2003; Mateus et al., 2007; Tiryaki, 2008; Yagiz, 2009; Kahraman et al., 2012; Haftani et al., 2013). Szwedzicki (1998) carried out a laboratory study to evaluate the empirical indentation index as an indicator of hardness. In his results, he mentioned the relationship between UCS and IHI values and showed that the standard indentation test is important for defining the rock's mechanical properties. He also stated that the index value could be used as an independent method for classifying rock hardness and evaluating rock strength. Tercan and Ozcetik

* Corresponding author.
E-mail address: ateymen@ohu.edu.tr.
performed UCS, BTS, SHH, SHI, modulus of elasticity, Bohme abrasion, Los Angeles test, and cone indenter hardness tests on andesite samples. The researchers have studied the relationship between the mechanical and hardness properties of the andesite and mechanical and abrasion properties using the canonical ridge technique. According to their results, the relationship between abrasion and mechanical properties showed strong correlations than between hardness and mechanical properties. Mateus et al. (2007) developed empirical equations about the indentation test (248 tests) and mechanical properties of Colombian sandstones. According to the results, the usage of the indentation test is very useful for in-situ calibration of the geomechanical models.

There is a series of studies (Auffmuth, 1973; Singh et al., 1983; Shorey et al., 1984; Haramy and De Marco, 1985; Ghose and Chakraborti, 1986; O’Rourke, 1989; Cargill and Shakoor, 1990; Sachpazis, 1990; Tugrul and Zarif, 1999; Katz et al., 2000; Kahraman, 2001; Yilmaz and Sendir, 2002; Yasar and Erdogan, 2004; Fener et al., 2005; Dincer et al., 2008; Kilic and Teymen, 2008; Yagiz, 2011; Torabi et al., 2011; Sharma et al., 2011; Karakas et al., 2015; Jamshidi et al., 2016; Selcuk and Nar, 2016; Hebib et al., 2017) investigating the usefulness of the SHH test on UCS predictions on different rock types. Auffmuth (1973) obtained a strong relationship between SHH and both tangent Young modulus and UCS taking into account the effect of density. Singh et al. (1983) in their study about sedimentary rocks developed a very good simple equation between the UCS and the SHH of the rock. The study by O’Rourke (1989) for the same purpose consisted of different sedimentary rocks. In the study by Sachpazis (1990), equations with high correlation coefficients between the USC and the SHH for the calcium carbonate rocks were determined. Cargill and Shakoor (1990), tested for UCS, IS, SHH, Los Angeles abrasion, and slate durability properties of five different types of rocks. The results indicated the presence of a strong linear correlation between IS and UCS. Tugrul and Zarif (1999) found a strong correlation between SHH and UCS values of granitic rocks. According to their determinations, one of the features that have the greatest effect on the strength of granitic rocks is the average grain size. Katz et al. (2000) performed a similar study on rocks with different origins such as limestone, granite, marble, sandstone, syenite, and chalk, and found a strong relationship between UCS and SHH. Yilmaz and Sendir (2002) conducted empirical studies on gyspum rock for the same purpose and found similar relationships between UCS and SHH. Kahraman (2001) correlated UCS with the parameters such as SHH, IS, and Vp. Yasar and Erdogan (2004) in their studies used a series of rocks consisting of marble, limestone, basalt, and sandstone and they found a good and strong statistical relationship between SHH and UCS. Fener et al. (2005) were used indirect test methods for estimating the UCS of rock. Cobanoglu and Celik (2008) investigated relationships between UCS and IS, Vp, SHH together with the effects of length/diameter ratio of the core. Yagiz (2011) determined some rock properties such as water absorption, elastic modulus, slate durability index, density, UCS, SHH and n_c, and aimed to estimate these engineering properties using Vp which non-destructive experiment. Sharma et al. (2011) published some statistical relationships between SHH with slate durability index, impact strength index, and Vp. Torabi et al. (2011) aimed to establish a correlation between SHH and UCS of a rock mass (the roof rock of coal seams) under particular geological circumstances. The researchers tested a significant number of test samples both in situ and in the laboratory to determine the SHH and UCS and established a new equation.

Some of the researchers who focused the prediction UCS of rocks with hardness tests transferred the SSH method (Griffith, 1937; Wuerker, 1953; Deere and Miller, 1966; Vervaele and Mulder, 1995; Holmegeirdtir and Thomas, 1998; Koncagul and Santi, 1999; Yasar and Erdogan, 2004; Tumac et al., 2007; Kilic and Teymen, 2008; Tiryaki, 2008), Wuerker (1953) determined the relationship between UCS and SSH using simple linear equations. Deere and Miller (1966) studied extensively with a large number of rocks of various rock types and developed a classification system for intact rocks. The authors determined that texture, mineralogy, and anisotropy were important parameters affecting the rock classification. Also, when the effect of unit weight is included, it is concluded that the correlation of module properties and UCS with SHH is more significant than SSH. Holmegeirdtir and Thomas (1998) conducted a study using different SSH test devices and established some equations relating to the relationship between UCS and SHH. Koncagul and Santi (1999) assessed the utility of SSH and slate durability tests to predict UCS according to correlations obtained from their laboratory tests and other studies. They base their work on the analysis of physical and structural characteristics that affect strength and durability. Yasar and Erdogan (2004) tried to relate UCS to SSH and found a strong statistical relationship between these two parameters. They also investigated the relationship between the physical and engineering properties of different rocks within this study. Tumac et al. (2007) tested 30 different rocks in their work named “Estimation of rock cuttability from shore hardness and compressive strength properties”. They calculated the two SHH values and a coefficient of deformation value (K) and determined the relationship between SSH values, K, and the road headers cutting rate for different rock types using these values. Researchers determined a relationship between SSH values, UCS, and specific energy, which may be used to estimate the instantaneous cutting rates and the rock cuttability. Kilic and Teymen (2008) tested nineteen rocks to obtain the relationships between SHH, IS, Vp, SHH, n_c, and UCS, BTS, and Bohme surface abrasion. Their SR results showed good correlations. Boutrid et al. (2013) showed that there is a beneficial correlation between HB and the strength properties of rocks as a result of their tests on rock samples taken from different depths of the Hassi Messaoud field between 1900m and 2900m. Teymen (2018) published a series of equations in which the basic engineering properties of tuffs were estimated by HB hardness in a study carried out using 27 tuffs.

Rock hardness is defined as the resistance of rock against a penetrating object that (sinks or impacts) the surface of a rock and it is regarded as a function of the mineral composition, bonding capacity, and strength of the matrix material. Hardness is an empirical test used to identify and classify materials and therefore the hardness value of rock varies according to the applied hardness method. Hardness is important in engineering investigations where rock-metal interaction is intensively observed. Mining operations such as rippering, drilling, crushing, transport, grinding, and excavation are the most important of these engineering applications. The hardness test methods used in this study have different test conditions from each other. The most widely used rock hardness methods are SHH and SSH since they have the advantage of being practically applied in the field. Metal hardness methods such as HB and HV require specially designed tools and have limited use in rock engineering applications. Among these methods, IHI is the newest proposed method for determining rock hardness. Until now, SHH and SSH tests have mostly been used in rock hardness measurement tests for UCS, and E estimation. In the literature, the number of experimental studies predicting UCS using hardness methods, mostly known as metal hardness, is very small. Many researchers have been focused on the relations between UCS-SHH and UCS-SH. The rocks used in this study have been tested with both commonly used hardness methods (SSH, SHH, and IHI) and metal hardness methods (HB, HV). Thus different test methods were compared with each other and their differences were revealed. This study which includes the new experimental relationships, it was aimed to contribute to the literature about the usefulness of HB and HV hardness tests, which are known as metal hardness, in the prediction of UCS and E. It is hoped that the equations determined using hardness tests in this study will assist geotechnical and rock engineers when decisions are made at the preliminary field survey stage.

2. Sampling and experimental studies

Plutonic (15), volcanic (20), subvolcanic (7), pyroclastic (10), sedimentary (28), and metamorphic (13) origin rocks were collected from various cities of Turkey. Standard laboratory test procedures ISRM, 1981 was used in the specimen preparation stage of the tests using core, block,
and fragment rocks. According to the intact rock strength classification proposed by Deere and Miller (1966); 1–25 MPa “Very Low Strength-VLS”, 25–50 MPa “Low Strength-LS”, 50–100 MPa “Medium Strength-MS”, 100–200 MPa “High Strength-HS” and rocks higher than 200 MPa are classified as “Very High Strength-VHS”. The analysis of the rocks used in this study according to this classification is given in Table 1, and the analysis following the porosity classification is given in Table 2.

Rocks are classified into three categories, low strength (<50 MPa; 21.5%), medium strength (50–100 MPa; 31.2%) and high strength (>100 MPa; 47.3%), respectively, using the analysis in Table 1. According to another important classification (Table 2), 38.7% of the tested rocks were quite compact, 29.0% were low porous and 32.3% were medium-high porous.

The interval of values examined, according to the test results of 93 specimens, is: Uniaxial Compressive Strength (UCS) 6.6–303.7 MPa; Elastic Modulus (E) 1.0–58.8 GPa; Schmidt Hammer Hardness (SHH) 16.9–65.1 rebound; Shore Scleroscope Hardness (SSH) 7.2–99.0; Brinell Hardness (HB) 1.9–814.9 HBW/10/3000; Vickers Hardness (HV) 7.5–580.8 HV50; Indentation Hardness Index (IHI) 0.8–26.9 kN/mm; Brazilian Tensile Strength (BTS) 1.0–21.3 MPa; Poisson Load Index (I_{PS}) 1.2–15.7 MPa; Block Punch Index (BPI) 1.2–42.2 MPa; Bohme Surface Abrasion (BSA) 5.0–139.1 cm²/50cm²; P-wave Velocity (Vp) 0.9–6.7 km/s; Unit Weight (UW) 1.05–2.96 gr/cm³; Impact Strength Index (SSI) 39.2–92.3 %; Crushing Index (CI) 51.6–93.2 %; Protodyakonov Index (f) 6.5–325.8 %; Effective Porosity (P) 0.01–49.0 %; Rock Impact Hardness Number (RIHN) 2.9–91.9 and Coefficient of Rock Strength (CRS) 0.2–7.0. All test devices used in the study were shown in Figure 1, and core specimens of some tested rocks in this study were shown in Figure 2.

While most of the tests (UCS, E, SHH, SSH, HB, HV, BTS, BPI, BSA, Vp, ISI, CRS, CI, P, f, and I_{PS}) are carried out according to the application procedures described in Teymen (2020), the application details of other tests (RIHN, ISI, CRS, CI, P, and UW) are explained in Teymen (2019). To carry out the IHI test, a point load test device that is compatible with the loading system (having 30 kN capacity) ISRM, 1981 test procedures, was used. This device has a 5 mm radius spherical tip and a conical platen. To carry out the IHI test, a point load test device that is compatible with the loading system (having 30 kN capacity) ISRM, 1981 test procedures, was used. This device has a 5 mm radius spherical tip and a conical platen. Having a 60° cone. For the test, smooth core specimens (42 mm diameter and 30 mm thickness) placed in a steel frame with a high strength plaster were used. A manual dial gauge was used on the Is device for penetration measurement. The disc specimens were placed on the base plate of the Is devices and loaded up to 20 kN. The penetration values reading from the dial gauge were recorded three times for each rock. IHI values of rocks were calculated by dividing the load by the penetration values (mm). For some weak rock specimens such as tuff, the load was applied below 20 kN.

3. Statistical analysis and results

SR and MR analyzes were performed using SPSS software to obtain predictive models. Power, exponential, linear, and logarithmic curve-fitting approaches were performed within the scope of SR analysis (Eqs. (1), (2), (3), (4), (5), (6), (7), (8), (9), and (10) in Tables 3 and 4). Within the scope of this study, MR equations related to UCS were shown in Table 5 (Eqs. (11), (12), (13), (14), (15), (16), (17), (18), (19), (20), (21), (22), and (23)) and equations developed for estimation of E were shown in Table 6 (Eqs. (24), (25), (26), (27), (28), (29), (30), (31), (32), (33), (34), (35), and (36)). In Figure 3, correlation graphs between BTS, BPI, and BSA tests and UCS and E tests are given. It is seen that these tests give significant correlations with UCS and E parameters. These tests, which are frequently used in direct estimation of UCS, were not used as independent variables in regression studies.

The detailed information of the models obtained according to 95% confidence interval using the least-squares technique is summarized in Table 3. While variance regression analysis (F test) was used to confirm the significance of the regressions, the t-test was chosen to establish the sig. level of the coefficients (R). As can be seen in the table, the significance of F and t-tests (p-values) were found to be less than 0.05 for both tests. This is proof of the reliability of the derived equations.

The most reliable method with the highest coefficient of determination was determined with the curve fitting approach. The nonlinear analysis was performed using unstandardized coefficients determined for constant and independent parameters. These coefficients were subjected to iteration until the relative reduction between the residual sums of squares was negligible. Regulated coefficients (A and B), standard error values, and derived SR equations as a result of nonlinear regression are summarized in Table 4.

\[
UCS = 5.5G_{0.06SHH} 
\]

(1)
\[
UCS = 0.27SSH^4 
\]

(2)
\[
UCS = 5.1HB^{0.62} 
\]

(3)
\[
UCS = 5.8HV^{0.62} 
\]

(4)
\[
UCS = 6.2HI^{1.08} 
\]

(5)
\[
E = 1.55G_{0.05SHH} 
\]

(6)
\[
E = 0.14SSH^{1.2} 
\]

(7)
\[
E = 1.54HB^{0.52} 
\]

(8)
\[
E = 1.62HV^{0.54} 
\]

(9)
\[
E = 2.04HI^{0.87} 
\]

(10)

The relationships between the hardness tests and UCS (Figures 4a, 5a, 6a, 7a, and 8a) and E (Figures 4b, 5b, 6b, 7b, and 8b) were shown by drawing regression curves together with residual graphs. Among the equations related to UCS, the highest coefficients of determination varied between 0.66 and 0.90, while the coefficients for E varied between 0.57 and 0.65. The weakest relationships for hardness tests belong to the SSH tests. This is proof of the reliability of the derived equations.

Table 1. Analysis of tested rocks according to the classification of rock strength.

| Rock classification | All rock specimens | Metamorphic | Sedimentary | Igneous |
|---------------------|--------------------|-------------|-------------|---------|
|                      |                    | Plutonic    | Subvolcanic | Volcanic | Pyroclastic |
| VLS                 | 9 (9.7 %)          | 1           | 3           | 0       | 0          | 0          | 5          |
| LS                  | 11 (11.8 %)        | 3           | 3           | 0       | 0          | 0          | 5          |
| MS                  | 29 (31.2 %)        | 7           | 10          | 3       | 1          | 8          | 0          |
| HS                  | 35 (37.6 %)        | 0           | 11          | 11      | 3          | 10         | 0          |
| VHS                 | 9 (9.7 %)          | 2           | 1           | 1       | 3          | 2          | 0          |
| Total rock specimens | 93 (100 %)         | 13 (14.0 %) | 28 (30.1 %) | 15 (16.1 %) | 7 (7.5 %) | 20 (21.5 %) | 10 (10.8 %) |
While performing MR analysis, one of the independent variables was kept constant provided that it was a hardness test, and two or three independent variables were used in the analyzes. For MR analysis Is50, Vp, ISI, RIHN, CRS, CI, f, UW, and P test values were used as independent variables in addition to hardness tests (SHH, SSH, HB, HV, IHI). The most significant and reliable MR equations determined and the statistical data of these equations are summarized in Tables 5 and 6. In the MR analyses, independent variables with a mutual correlation ranging between 0.46 and 0.67 were used together.

To further strengthen the verification of MR equations, the multicollinearity problem was also examined (Tables 5 and 6). Scatter plots show confidence interval lines and prediction lines (minimum and

Table 2. Classification of rock porosity.

| Rock classification     | Porosity (%) | All rock specimens |
|-------------------------|--------------|--------------------|
| Very Compact            | <1.0         | 36                 | 38.7 |
| Low Porous              | 1.0–2.5      | 27                 | 29.0 |
| Medium Porous           | 2.5–5        | 9                  | 9.7  |
| Highly Porous           | 5–10         | 7                  | 7.5  |
| Very Porous             | 10–20        | 6                  | 6.5  |
| Very High Porous        | >20          | 8                  | 8.6  |
| Total rock specimens    |              | 93                 | 100  |
maximum) concerning the 95% confidence interval. The scatter plots shown in these figures represent the hardness methods, respectively, and are evidence that MR models are more confidential than SR models.

UCS = 1.72SHH + 32.05CRS – 43.5 \hspace{1cm} (11)

UCS = 0.98SHH + 30.88CRS – 17.4 \hspace{1cm} (12)

UCS = 1.34SHH + 0.51f – 20.3 \hspace{1cm} (13)

UCS = 0.3HB + 1.91ISI – 86.6 \hspace{1cm} (14)

UCS = 0.39HV + 1.91ISI – 85.7 \hspace{1cm} (15)

UCS = 4.71IHI + 0.47f – 1.1 \hspace{1cm} (16)

UCS = 2.38SHH + 0.54f – 55.9 \hspace{1cm} (17)

UCS = 0.47HV + 38.05UW – 47.1 \hspace{1cm} (18)

UCS = 1.35SHH + 5.25b_{50} + 25.16CRS – 37.7 \hspace{1cm} (19)
Table 6. Verification of MR models related to E estimation of rocks.

| Eq. no | Independent variables | F ratio | p value | F-tabu. | t | p value | t | max. | p value | t-tabu. | VIF max. | Adj. R² |
|--------|-----------------------|---------|---------|---------|----|---------|----|------|---------|---------|----------|--------|
| Eq. (24) | SHH, CRS | 222 | 0.00 | 3.1 | 3.6 | 0.00 | 10.7 | 0.00 | 2.0 | 1.8 | 0.83 |
| Eq. (25) | SHH, f | 175 | 0.00 | 3.9 | 0.00 | 8.9 | 0.00 | 1.6 | 0.79 |
| Eq. (26) | SSH, Vp | 137 | 0.00 | 6.5 | 0.00 | 8.1 | 0.00 | 1.6 | 0.75 |
| Eq. (27) | HB, Vp | 253 | 0.00 | 2.9 | 0.00 | 11.3 | 0.00 | 1.5 | 0.85 |
| Eq. (28) | HB, ISI | 176 | 0.00 | 3.6 | 0.00 | 9.6 | 0.00 | 1.7 | 0.79 |
| Eq. (29) | HV, Vp | 276 | 0.00 | 3.3 | 0.00 | 12.0 | 0.00 | 1.5 | 0.86 |
| Eq. (30) | HV, UW | 179 | 0.00 | 3.8 | 0.00 | 12.9 | 0.00 | 1.3 | 0.80 |
| Eq. (31) | IHl, Vp | 142 | 0.00 | 4.5 | 0.00 | 6.9 | 0.00 | 1.8 | 0.75 |
| Eq. (32) | SHH, Vp, CRS | 184 | 0.00 | 2.7 | 2.6 | 0.01 | 10.3 | 0.01 | 2.0 | 3.1 | 0.86 |
| Eq. (33) | SSH, Vp, CRS | 199 | 0.00 | 3.7 | 0.00 | 9.0 | 0.00 | 2.2 | 0.87 |
| Eq. (34) | HB, Vp, CRS | 210 | 0.00 | 3.0 | 0.00 | 8.1 | 0.00 | 4.3 | 0.87 |
| Eq. (35) | HV, Vp, CRS | 215 | 0.00 | 3.2 | 0.00 | 8.5 | 0.00 | 4.8 | 0.88 |
| Eq. (36) | IHl, Vp, CRS | 199 | 0.00 | 3.5 | 0.00 | 8.6 | 0.00 | 2.5 | 0.86 |

Figure 3. Relationship between BTS, BPI, BSA, and UCS-E tests.

Figure 4. Correlation and residual graphs a) between SHH and UCS and b) between SHH and E test.

\[ UCS = 0.75 \times SHH + 0.86 \times RIHN + 23.23 \times CRS - 18.3 \]  \hspace{1cm} (20)

\[ E = 0.38 \times SHH + 4.65 \times CRS - 8.2 \]  \hspace{1cm} (24)

\[ UCS = 0.15 \times HB + 1.21 \times RIHN + 14.39 \times CRS + 9 \]  \hspace{1cm} (21)

\[ E = 0.46 \times SHH + 0.08 \times f - 9.6 \]  \hspace{1cm} (25)

\[ UCS = 0.22 \times HV - 2.02 \times CI + 15.11 \times CRS + 191.5 \]  \hspace{1cm} (22)

\[ E = 0.22 \times SHH + 4.31 \times Vp - 13.8 \]  \hspace{1cm} (26)

\[ UCS = 2.29 \times Hl - 0.87 \times CI + 26.86 \times CRS + 73.7 \]  \hspace{1cm} (23)

\[ E = 0.05 \times HB + 3.71 \times Vp - 5 \]  \hspace{1cm} (27)
The t-value was calculated for all independent variables in the given MR equations, but only the t-value with the smallest and highest absolute value is given in Tables 5 and 6. As can be seen, the minimum t-values in all equations except Eq. (16) are higher than the tabulated t-value. A similar application was made for the VIF (Variance Inflation Factor) value, and only the maximum VIF values were included in the tables. Since the maximum VIF values are less than 10, there is no perfect linear relationship between the independent variables.

All the obtained equations are successful in confidence tests performed at a 95% level for VIF, F, and t-tests. HV, HB, and SHH tests gave the most confident results and high coefficients of determination in the prediction of UCS and E parameters, respectively. Among the hardness tests, the weakest reliability results belong to the SSH and IHI tests. It is clear that the MR equations detailed in Tables 5 and 6 can be easily used to make stronger and more accurate predictions. Since MR models contain two or three independent variables, their prediction capabilities and coefficients of determination are higher than SR equations. In Figures 9, 10, 11, 12, and 13, the predicted UCS (UCSp)–measured UCS values are shown.

\[
E = 0.05HB + 0.35ISI - 14 \quad (28)
\]
\[
E = 0.06HV + 3.8V_p - 5.3 \quad (29)
\]
\[
E = 0.07HV + 10.43UW - 14.8 \quad (30)
\]
\[
E = 0.8IHI + 3.81V_p - 9.2 \quad (31)
\]
\[
E = 0.18SSH + 2.4V_p + 4.21CRS - 9.2 \quad (32)
\]
\[
E = 0.1SSH + 2.86V_p + 3.82CRS - 8 \quad (33)
\]
\[
E = 0.03HB + 3.17V_p + 2.58CRS - 4.7 \quad (34)
\]
\[
E = 0.03HV + 3.3V_p + 2.28CRS - 4.9 \quad (35)
\]
\[
E = 0.36IHI + 2.71V_p + 3.76CRS - 5.9 \quad (36)
\]
(UCS_M) and predicted E (E_P)-measured E (E_M) for some MR equations are correlated. Adjusted coefficients of determination ranged from 0.83 to 0.94 for UCS and 0.75 to 0.88 for E.

The normal distribution control of estimation and measurement values was examined in terms of five main parameters (Kurtosis-Skewness, histogram graph, Kolmogorov-Smirnov normality test, coefficient of variation, and detrended Q-Q plots). As a result of the evaluation with these five parameters (for UCS), Eqs. (11), (12), (13), (16), (17), (19), (20), and (23) shows normal distribution, while Eqs. (14), (15), (18), (21), and (22) shows a-normal distribution. After this stage, the data set used in the study was analyzed with parametric-nonparametric procedures.

As a result of the Anova test, Levene statistics of the variations of UCS_P and UCS_M values were found to be 0.340 and the sig. level to be 0.986. The significance level of being close to 1.00 indicates the perfection of variance homogeneity. Also, since the F value is 0 and the sig. level is 1, it was determined that there is no difference between the mean values of the UCS groups. Provided that UCS_M values are the control group, Dunnett's two-sided T test (post-hoc) was chosen for the comparison of MR equations (Table 7; Figure 14). The new significance value (NVS) was revised by considering the number of compared groups and using the NVS equation previously published in Teymen and Mengüç (2020). NVS values were calculated as 0.00054 and 0.00055 for UCS and E, respectively. According to the applied post-hoc test, the standard error values of the data pairs are equal and the average differences are very close. It is seen that E and UCS of rocks can be predicted reliably from any equation presented in this study, taking into account the correlations and Anova analysis results.

In addition to all analyzes, percentage errors between UCS_P-UCS_M and EP-E_M were also evaluated. Absolute error is the difference between UCS_P and UCS_M (or EP-E_M). The relative error is the error value obtained by dividing the absolute error by the magnitude of the UCS_M (or E_M). Both are expressed as percentages. Percentage error analysis for UCS values is given in Table 8, Eq. (20) resulted in an error value of 47.3%, while Eq. (13) resulted in less than 10% error value for only 19 specimens (20.4% of the specimens). Therefore, it is clear that Eq. (13) will have lower reliability than Eq. (20) for UCS prediction.

Within the non-parametric test using the Welch Anova method, Tamhane's T2 test (post-hoc) was chosen. With this method in which the UCS_M was taken as the control group, the relationships between the UCS_P
and UCSM values were investigated and multiple tests were compared. The fact that the Welch statistic value has a value of 0 and the sig. level a value of 1 indicates that the groups are homogeneously distributed. Therefore, there is no remarkable difference between the groups (UCSP and UCSM).

All studies for UCS estimation equations have been repeated for the modulus of elasticity. The results obtained were similar (Levene statistic $= 0.441$; sig. level $= 0.955$ and $F = 0.000$; sig. level $= 1.00$). Similar to UCS, post-hoc test results for $E$ were summarized in Table 9.

According to the elasticity percentage error analysis detailed in Table 10, the lowest reliability for the prediction of $E$ will be obtained by Eq. (26) and the highest reliability by Eq. (35). The results determined for UCS by the Welch Anova method are similar for the $E$ values. That is, the $E$ groups are homogeneously distributed and there was no significant difference between the groups (Welch statistic $= 0.000$ and sig. level $= 1.00$). In addition to statistical analysis, evaluations were made using a series of classification methods (Table 11). UCS and $E$ data were grouped using the same nominal values to understand the variability caused by parameters such as measurement repeatability and material uniformity. The measurement capabilities of the methods were tried to be explained in this way. The classification systems mentioned in the study have been rearranged so that the nominal groups contain the desired number of rocks. In Table 11, the method which gives the highest coefficient of determination from linear, power, exponential, and logarithmic methods by curve fitting approach is considered. The main purpose of this part of the study is not a deep statistical evaluation of classified data. This section aims to give an idea to the researchers about the possible effects of parameters such as rock origin, porosity, and strength.
The data set is divided into two groups according to Table 1, such that it has a strength below 100 MPa and above 100 MPa.

The porosity classification given in Table 2 and divided into six categories was evaluated in three categories for this study; compact rocks (<1%), low porous rocks (1.0–2.5%), porous rocks (>2.5%). Finally, rock origin classification was used. Ninety-three rocks were divided into three basic categories as igneous, metamorphic, and sedimentary.

When the coefficients of determination are considered, the best results according to the rock origin classification belong to the igneous rocks group consisting of 52 rocks (Figure 15a). All of the hardness methods show a power relationship with UCS. The coefficients of determination are similarly high for metamorphic rocks and the relationships are linear. However, the very few metamorphic rocks tested somewhat reduce the predictive reliability of the equations. Here, it is seen that the cluster of two high-strength quartzites joining the cluster of Figure 12. Comparison of predicted and measured values in MR equations about HV a) for Eq. (22), for b) Eq. (35).

![Figure 12](image)

![Figure 13](image)

Table 7. Multiple comparisons of the UCSM and UCSP.

| (I)       | (J)       | Mean Difference (I-J) | Std. Error | sig.  | 99.946% Confidence Interval |
|-----------|-----------|-----------------------|------------|-------|-----------------------------|
| UCS [Eq. (11)] | UCSM     | 0.0032                | 9.0931     | 1.0   | -37.251 - 37.258            |
| UCS [Eq. (12)] | UCSM     | 0.0022                | 9.0931     | 1.0   | -37.252 - 37.257            |
| UCS [Eq. (13)] | UCSM     | 0.0032                | 9.0931     | 1.0   | -37.251 - 37.258            |
| UCS [Eq. (14)] | UCSM     | 0.0011                | 9.0931     | 1.0   | -37.253 - 37.255            |
| UCS [Eq. (15)] | UCSM     | 0.0032                | 9.0931     | 1.0   | -37.251 - 37.258            |
| UCS [Eq. (16)] | UCSM     | -0.0022               | 9.0931     | 1.0   | -37.257 - 37.252            |
| UCS [Eq. (17)] | UCSM     | -0.0065               | 9.0931     | 1.0   | -37.261 - 37.248            |
| UCS [Eq. (18)] | UCSM     | 0.0011                | 9.0931     | 1.0   | -37.253 - 37.255            |
| UCS [Eq. (19)] | UCSM     | -0.0011               | 9.0931     | 1.0   | -37.253 - 37.255            |
| UCS [Eq. (20)] | UCSM     | -0.0011               | 9.0931     | 1.0   | -37.255 - 37.253            |
| UCS [Eq. (21)] | UCSM     | -0.0032               | 9.0931     | 1.0   | -37.258 - 37.251            |
| UCS [Eq. (22)] | UCSM     | 0.0032                | 9.0931     | 1.0   | -37.251 - 37.258            |
| UCS [Eq. (23)] | UCSM     | -0.0011               | 9.0931     | 1.0   | -37.255 - 37.253            |

* Dunnett t-tests treat one group as a control and compare all other groups against it.
eleven rocks with a strength less than 100 MPa (Figure 15b). High coefficient equations between UCS and metal hardness tests were obtained in sedimentary rocks. The most prominent finding in the evaluation made by strength classification was the low coefficients of the equations obtained from rock hardness methods (SHH, SSH, and IHI) applied to medium strength rocks (>100 MPa). When the plots between the UCS<sub>p</sub> and UCS<sub>M</sub> values are examined, approximately half of the 44 rocks exhibit a narrow range of strength between 100 MPa and 140 MPa, while

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**Table 8. Percentage error values for predicted methods for UCS.**

| Eq. number of methods | Percentage error ≤10 % | Percent of specimens (%) | Differences between Eq. (20) and other equations | Differences (%) |
|----------------------|-------------------------|---------------------------|-----------------------------------------------|----------------|
| Eq. (11)             | 36                      | 38.7                      | [Eq. (20) - Eq. (11)]                         | 8.6            |
| Eq. (12)             | 35                      | 37.6                      | [Eq. (20) - Eq. (12)]                         | 9.7            |
| Eq. (13)             | 19                      | 20.4                      | [Eq. (20) - Eq. (13)]                         | 26.9           |
| Eq. (14)             | 35                      | 37.6                      | [Eq. (20) - Eq. (14)]                         | 9.7            |
| Eq. (15)             | 38                      | 40.9                      | [Eq. (20) - Eq. (15)]                         | 6.5            |
| Eq. (16)             | 27                      | 29.0                      | [Eq. (20) - Eq. (16)]                         | 18.3           |
| Eq. (17)             | 22                      | 23.7                      | [Eq. (20) - Eq. (17)]                         | 23.7           |
| Eq. (18)             | 38                      | 40.9                      | [Eq. (20) - Eq. (18)]                         | 6.5            |
| Eq. (19)             | 36                      | 38.7                      | [Eq. (20) - Eq. (19)]                         | 8.6            |
| Eq. (20)             | 44                      | 47.3                      | [Eq. (20) - Eq. (20)]                         | 0.0            |
| Eq. (21)             | 36                      | 38.7                      | [Eq. (20) - Eq. (21)]                         | 8.6            |
| Eq. (22)             | 39                      | 41.9                      | [Eq. (20) - Eq. (22)]                         | 5.4            |
| Eq. (23)             | 42                      | 45.2                      | [Eq. (20) - Eq. (23)]                         | 2.2            |

**Table 9. Multiple comparisons of the EP and EM.**

| Multiple Comparisons of EP and EM | Dunnett t-tests treat one group as a control and compare all other groups against it. |
|----------------------------------|-------------------------------------------------------------------------------------|
| (I)                              | (J)                                   | Mean Difference (I-J) | Std. Error | sig. | 99.945 % Confidence Interval |
|----------------------------------|---------------------------------------|-----------------------|------------|------|-----------------------------|
|                                 |                                       |                       |            |      | Lower Bound | Upper Bound |
| Eq. [Eq. (24)]                  | EM                                    | 0.00000               | 1.51567    | 1.0  | -6.2031       | 6.2031       |
| Eq. [Eq. (25)]                  | EM                                    | -0.00108              | 1.51567    | 1.0  | -6.2041       | 6.2020       |
| Eq. [Eq. (26)]                  | EM                                    | 0.00215               | 1.51567    | 1.0  | -6.2009       | 6.2052       |
| Eq. [Eq. (27)]                  | EM                                    | 0.00000               | 1.51567    | 1.0  | -6.2031       | 6.2031       |
| Eq. [Eq. (28)]                  | EM                                    | -0.00108              | 1.51567    | 1.0  | -6.2041       | 6.2020       |
| Eq. [Eq. (29)]                  | EM                                    | 0.00215               | 1.51567    | 1.0  | -6.2009       | 6.2052       |
| Eq. [Eq. (30)]                  | EM                                    | 0.00430               | 1.51567    | 1.0  | -6.1987       | 6.2074       |
| Eq. [Eq. (31)]                  | EM                                    | 0.00232               | 1.51567    | 1.0  | -6.1998       | 6.2063       |
| Eq. [Eq. (32)]                  | EM                                    | 0.00108               | 1.51567    | 1.0  | -6.2020       | 6.2041       |
| Eq. [Eq. (33)]                  | EM                                    | 0.00108               | 1.51567    | 1.0  | -6.2020       | 6.2041       |
| Eq. [Eq. (34)]                  | EM                                    | 0.00000               | 1.51567    | 1.0  | -6.2031       | 6.2031       |
| Eq. [Eq. (35)]                  | EM                                    | -0.00215              | 1.51567    | 1.0  | -6.2052       | 6.2009       |
| Eq. [Eq. (36)]                  | EM                                    | 0.00000               | 1.51567    | 1.0  | -6.2031       | 6.2031       |

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Table 10. Percentage error values for predicted methods for E.

| Eq. number of methods | Percentage error <10 % | Percent of specimens (%) | Differences between Eq. (35) and other equations | Differences (%) |
|-----------------------|-------------------------|---------------------------|-------------------------------------------------|-----------------|
|                       | Number of specimens     |                           |                                                  |                 |
| Eq. (24)              | 28                      | 30.1                      | [Eq. (35) - Eq. (24)]                           | 10.8            |
| Eq. (25)              | 22                      | 23.7                      | [Eq. (35) - Eq. (25)]                           | 17.2            |
| Eq. (26)              | 21                      | 22.6                      | [Eq. (35) - Eq. (26)]                           | 18.3            |
| Eq. (27)              | 33                      | 35.5                      | [Eq. (35) - Eq. (27)]                           | 5.4             |
| Eq. (28)              | 23                      | 24.7                      | [Eq. (35) - Eq. (28)]                           | 16.1            |
| Eq. (29)              | 29                      | 31.2                      | [Eq. (35) - Eq. (29)]                           | 9.7             |
| Eq. (30)              | 25                      | 26.9                      | [Eq. (35) - Eq. (30)]                           | 14.0            |
| Eq. (31)              | 23                      | 24.7                      | [Eq. (35) - Eq. (31)]                           | 16.1            |
| Eq. (32)              | 29                      | 31.2                      | [Eq. (35) - Eq. (32)]                           | 9.7             |
| Eq. (33)              | 29                      | 31.2                      | [Eq. (35) - Eq. (33)]                           | 9.7             |
| Eq. (34)              | 35                      | 37.6                      | [Eq. (35) - Eq. (34)]                           | 3.2             |
| Eq. (35)              | 38                      | 40.9                      | [Eq. (35) - Eq. (35)]                           | 0.0             |
| Eq. (36)              | 33                      | 35.5                      | [Eq. (35) - Eq. (36)]                           | 5.4             |

Table 11. Classification systems and coefficients of determination according to categories (for UCS).

| Classification | Rock strength <100 MPa | >100 MPa | Rock porosity <1% | 1–2.5% | >2.5% | Rock origin Metamorphic | Sedimentary | Igneous |
|----------------|-------------------------|----------|-------------------|--------|--------|-------------------------|-------------|---------|
| Parameters     |                         |          |                   |        |        |                         |             |         |
| Rock Number    | 49 rocks                | 44 rocks | 36 rocks          | 27 rocks | 30 rocks | 13 rocks                | 28 rocks    | 52 rocks |
| Nominal Value  | 0                       | 1        | 0                 | 1      | 2      | 0                       | 1           | 2       |
| SHH            | 0.72 (EX)               | 0.21 (LN)| 0.69 (PW)         | 0.72 (EX) | 0.78 (PW) | 0.84 (EX)               | 0.70 (PW)  | 0.83 (PW) |
| SSH            | 0.76 (PW)               | 0.31 (LN)| 0.56 (PW)         | 0.74 (PW) | 0.84 (PW) | 0.92 (LN)               | 0.72 (PW)  | 0.85 (PW) |
| HB             | 0.77 (PW)               | 0.76 (LN)| 0.84 (PW)         | 0.66 (PW) | 0.88 (PW) | 0.91 (LN)               | 0.84 (LN)  | 0.92 (PW) |
| HV             | 0.69 (PW)               | 0.83 (LN)| 0.86 (PW)         | 0.88 (LG) | 0.79 (LN) | 0.92 (LN)               | 0.87 (LN)  | 0.89 (PW) |
| IHI            | 0.85 (PW)               | 0.35 (PW)| 0.70 (PW)         | 0.81 (PW) | 0.91 (PW) | 0.81 (LN)               | 0.79 (EX)  | 0.90 (PW) |

LN: linear; PW: power; LG: logarithmic; EX: exponential.

Figure 15. Comparison of SHH-UCS simple equations a) origin classification (igneous) b) origin classification (metamorphic) c) rock strength classification (>100 MPa) and d) porosity classification (compact rocks).
the other half is distributed in a wide range between 140 MPa and 300 MPa (Figure 15c).

In the analysis performed according to porosity classification, the best and most reliable results were obtained from rocks with high porous rocks. In compact rocks, it can be said that metal hardness methods give more reliable results than rock hardness methods (Table 11). It is also clear that the equations obtained from low porosity rocks have acceptable determination coefficients. The main reason why the coefficients of determination of the equations obtained from rock hardness are relatively low is the rocks having the same porosity values but different origin and strength in the data set (Figure 15d).

4. Comparison with other studies

There are many studies in the literature exploring the relationship between UCS and different rock hardness methods. Some of the equations (Eqs. (37), (38), (39), (40), (41), (42), (43), (44), (45), (46), (47), (48), (49), and (50)) obtained because of these studies and having coefficients of determination varying between low and high were given in Table 12. In the final part of the study, the correlation results of the paper were compared with the results of other researchers obtained by a comprehensive literature search. Figure 16 shows that the relationship between UCS and SHH, SSH, IHI are compared with the results obtained by other researchers. In literature, the number of studies estimated for UCS from HB and HV hardness tests is negligible. For this reason, it was not possible to compare the work of other researchers with the correlations obtained in this study.

\[
\text{UCS} = 2.208e^{0.067HR}
\]  
(37)

\[
\text{UCS} = 4.24e^{0.059Ra}
\]  
(38)

\[
\text{UCS} = 0.0465N^2 - 0.1756N + 27.68
\]  
(39)

\[
\text{UCS} = 3.656R - 63
\]  
(40)

\[
\text{UCS} = 1.356e^{0.097BN}
\]  
(41)

\[
\text{UCS} = 2.8555e^{0.0632SN}
\]  
(42)

\[
\text{UCS} = 4.6521SH - 40.454
\]  
(43)

\[
\text{UCS} = 2.2052SSH - 31.208
\]  
(44)

\[
\text{UCS} = 2.6796SH - 35.054
\]  
(45)

\[
\text{UCS} = 0.1595e^{1.5269}
\]  
(46)

\[
\text{UCS} = 17.38IM
\]  
(47)

\[
\text{UCS} = 14.988CI e^{1.9663}
\]  
(48)

\[
Bln = 2.57UCS^{0.405}
\]  
(49)
5. Conclusions

This study was carried out to add more information to the relation between UCS (or E) the rock hardness tests, which are not encountered in literature very much. In this study, the different hardness tests and some engineering properties of rocks were tested. The results of the regression analysis are summarized as follows.

1. According to the results of SR analysis, there are significant relationships between UCS (or E) and SHH, SH, IH, IH. Similarly, HB and HV tests, also known as metal hardness, are closely related to UCS and E. The weakest correlation was obtained from the SSH hardness test. For predicting the UCS and E, the strongest correlations were obtained with the HV and HB tests respectively. The results show that rock hardness tests are as good and reliable as index properties such as Vp and Hv which are often used to estimate UCS.

2. Equations produced using MR analyses can be used more reliably to predict UCS and E if there are some test data about rock properties used in this paper besides the hardness tests.

3. SR equations are practical enough, especially when used for predictive purposes. However, MR equations with high predictive performance can be used for more precise estimation in the presence of multiple independent variables.

4. In most of the tests used to predict UCS and E, either aggregate fragments or very small-sized cylindrical/prismatic specimens were used. The high coefficient of determination equations obtained in this study can be used confidently for rocks when UCS and E mechanical tests are not applicable.

5. When SR and MR equations are examined, it can be said that the equations related to UCS have higher success than the elastic modulus.

6. One of the most striking findings is that the Vp test is included in almost all of the MR equations developed for the modulus of elasticity. As is known, the dynamic modulus of elasticity can be calculated from P and S wave velocity measurements.

7. One of the important results revealed by this study is as follows. Rock mechanics tests such as BTS, BPI, Hv which can be performed with small but certain geometric-shaped rocks. However, both small and amorphous rock fragments can be used in aggregate tests such as CRS, ISI, CI, and f. MR equations obtained by using aggregate tests and hardness tests can be used successfully in estimating basic engineering parameters such as UCS and E.

Declarations

Author contribution statement

Ahmet Teymen: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

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The authors declare no conflict of interest.

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Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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UCS = 0.97IH + 28.28 (50)
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