Empirical Estimation of Uniaxial Compressive Strength of Rock: Database of Simple, Multiple, and Artificial Intelligence-Based Regressions

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Abstract Empirical relationships for estimating Uniaxial Compressive Strength (UCS) of rock from other rock properties are numerous in literature. This is because the laboratory procedure for determination of UCS from compression tests is cumbersome, time consuming, and often considered expensive, especially for small to medium-sized mining engineering projects. However, these empirical models are scattered in literature, making it difficult to access a considerable number of them when there is need to select empirical model for estimation of UCS. This often leads to bias in estimated UCS data as there may be underestimation or overestimation of UCS, because of the site-specific nature of rock properties. Therefore, this study develops large database of empirical relationships between UCS and other rock properties that are reported in literatures. Statistical analysis was performed on the regression equations in the database developed. The typical ranges and mean of data used in developing the regressions, and the range and mean of their $R^2$ values were evaluated and summarised. Most of the regression equations were found to be developed from reasonable quantity of data with moderate to high $R^2$ values. The database can be easily assessed to select appropriate regression equation when there is need to estimate UCS for a specific site.

Keywords Regression analysis • Uniaxial compressive strength • Rock properties • Models • Database

1 Introduction

The uniaxial compressive strength (UCS) is a mechanical property of intact rocks that is important in civil and mining engineering works (Aladejare 2020; Aladejare et al. 2020; Wang and Aladejare 2016a). Design and stability analysis of underground excavations and other geotechnical structures require the input of data like UCS on the geomechanical behaviour of rocks (Ulusay et al. 1994). Adebayo and Aladejare (2013) explained that UCS of rock has effect on excavation-loading operation of rock fragments. According to Hoek (1977), UCS is a required property when considering a variety of problems encountered during blasting, excavation, and support
in engineering works. In addition, UCS is essential for classification of rock masses into different groups for engineering applications, and these classifications are used to determine their suitability for different construction purposes (Sachpazis 1990). For example, UCS is used as input in rock mass classification systems like rock mass rating (RMR) (Bieniawski 1974; Aladejare and Wang 2019a; Aladejare and Idris 2020) and rock mass index (RMI) (Palmstrøm 1996), and in predicting strength parameters of rock masses through Hoek–Brown failure criterion (Hoek et al. 2002). In the probabilistic characterization of Hoek–Brown $m_i$, Aladejare and Wang (2019b) used UCS data in a Bayesian framework to simulate samples of Hoek–Brown $m_i$, which are useful for probability-based estimation of rock mass properties through the Hoek–Brown failure criterion. The UCS also serve as input data when using empirical equations to predict deformation modulus of rock masses (Aladejare and Wang 2019b) and characteristic impedance of rocks (Zhang et al. 2020). All these make UCS an important parameter to most rock and mining engineering designs and analyses. According to a survey reported by Bieniawski (1976), mining engineers request the UCS more often than any other rock material property. From surface to underground mine design and construction, UCS is a key parameter and it is required that UCS be known with certainty to a great extent for engineering analysis.

The guidelines and method for laboratory determination of UCS have been suggested by International Society of Rock Mechanics (ISRM) (Ulusay and Hudson 2007). However, the laboratory determination of UCS is expensive and time consuming. Therefore, for most mining projects, especially small to medium-sized projects, data of UCS are not often available (Aladejare 2016). For this reason, numerous regression equations have been developed in literature for estimation of UCS, when they cannot be directly obtained through laboratory testing (Sachpazis 1990; Gökçeoglu 1996; Chatterjee and Mukhopadhyay 2002; Yilmaz and Sendir 2002; Dincer et al. 2004, 2008; Gokceoglu and Zorlu 2004; Hudyma et al. 2004; Sabatakakis et al. 2008; Tiryaki 2008; Diamantis et al. 2009; Khandelwal and Singh 2009; Moradian and Behnia 2009; Yasar et al. 2010; Mishra and Basu 2012; Khandelwal 2013; Minaeian and Ahangari 2013; Mohamad et al. 2015; Kallu and Roghanchi 2015; Fereidooni 2016; Sharma et al. 2017; Heidari et al. 2018; Aliyu et al. 2019). Results of some physical and mechanical tests have been recommended for indirect estimation of UCS. Numerous studies of empirical equations developed for indirect estimation of UCS in the literature generally include those using physical properties such as Schmidt hardness number, shore hardness, density, water content, porosity, P-wave velocity, S-wave velocity, unit weight, Equotip hardness number (also referred to as Leeb hardness number) and slake durability index, and mechanical properties such as block punch index, Young’s modulus, Brazilian tensile strength, and point load strength as inputs (Tugrul and Zarif 1999; Vasarhelyi 2005; Shalabi et al. 2007; Cobanoglu and Celik 2008; Török and Vasarhelyi 2010; Mishra and Basu 2013; Tandon and Gupta 2015; Mohamad et al. 2015; Najibi et al. 2015; Kahraman et al. 2016; Sharma et al. 2017; Uyanik et al. 2019). Simple and multiple regressions are available in literature for estimating UCS from these properties. In the recent past, artificial intelligence has been used to develop models for estimation of UCS, using techniques such as artificial neural network (ANN), support vector machine (SVM), Fuzzy inference system (FIS), genetic programming (GP) and hybrid ANN (Monjezi et al. 2012; Rezaei et al. 2014; Jalali et al. 2017; Aboutaleb et al. 2018; Armaghani et al. 2018; Mohamad et al. 2018; Ren et al. 2019).

With the numerous regression equations available in literature, there is a need to systematically select equations which suit specific sites. Wang and Aladejare (2015, 2016a) developed methods for selecting models and estimation of UCS. The Bayesian frameworks developed in studies such as Wang and Aladejare (2015, 2016a, b) need empirical equations as input. However, lack of accessibility to a great number of equations is a drawback. This is because when decision is to be made on the regression equation to be used for estimation of UCS, only equations that are readily assessed in literatures are considered. The regression equations developed are scattered in literatures, with no study yet that has systematically compiled them together for use during selection and estimation of UCS of rock. In order to solve this problem, this paper develops a database, which is a global compilation of empirical equations for estimating UCS from physical and mechanical properties of rocks. To provide a global compilation of different forms of regression equations, an extensive review of
previous studies is performed to collect and compile information of different regression equations for estimation of the UCS of rock. This study is particularly beneficial for engineering projects when considering any analysis that involves the use of UCS as an input. This is because it serves as the equations bank from which different regression equations can be assessed for selection and their subsequent use for estimation of UCS.

2 Database Development and Description

A total of 163 research articles from internationally leading journals such as International Journal of Rock Mechanics and Mining Sciences, Rock Mechanics and Rock Engineering, Bulletin of Engineering Geology and the Environment, Journal of Rock Mechanics and Geotechnical Engineering, Engineering Geology, Neural Computing and Applications, Geotechnical and Geological Engineering, Applied Soft Computing, Environmental Earth Sciences, International Journal of Mining Science and Technology, Tunnelling and Underground Space Technology, Measurement, and Engineering with Computers were used to compile information of regression equations for estimating UCS, ranging from simple to multiple regression and artificial intelligence-based models. The regression equations that are documented in the database only includes those whose data were obtained according to testing procedure standards set by ISRM or American Society for Testing and Materials (ASTM). This ensures that all equations in the database were developed from test results involving consistent sample length to diameter ratio and testing conditions (Aladejare and Wang 2017). Note that only equations developed for rocks are considered in the database, soil and other weathered rocks which behave as soil are not considered in the database. Geo-materials whose equations are included in the database are generally referred to as rock samples in the original literatures. They generally include grade I–III weathered rocks (i.e., ranging from fresh rocks to slightly weathered rock and moderately weathered rocks. Grade IV or above weathered geo-material is generally referred to as soil (e.g. Ehlen 2002; Aladejare and Wang 2017) and are not considered in the database.

In the database, there are different types of regression equations ranging from simple to multiple regressions and artificial intelligence-based regressions such as ANN, SVM, FIS, GP, and hybrid ANNs. In addition, there are different modes of equations such as linear, power, exponential, logarithmic and polynomial functions in the database. The equations contained in the database include those developed for estimating UCS from rock properties such as Schmidt hardness number (N), shore hardness (SH), density (ρ), porosity (n), P-wave velocity (Vp), S-wave velocity (Vs), unit weight (γ), equitop hardness number (LD), slake durability index (LD), block punch index (BPI), Young’s modulus (E), Brazilian tensile strength (BTS) and point load strength (IS,S0). Equations between UCS and other less frequently measured rock properties such as grain size (GS), shape factor (SF), quartz content (Qtz), particle diameter (D), single compressive strength index (SCSI) among others that are available in literature are also included in the database.

For each regression equation, number of data from which it was developed and the correlation coefficient (R²) are documented. The mean (μ) of a group of data is calculated as:

$$\mu = \frac{1}{n_i} \sum_{i=1}^{n_i} \theta_i, \quad \text{for} \quad i = 1, 2, 3, \ldots n_i$$ (1)

where θi is a set of rock property data and ni is the total number of rock data present in a group of data. The range and mean of number of data used in equation development and their R² for each regression equation are also included in the database.

3 Simple Regression

Simple regression is a statistical method for studying relationships between two continuous variables, in which one variable is regarded as the predictor or independent variable, and the other variable is regarded as the outcome or dependent variable (Freedman 2009). Assuming two groups of data (Y; Xa), i = 1, ..., n, where Xa = (Xa1, ..., Xan) is a vector of independent variable and Y; a real-valued dependent variable for the ith observation, a regression equation f is a model that makes a prediction \( \hat{Y} \) of Y for a potentially new input vector Xa, written as:

$$\hat{Y} = f(X_a)$$ (2)

Simple regression for estimating UCS can take any form such as linear, logarithmic, exponential, power,
and polynomial forms (Diamantis et al. 2009; Yasar et al. 2010; Nefeslioglu 2013; Azimian et al. 2014; Kallu and Roghanchi 2015), and the difference in the models is the way that \( f(X_a) \) in Eq. (2) is expressed for each regression equation. In this study, the simple regressions are grouped under two headings into those regressions derived from physical properties and those derived from mechanical properties as discussed in the following subsections.

3.1 Simple Relationship Between UCS and Physical Properties

Physical tests are generally easier and less expensive to perform, and for this reason many simple regressions are available in literature for estimating UCS from physical properties of rock (Cobanoglu and Celik 2008; Heidari et al. 2018; Aliyu et al. 2019; Aladejare 2020). Tables 1, 2, 3, 4, 5, 6, 7, 8, and 9 list regression equations for estimating UCS based on equotip number, Schmidt rebound number, shore hardness, density, porosity, P-wave velocity, S-wave velocity, unit weight, and slake durability index, respectively. For each regression equation listed in the tables, the number of data used to develop them, \( R^2 \) value and the rock type from which the equation was developed are presented. The tables show that regression equations using physical properties to estimate UCS for the three types of rock (i.e., igneous, sedimentary, and metamorphic rocks) are numerous and also for cases where different rock types are mixed together to develop regression equations. The different regression equations available in literature as can be observed from Tables 1, 2, 3, 4, 5, 6, 7, 8, and 9 indicate that not all equations will be suitable for specific site. Having database of regression equations will give mining engineers and other practitioners the opportunity to fairly assess all regression equations before deciding on the regression equations for a specific site. Recent studies in mining and geotechnical engineering have developed model selection approaches to select appropriate model from candidate models (e.g., Wang and Aladejare, 2015, 2016a). With many regression equations available in a paper, mining practitioners can subject many regression equations to assessment before deciding on the appropriate regression equation. Table 10 shows the information about the statistics of the regression equations in Tables 1, 2, 3, 4, 5, 6, 7, 8, and 9 that were used to develop the regression equations and the range and mean of their \( R^2 \) values. The mean of group data ranges from 24 to 210, while the lowest and highest \( R^2 \) values are 0.11 and 0.98, respectively. The quantity of data in a group and \( R^2 \) values shows that the equations collated in Tables 1, 2, 3, 4, 5, 6, 7, 8, and 9 may produce satisfactory estimation of UCS when they are used to estimate UCS for deposits of similar rock type.

| S/ N | Relationship | No of data | \( R^2 \) | Rock types | Country of origin | References |
|------|--------------|------------|----------|-------------|------------------|------------|
| 1    | \( UCS = 8 \times 10^{-6}L_s^{2.5} \) | 33         | 0.77     | Mixed       | Japan and Indonesia | Aoki and Matsukura (2008) Based on part of dataset by Verwaal and Mulder (1993) |
| 2    | \( UCS = 15.7L_d^{2.42} \times 10^{-6} \) | 31         | 0.70     | Mixed       | Various countries | Corkum et al. (2018) |
| 3    | \( UCS = 0.1L_d^{3.18} \times 10^{-6} \) | 31         | 0.71     | Sedimentary | Various countries | Corkum et al. (2018) |
| 4    | \( UCS = 0.3L_d^{2.98} \times 10^{-6} \) | 31         | 0.79     | Metamorphic | Various countries | Corkum et al. (2018) |
| 5    | \( UCS = 3L_d^{2.64} \times 10^{-6} \) | 31         | 0.65     | Igneous     | Various countries | Corkum et al. (2018) |
| 6    | \( UCS = 1.75 \times 10^{-9}L_d^{3.8} \) | 194        | 0.81     | Mixed       | Spain | Meulenkamp (1997) |
| 7    | \( UCS = 4.906 \times 10^{-7}L_d^{2.974} \) | 28         | NA       | Mixed       | Netherlands | Verwaal and Mulder (2000) |
| 8    | \( UCS = 2.3007L_d^{0.0057L_d} \) | 62         | 0.82     | Mixed       | USA | Lee et al (2014) exclusive of shale rocks |
| 9    | \( UCS = 2.1454L_d^{0.0058L_d} \) | 86         | 0.81     | Mixed       | USA | Lee et al (2014) inclusive of shale rocks |
| 10   | \( UCS = 4.5847L_d - 142.22 \) | 18         | 0.82     | Sedimentary | Turkey | Yilmaz (2013) |
Table 2  Empirical equations for estimating UCS based on Schmidt Hammer rebound number

| S/ N | Relationship | No of data | $R^2$ | Rock types | Country of origin | References |
|------|--------------|------------|-------|------------|-------------------|------------|
| 1    | $UCS = 6.59N - 212.63$ | 150        | 0.65  | Sedimentary | Turkey            | Cobanoglu and Celik (2008) |
| 2    | $UCS = 2N$    | 30         | 0.72  | Sedimentary | USA               | Singh et al. (1983) |
| 3    | $UCS = 0.4N - 3.6$ | 20         | 0.94  | Sedimentary | USA               | Shorey et al. (1984) |
| 4    | $UCS = 0.994N - 0.383$ | 10         | 0.7   | Sedimentary | USA               | Haramy and DeMarco (1985) |
| 5    | $UCS = 0.88N - 12.11$ | 13         | 0.87  | Sedimentary | India             | Ghose and Chakraborti (1986) |
| 6    | $UCS = 4.85N - 76.18$ | NA         | 0.77  | Sedimentary | USA               | O'Rourke (1989) |
| 7    | $UCS = 2.98e^{0.06N}$ | NA         | 0.95  | Metamorphic | NA                | Xu et al. (1990) |
| 8    | $UCS = 1.31N - 2.52$ | 30         | 0.55  | Igneous     | Greece            | Aggustali et al. (1996) |
| 9    | $UCS = 0.9001N^{3.2658}$ | NA         | 0.84  | Sedimentary | Japan             | Gökçeoğlu (1996) |
| 10   | $UCS = exp(0.818 + 0.059N)$ | 20         | 0.98  | Sedimentary | Turkey            | Yilmaz and Sendir (2002) |
| 11   | $UCS = 2.75N - 36.83$ | 24         | 0.95  | Igneous     | Turkey            | Dincer et al. (2004) |
| 12   | $UCS = 104.3ln(N) - 308.6$ | 24         | 0.96  | Igneous     | Turkey            | Dincer et al. (2004) |
| 13   | $UCS = 13.02e^{0.0141N}$ | 24         | 0.96  | Igneous     | Turkey            | Dincer et al. (2004) |
| 14   | $UCS = 0.267N - 2.210$ | 19         | 0.64  | Sedimentary | Turkey            | Dincer et al. (2008) |
| 15   | $UCS = 7.044lnN - 17.96$ | 19         | 0.60  | Sedimentary | Turkey            | Dincer et al. (2008) |
| 16   | $UCS = 4.6 \times 10^{-2}A^{1.406}$ | 19         | 0.66  | Sedimentary | Turkey            | Dincer et al. (2008) |
| 17   | $UCS = 1.143e^{0.051N}$ | 19         | 0.65  | Sedimentary | Turkey            | Dincer et al. (2008) |
| 18   | $UCS = 1246N - 34890$ | 257        | 0.88  | Mixed       | USA               | Deere and Miller (1966) (UCS in psi) |
| 19   | $UCS = 4.29N - 67.52$ | 29         | 0.96  | Sedimentary | Greece and England | Sachpazis (1990) |
| 20   | $UCS = 4.5 \times 10^{-0.2A^{4.46}}$ | 10         | 0.93  | Mixed       | Turkey            | Kahraman (1996) |
| 21   | $UCS = 8.36N - 416$ | 19         | 0.87  | Igneous     | Turkey            | Turgul and Zarrif (1999) |
| 22   | $UCS = 6.97e^{0.041N}$ | 48         | 0.78  | Mixed       | Turkey            | Kahraman (2001) |
| 23   | $UCS = exp(10^{-0.2917})$ | 9          | 0.89  | Mixed       | Turkey            | Yasar and Erdogan (2004a, b) |
| 24   | $UCS = 1.4459e^{0.0706N}$ | 40         | 0.92  | Igneous     | Hong Kong         | Aydin and Basu (2005) |
| 25   | $UCS = 3.20N - 46.59$ | 58         | 0.76  | Sedimentary | USA               | Shalabi et al. (2007) |
| 26   | $UCS = 0.0028N^{2.584}$ | 9          | 0.92  | Mixed       | Turkey            | Yagiz (2009) |
| 27   | $UCS = 2.262N - 29.38$ | 21         | 0.91  | Metamorphic | India             | Tandon and Gupta (2015) |
| 28   | $UCS = 2.729N - 41.78$ | 9          | 0.96  | Igneous (Granitoid) | India | Tandon and Gupta (2015) |
| 29   | $UCS = 2.547N - 33.08$ | 12         | 0.71  | Igneous (Gneiss) | India | Tandon and Gupta (2015) |
| 30   | $UCS = 2.722N - 30.19$ | 12         | 0.93  | Metamorphic | India             | Tandon and Gupta (2015) |
| 31   | $UCS = 1.233N - 2.846$ | 6          | 0.89  | Sedimentary | India             | Tandon and Gupta (2015) |
| 32   | $UCS = 1.910N - 10.30$ | 60         | 0.75  | Mixed       | India             | Tandon and Gupta (2015) |
| 33   | $UCS = 0.994N - 0.383$ | 10         | 0.70  | Mixed       | USA               | Haramy and DeMarco (1985) |
| 34   | $lnUCS = 1.88 \times 10^{-2} (N \times \rho_d) + 2.9$ | 14         | 0.98  | Sedimentary | USA               | Cargill and Shakoor (1990) |
| 35   | $UCS = exp(1.332 + 0.053N)$ | 99         | 0.94  | Sedimentary | Spain             | Morales et al. (2004) |
| 36   | $UCS = 3.1e^{0.09N}$ | 75         | 0.79  | Sedimentary | Greece            | Sabatakakis et al. (2008) |
| 37   | $UCS = 3.201N - 46.59$ | 58         | 0.76  | Sedimentary | USA               | Shalabi et al. (2007) |
| 38   | $UCS = 3.6468N - 98.777$ | 1700       | 0.81  | Metamorphic | Turkey            | Yavuz et al. (2005) |
| 39   | $UCS = exp(0.818 + 0.059N)$ | 20         | 0.98  | Metamorphic | Turkey            | Yilmaz and Sendir (2002) |
| 40   | $UCS = 5.3466N - 99.878$ | 53         | 0.76  | Sedimentary | Iran              | Heidari et al. (2017) |
3.2 Simple Relationship Between UCS and Mechanical Properties

Mechanical tests are generally more difficult and expensive to perform than physical tests, because most mechanical tests require rigorous sample preparation. Despite the difficulties in performing the mechanical tests, some of these tests are easier to be performed than UCS. For this reason, researchers have developed simple regressions for estimating UCS from mechanical properties of rock (Kahraman and Gunaydin 2009; Mishra and Basu 2012; Moradian and Behnia 2009; Fereidooni 2016). Tables 11, 12, 13 and 14 list regression equations for estimating UCS based on

Table 2 continued

| S/N | Relationship | No of data | $R^2$ | Rock types | Country of origin | References |
|-----|--------------|------------|------|------------|-------------------|------------|
| 41  | $UCS = 0.25N^{1.77}$ | 200 | 0.88 | Igneous | USA | Kallu and Roghanchi (2015) |
| 42  | $lnUCS = 0.792 + 0.067N ± 0.231$ | 7 | 0.96 | Mixed | Israel and USA | Katz et al. (2000) |
| 43  | $UCS = 0.0137N^{2.2721}$ | 19 | 0.94 | Mixed | Turkey | Kılıç and Teymen (2008) |
| 44  | $UCS = 0.64N + 37.5$ | 3 | 0.96 | Metamorphic | India | Gupta (2009) |
| 45  | $UCS = \exp(-4.04 + 2.28\ln N)$ | 95 | 0.97 | Sedimentary | Various countries | Bruno et al. (2012) |
| 46  | $UCS = 4.24e^{0.050N}$ | 11 | 0.81 | Mixed | Turkey | Fener et al. (2005) |
| 47  | $UCS = 0.02N^{2.28}$ | 8 | 0.92 | Metamorphic | Iran | Fereidooni (2016) |
| 48  | $UCS = 0.0465N^2 - 0.1756N + 27.682$ | 41 | 0.86 | Metamorphic | Iran | Torabi et al. (2010) |
| 49  | $UCS = 1.15N - 15$ | 7 | 0.91 | Igneous | India | Gupta (2009) |
| 50  | $UCS = 0.9165\times0.0609N^2/0.01756N + 27.682$ | 40 | 0.94 | Igneous | Hong Kong | Aydin and Basu (2005)b |
| 51  | $lnUCS = 4.3X10^{-2}(N \times \rho_d) + 1.2$ | 14 | 0.93 | Sedimentary | USA | Cargill and Shakoor (1990)c |

**psi** pounds per square inch

*Type Schmidt Hammer

**Table 3** Empirical equations for estimating UCS based on Shore hardness

| S/N | Relationship | No of data | $R^2$ | Rock types | Country of origin | References |
|-----|--------------|------------|------|------------|-------------------|------------|
| 1   | $UCS = 0.397SH + 0.332$ | 19 | 0.71 | Sedimentary | Turkey | Dincer et al. (2008) |
| 2   | $UCS = 4.830\ln(SH) - 6.546$ | 19 | 0.67 | Sedimentary | Turkey | Dincer et al. (2008) |
| 3   | $UCS = 0.461SH^{0.957}$ | 19 | 0.72 | Sedimentary | Turkey | Dincer et al. (2008) |
| 4   | $UCS = 1.918\times0.0745SH$ | 19 | 0.68 | Sedimentary | Turkey | Dincer et al. (2008) |
| 5   | $UCS = 514SH - 6213$ | 275 | 0.90 | Mixed | USA | Deere and Miller (1966) |
| 6   | $UCS = 3.54(SH - 12)$ | NA | 0.57 | – | USA | Atkinson (1993) |
| 7   | $UCS = 0.895SH + 41.977$ | 30 | 0.57 | Sedimentary | USA | Koncagul and Santi (1999) |
| 8   | $UCS = 1 \times 10^{-3}(SH)^{5.555}$ | 9 | 0.91 | Mixed | Turkey | Yasar and Erdogan (2004a, b) |
| 9   | $UCS = 3.326SH - 79.76$ | 8 | 0.80 | Sedimentary (high density dolomite) | USA | Shalabi et al. (2007) |
| 10  | $UCS = 1.581SH - 62.2$ | 9 | 0.85 | Sedimentary (Shale rock) | USA | Shalabi et al. (2007) |
| 11  | $UCS = 14.868e^{0.042SH}$ | 1700 | 0.84 | Metamorphic | Turkey | Yavuz et al. (2005) |
### Table 4  Empirical equations for estimating UCS based on Density

| S/No | Relationship | No of data | R² | Rock types | Country of origin | References |
|------|--------------|------------|----|------------|-------------------|------------|
| 1    | UCS = 55.57ρ − 100.75 | 22         | 0.89 | Sedimentary | India (Krishna-Godavari basin) | Chatterjee and Mukhopadhyay (2002) |
| 2    | UCS = 37.47ρ − 63.11 | 22         | 0.98 | Sedimentary | India (Cauvery basin) | Chatterjee and Mukhopadhyay (2002) |
| 3    | UCS = 178.33 × ρ − 384.65 | 44         | 0.11 | Mixed       | England and Turkey | Tiryaki (2008) |
| 4    | UCS = (28812.5ρ − 52.586) × 0.0069 | 257       | 0.90 | Mixed       | USA | Deere and Miller (1966) |
| 5    | UCS = 10⁻⁵ρ₁⁸⁷ | 12         | 0.97 | Igneous (basalts) | Turkey | Tugrul and Gurpinar (1997) |
| 6    | UCS = 139.34ρ − 272.25 | 94         | 0.87 | Sedimentary | India | Sharma et al. (2017) |
| 7    | UCS = −47454.4 + 35905.6ρ − 671.68ρ² | 7          | 0.90 | Sedimentary | UK, France and Denmark | Aliyu et al. (2019) |

### Table 5  Empirical equations for estimating UCS based on Porosity

| S/No | Relationship | No of data | R² | Rock types | Country of origin | References |
|------|--------------|------------|----|------------|-------------------|------------|
| 1    | UCS = 34.44ε⁻⁰.⁰⁴⁴n | 22         | 0.83 | Sedimentary | India (Krishna-Godavari basin) | Chatterjee and Mukhopadhyay (2002) |
| 2    | UCS = 64.23ε⁻⁰.⁰⁸⁵n | 22         | 0.92 | Sedimentary | India (Cauvery basin) | Chatterjee and Mukhopadhyay (2002) |
| 3    | UCS = −33.13ln(n) + 64.6 | 32         | 0.82 | Metamorphic | Greece | Diamantis et al. (2009) |
| 4    | UCS = 97.77exp⁻⁰.⁴⁰n | 32         | 0.76 | Metamorphic | Greece | Diamantis et al. (2009) |
| 5    | UCS = −21.58n + 91.87 | 32         | 0.80 | Metamorphic | Greece | Diamantis et al. (2009) |
| 6    | UCS = −49.36ln(n) + 189.35 | 8          | 0.62 | Igneous tuff | USA | Hudyma et al. (2004) |
| 7    | UCS = 78.22n + 201 | 19         | 0.81 | Igneous | Turkey | Tugrul and Zarif (1999) |
| 8    | UCS = 274 − 8.51n | 20         | 0.98 | Igneous | Saudi Arabia | Al-Harthi et al. (1999) |
| 9    | UCS = 104 − 1.01n | 33         | 0.96 | Igneous | Saudi Arabia | Al-Harthi et al. (1999) |
| 10   | UCS = −0.439n + 16.717 | 19         | 0.78 | Sedimentary | Turkey | Dincer et al. (2008) |
| 11   | UCS = −10.960ln(n) − 40.826 | 19       | 0.80 | Sedimentary | Turkey | Dincer et al. (2008) |
| 12   | UCS = 3439.38n⁻²⁻² | 19         | 0.76 | Sedimentary | Turkey | Dincer et al. (2008) |
| 13   | UCS = 42.111ε⁻⁰.⁰⁸³n | 19         | 0.77 | Sedimentary | Turkey | Dincer et al. (2008) |
| 14   | UCS = 149.33n⁻⁰.⁵³ | 8          | 0.89 | Metamorphic | Iran | Fereidooni (2016) |
| 15   | UCS = −2.270n² + 33.88n + 16.30 | 11       | 0.96 | Sedimentary (sandstone) | Australia | Yasar et al. (2010) |
| 16   | UCS = −2.135n² + 28.74n + 18.82 | 11       | 0.90 | Sedimentary (siltstone) | Australia | Yasar et al. (2010) |
| 17   | UCS = −0.663n³ + 9.648n + 21.01 | 11       | 0.92 | Sedimentary (mudstone) | Australia | Yasar et al. (2010) |
| 18   | UCS = 123exp⁻¹⁻¹n | 95         | 0.63 | Sedimentary | Greece | Sabatakakis et al. (2008) |
| 19   | UCS = 16.55n + 183 | 19         | 0.83 | Igneous | Turkey | Tugrul and Zarif (1999) |
| S/N | Relationship | No of data | $R^2$ | Rock types | Country of origin | References |
|-----|--------------|------------|-------|------------|------------------|------------|
| 1   | $UCS = 56.71V_p - 192.93$ | 150        | 0.67  | Sedimentary | Turkey           | Cobanoglu and Celik (2008) |
| 2   | $UCS = 6 \times 10^{-3}V_p - 0.556$ | 19         | 0.91  | Sedimentary | Turkey           | Dincer et al. (2008) |
| 3   | $UCS = 5.136\ln(V_p) - 28.337$ | 19         | 0.91  | Sedimentary | Turkey           | Dincer et al. (2008) |
| 4   | $UCS = 9 \times 10^{-3}V_p^{0.963}$ | 19         | 0.89  | Sedimentary | Turkey           | Dincer et al. (2008) |
| 5   | $UCS = 2.054\exp^{0.001V_p}$ | 19         | 0.82  | Sedimentary | Turkey           | Dincer et al. (2008) |
| 6   | $UCS = 0.0642V_p - 117.99$ | 49         | 0.90  | Mixed      | India            | Sharma and Singh (2008) |
| 7   | $UCS = 9.95V_p^{0.21}$ | 27         | 0.83  | Mixed      | Turkey           | Kahraman (2001) |
| 8   | $UCS = 165.05\exp^{-[4.452/V_p]}$ | 64         | 0.70  | Sedimentary | Iran             | Moradian and Behnia (2009) |
| 9   | $UCS = 0.033V_p - 34.83$ | 13         | 0.87  | Mixed      | India            | Khandelwal (2013) |
| 10  | $UCS = 133.3V_p - 227.19$ | 12         | 0.96  | Mixed      | India            | Khandelwal and Singh (2009) |
| 11  | $UCS = 0.005V_p$ | 140        | 0.94  | Sedimentary | Iran             | Minaeian and Ahangari (2013) |
| 12  | $UCS = 110V_p - 515.56$ | 32         | 0.81  | Metamorphic | Greece           | Diamantis et al. (2009) |
| 13  | $UCS = 0.78\exp^{[0.888V_p]}$ | 171        | 0.53  | Metamorphic | Greece           | Entwistle et al. (2005) |
| 14  | $UCS = 0.032V_p - 44.227$ | 40         | 0.83  | Mixed      | Malaysia         | Mohamad et al. (2015) |
| 15  | $UCS = 64.2V_p - 117.99$ | 49         | 0.90  | Mixed      | India            | Sharma and Singh (2008) |
| 16  | $UCS = 35.54V_p - 55$ | 19         | 0.80  | Igneous    | Turkey           | Tugrul and Zariff (1999) |
| 17  | $UCS = 31.5V_p - 63.7$ | 9          | 0.80  | Mixed      | Turkey           | Yasar and Erdogan (2004a, b) |
| 18  | $UCS = 0.14V_p - 899.23$ | 32         | 0.90  | Metamorphic | Greece           | Diamantis et al. (2011) |
| 19  | $UCS = 0.0675V_p - 245.13$ | 20         | 0.92  | Igneous    | Turkey           | Kurtulus et al. (2012) (across foliation) |
| 20  | $UCS = 0.0188V_p - 71.04$ | 20         | 0.83  | Igneous    | Turkey           | Kurtulus et al. (2012) (along foliation) |
| 21  | $UCS = 0.005V_p$ | 140        | 0.94  | Sedimentary | Iran             | Minaeian and Ahangari (2013) |
| 22  | $UCS = 6.6V_p^{1.6}$ | 46         | 0.92  | Sedimentary | Turkey           | Uyanik et al. (2019) |
| 23  | $UCS = 0.11V_p - 515.56$ | 32         | 0.81  | Metamorphic | Greece           | Diamantis et al. (2009) |
| 24  | $UCS = 2.6 \times 10^{-3}\exp^{0.001V_p}$ | 32         | 0.80  | Metamorphic | Greece           | Diamantis et al. (2009) |
| 25  | $UCS = 570.94\ln(V_p) - 4840.1$ | 32         | 0.79  | Metamorphic | Greece           | Diamantis et al. (2009) |
| 26  | $UCS = 0.457983\exp^{[0.504268(V_p)]}$ | 66         | 0.82  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 27  | $UCS = 2.258013(V_p) + 0.060749$ | 66         | 0.92  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 28  | $UCS = 0.499138e^{[1.575579(V_p)]}$ | 66         | 0.91  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 29  | $UCS = 3.313262(V_p) - 0.814776$ | 66         | 0.92  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 30  | $UCS = 1.779459(V_p)^{1.409563}$ | 66         | 0.96  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 31  | $UCS = 1.902589(V_p)^{1.031474}$ | 66         | 0.87  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 32  | $UCS = 4.751294(V_p) - 2.354974$ | 66         | 0.92  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 33  | $UCS = 4.585574(V_p) - 2.230556$ | 66         | 0.87  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 34  | $UCS = 1.642474(V_p)^{1.277730}$ | 66         | 0.87  | Sedimentary | Turkey           | Nefeslioglu (2013) |
| 35  | $UCS = 35.54V_p - 55$ | 19         | 0.64  | Igneous    | Turkey           | Tugrul and Zariff (1999) |
| 36  | $UCS = 0.026V_p - 20.207$ | 40         | 0.91  | Sedimentary | India            | Azimian et al. (2014) |
| 37  | $UCS = 0.0375V_p - 50.969$ | 53         | 0.67  | Sedimentary | India            | Heidari et al. (2018) |
| 38  | $UCS = 22.032V_p^{1.247}$ | 9          | 0.72  | Igneous    | Portugal         | Sousa et al. (2005) |
| 39  | $UCS = 0.039V_p - 50.01$ | 94         | 0.93  | Mixed      | India            | Sarkar et al. (2012) |
Table 6 continued

| S/ N | Relationship | No of data | R^2  | Rock types | Country of origin | References                      |
|------|--------------|------------|------|------------|-------------------|---------------------------------|
| 40   | UCS = 12.743V_p^{1.194} | 72         | 0.76 | Sedimentary | Several countries | Altindag (2012)                  |
| 41   | UCS = 0.026V_p + 20.47 | 40         | 0.91 | Sedimentary | Iran             | Abdolazim and Rassoul (2015)     |
| 42   | InUCS = 3.94lnV_p − 28.12 | 10        | 0.92 | Igneous | USA               | Kallu and Roghanchi (2015)       |
| 43   | UCS = 165.05exp(−4.452/V_p) | 64      | 0.70 | Mixed      | Iran             | Moradian and Behnia (2009)       |
| 44   | UCS = 0.0389V_p − 50.009 | 94        | 0.93 | Sedimentary | India            | Sharma et al. (2017)             |
| 45   | UCS = 0.91V_p − 4500.6  | 7          | 0.87 | Sedimentary | UK, France and Denmark | Aliyu et al. (2019)          |

**Note:** Genetic rock type codes representing varying spectral absorptions using reflectance spectroscopy

Table 7 Empirical equations for estimating UCS based on S-wave Velocity

| S/N | Relationship | No of data | R^2  | Rock types | Country of origin | References                      |
|-----|--------------|------------|------|------------|-------------------|---------------------------------|
| 1   | UCS = 16V_s^{1.6} | 46        | 0.82 | Sedimentary | Turkey            | Uyanik et al. (2019)               |
| 2   | UCS = 0.14V_s − 336.05 | 32 | 0.80 | Metamorphic | Greece            | Diamantis et al. (2009)           |
| 3   | UCS = 0.057\gamma^{0.0025}V_s | 32 | 0.79 | Metamorphic | Greece            | Diamantis et al. (2009)           |
| 4   | UCS = 391.38ln(V_s) − 3043.2 | 32 | 0.79 | Metamorphic | Greece            | Diamantis et al. (2009)           |

Table 8 Empirical equations for estimating UCS based on unit weight/dry unit weight

| S/N | Relationship | No of data | R^2  | Rock types | Country of origin | References                      |
|-----|--------------|------------|------|------------|-------------------|---------------------------------|
| 1   | UCS = 56.71\gamma + 16.471 | 19         | 0.79 | Sedimentary | Turkey            | Dincer et al. (2008)               |
| 2   | UCS = 21.035ln\gamma − 56.81 | 19        | 0.76 | Sedimentary | Turkey            | Dincer et al. (2008)               |
| 3   | UCS = 2.60 \times 10^{−5}\gamma^{4.108} | 19       | 0.80 | Sedimentary | Turkey            | Dincer et al. (2008)               |
| 4   | UCS = 0.0737\gamma^{0.217} | 19        | 0.81 | Sedimentary | Turkey            | Dincer et al. (2008)               |
| 5   | UCS = 0.057\gamma^{2.9168} | 154       | 0.74 | Sedimentary | Turkey            | Cobanoglu and Celik (2012)        |
| 6   | UCS = 0.0063\gamma^{3.813} | 40        | 0.90 | Sedimentary | Hungary           | Török and Vasarhelyi (2010)       |
| 7   | UCS = 0.4182\gamma^{0.037} | 15        | 0.97 | Sedimentary | France            | Moh’d (2009)                     |
| 8   | UCS = 42.63\gamma_d − 1057.8 | 32        | 0.80 | Metamorphic | Greece            | Diamantis et al. (2009)           |
| 9   | UCS = 2 \times 10^{−7}\exp^{0.75\gamma_d} | 32        | 0.79 | Metamorphic | Greece            | Diamantis et al. (2009)           |
| 10  | UCS = 1115.6ln(\gamma_d) − 3558.2 | 32 | 0.79 | Metamorphic | Greece            | Diamantis et al. (2009)           |
| 11  | UCS = 461\gamma − 52586 | 257       | 0.60 | Mixed       | USA               | Deere and Miller (1966) (UCS in psi, \gamma in pcf) |
| 12  | UCS = 7.3\gamma − 110.32 | 43        | 0.62 | Sedimentary | USA               | Shalabi et al. (2007)             |
| 13  | UCS = 60.75\gamma − 1430 | 19        | 0.81 | Igneous  | Turkey            | Tugrul and Zarif (1999)           |
| 14  | UCS = 57.72\gamma_d − 1347 | 19       | 0.82 | Igneous  | Turkey            | Tugrul and Zarif (1999)           |

Dry density indicated by subscript d
psi pounds per square inch
pcf pounds per cubic feet
block punch index, Young’s modulus, tensile strength and point load strength, respectively. The tables show that regression equations using mechanical properties for estimating UCS for the three types of rock are also numerous like those using physical properties.

Table 15 shows the information about the statistics of the regression equations in Tables 11, 12, 13 and 14, which includes the range and mean of group of data that were used to develop the regression equations and the range and mean of their $R^2$ values. The mean of group data ranges from 46 to 150, while the lowest and highest $R^2$ values are $0.33$ and $0.99$, respectively. The $R^2$ value for regression equations using physical properties are higher than those using mechanical properties. This may indicate that the regression equations using physical properties produce low errors when they are used to estimate UCS.

## 4 Multiple Regression

Multiple regression is an extension of simple regression. It is used to predict the value of a variable based on the value of two or more other variables. The concept of multiple regression reflects the likelihood that a variable may have relationship with more than one variable. In such case, all the independent variables can be systematically combined to estimate a dependent variable (Aiken et al. 1991). Assuming groups of data $(Y_i; X_{ai}...X_{ci})$; where $X_{ai}...X_{ci}$ are vector of independent variables from $X_a...X_c$, $i = 1, ..., n$
representing the number of data for each independent variable, and \( Y_i \) a real-valued dependent variable for the \( i \)th observation, a regression equation \( f \) is a model that makes a prediction \( \hat{Y} \) of \( Y \) for a potentially new input vectors \( X_1 \ldots X_z \), written as:

\[
\hat{Y} = f(X_1 \ldots X_z) \tag{3}
\]

Like simple regression, multiple regression for estimating UCS can take any form such as linear, logarithmic, exponential, power, and polynomial forms (Majdi and Rezaei 2013; Cheshomi et al. 2015; Madhubabu et al. 2016; Armaghani et al. 2018), and the difference in the models will reflect how \( f(X_1 \ldots X_q) \neq f(X_a \ldots X_z) \) in Eq. (3) is expressed for each regression equation.

Table 11 lists multiple regression equations for estimating UCS based on different properties of rock, including physical and mechanical properties. The number of data per group for the equations ranges between 5 and 600 with a mean of 78 data per group. The R² values for the equations range from 0.53 to 0.99. The table shows that multiple regressions for estimating UCS for the three types of rock are numerous, and for cases where different rock types are mixed to develop multiple regressions.

5 Artificial Intelligence

Artificial intelligence refers to the simulation of human intelligence in machines that are programmed
to think like humans and mimic their actions (Carbonell 2003; Cawsey and Aylett 2009; Lawal and Kwon 2020). This reasoning capability is valuable in applications where repetition, complexity, or tediousness makes human-like intervention impractical. Dershowitz and Einstein (1984) explained that artificial intelligence is applicable in rock mechanics, even where some complex decision-making is required. There are many approaches of artificial intelligence that are being used in rock mechanics and mining engineering, such as ANN, SVM, FIS, GP, and hybrid artificial intelligence such as Genetic Algorithm Artificial Neural Network (GA-ANN), Particle Swarm Optimisation Artificial Neural Network (PSO-ANN), Particle Swarm Optimisation Artificial Neural Network (PSO-ANN), Imperialist Competitive Algorithm Artificial Neural Network (ICA-ANN) and Adaptive neuro-fuzzy inference system (ANFIS) (Majdi and Beiki 2010; Manouchehrian et al. 2012; Beiki et al. 2013; Rezaei et al. 2014; Mohamad et al. 2015; Sharma et al. 2017; Aboutaleb et al. 2018; Lawal and Kwon 2020).

5.1 Artificial Neural Network

ANN is an approach of artificial intelligence, introduced by McCulloch and Pitts (1943). ANN is trained using a set of real inputs and their corresponding outputs. A neural network must be trained so that a known set of inputs produces the desired outputs. Once the network is trained with enough sample dataset, for a new input of relatively similar patterns, predictions can be made based on previous learning. Many researchers have used ANN to predict UCS from other rock properties (Yagiz et al. 2012; Jalali et al. 2017; Aboutaleb et al. 2018; Ren et al. 2019).

Table 13: Empirical equations for estimating UCS based on Brazilian tensile strength

| S/N | Relationship | No of data | R² | Rock types | Country of origin | References |
|-----|--------------|------------|----|------------|------------------|------------|
| 1   | $UCS = 10.33TS^{0.89}$ | 22         | 0.94 | Sedimentary | India            | Chatterjee and Mukhopadhyay (2002) |
| 2   | $UCS = 6.89TS + 5.39$ | 22         | 0.93 | Sedimentary | India            | Chatterjee and Mukhopadhyay (2002) |
| 3   | $UCS = 10.61BTS$ | 46         | 0.54 | Mixed       | Turkey           | Kahraman et al. (2012) |
| 4   | $UCS = 7.86BTS - 447.63$ | 37         | 0.92 | Sedimentary | USA              | Farah (2011) |
| 5   | $UCS = 6.8TS + 13.5$ | 82         | 0.65 | Sedimentary (Greywacke) | Turkey | Gokceoglu and Zorlu (2004) |
| 6   | $UCS = 12.308TS^{0.0725}$ | 143        | 0.90 | Mixed       | Several countries | Altimdag and Guney (2010) |
| 7   | $UCS = 9.25TS^{0.947}$ | 20         | 0.90 | Sedimentary | Malaysia         | Nazir et al. (2013) |
| 8   | $UCS = 15.36TS - 10.303$ | 40         | 0.82 | Mixed       | Malaysia         | Mohamad et al. (2015) |
| 9   | $UCS = 12.195BTS$ | 406        | NA  | Sedimentary | Nigeria          | Clifford (1991) |
| 10  | $UCS = 7.53BTS$ | 60         | 0.45 | Sedimentary | Pakistan         | Tahir et al. (2011) |
| 11  | $UCS = 6.75BTS^{1.08}$ | 22         | 0.80 | Igneous     | USA              | Kallu and Roghanchi (2015) |
| 12  | $UCS = 10.03BTS + 55.19$ | 8          | 0.92 | Metamorphic | Iran             | Fereidooni (2016) |
| 13  | $UCS = 10.4TS + 18.2$ | 7          | 0.63 | Sedimentary | UK, France and Denmark | Aliyu et al. (2019) |
| 14  | $UCS = 12.4TS - 9$ | 10         | 0.76 | Sedimentary | USA              | Gunsallus and Kulhawy (1984) |

TS tensile strength, BTS Brazilian tensile strength
Table 14 Empirical equations for estimating UCS based on Point load strength

| S/N | Relationship                     | No of data | R² | Rock types       | Country of origin | References                      |
|-----|----------------------------------|------------|----|------------------|-------------------|---------------------------------|
| 1   | \( UCS = 8.66 I_{s(50)} + 10.85 \) | 75         | 0.76 | Sedimentary\(a\) | Turkey            | Cobanoglu and Celik (2008)      |
| 2   | \( UCS = 7.18 I_{s(50)} + 27.78 \) | 15         | 0.80 | Sedimentary\(b\) | Turkey            | Cobanoglu and Celik (2008)      |
| 3   | \( UCS = 11.78 I_{s(50)} - 9.17 \) | 15         | 0.91 | Sedimentary\(c\) | Turkey            | Cobanoglu and Celik (2008)      |
| 4   | \( UCS = 10.73 I_{s(50)} - 5.50 \) | 15         | 0.88 | Sedimentary\(d\) | Turkey            | Cobanoglu and Celik (2008)      |
| 5   | \( UCS = 8.87 I_{s(50)} + 4.11 \)  | 15         | 0.86 | Sedimentary\(e\) | Turkey            | Cobanoglu and Celik (2008)      |
| 6   | \( UCS = 8.25 I_{s(50)} + 14.02 \) | 15         | 0.67 | Sedimentary\(f\) | Turkey            | Cobanoglu and Celik (2008)      |
| 7   | \( UCS = 5.096 I_{s(50)} - 0.533 \)| 19         | 0.83 | Sedimentary      | Turkey            | Dincer et al. (2008)            |
| 8   | \( UCS = 6.088 \ln(I_{s(50)}) + 4.833 \) | 19   | 0.81 | Sedimentary      | Turkey            | Dincer et al. (2008)            |
| 9   | \( UCS = 4.413 I_{s(50)}^{1.62} \) | 19         | 0.82 | Sedimentary      | Turkey            | Dincer et al. (2008)            |
| 10  | \( UCS = 1.662 I_{s(50)}^{0.932} \) | 19         | 0.77 | Sedimentary      | Turkey            | Dincer et al. (2008)            |
| 11  | \( UCS = 8.41 I_{s(50)} + 9.51 \)  | 27         | 0.85 | Mixed            | Turkey            | Kahraman (2001)                 |
| 12  | \( UCS = 15.31 I_{s(50)} \)        | 23         | 0.83 | Mixed            | Turkey            | Sulu and Ulusay (2001)          |
| 13  | \( UCS = 7.3 I_{s(50)}^{1.71} \)   | 188        | 0.82 | Sedimentary      | Greece            | Tsiambaos and Sabatakakis (2004) |
| 14  | \( UCS = 10.22 I_{s(50)} + 24.31 \) | 23         | 0.75 | Mixed\(g\)      | Turkey            | Kahraman et al. (2005)          |
| 15  | \( UCS = 24.83 I_{s(50)} - 39.64 \) | 15         | 0.72 | Mixed\(h\)      | Turkey            | Kahraman et al. (2005)          |
| 16  | \( UCS = 18 I_{s(50)} \)           | 40         | 0.97 | Igneous          | Hong Kong         | Basu and Aydin (2006)           |
| 17  | \( UCS = 13.4 I_{s(50)} \)         | 39         | 0.89 | Mixed            | Indonesia         | Agustawijaya (2007)             |
| 18  | \( UCS = 12.4 I_{s(50)} - 9.0859 \)| 39         | 0.81 | Sedimentary      | Turkey            | Yilmaz and Yuksel (2008)        |
| 19  | \( UCS = 19.79 I_{s(50)} \)        | 32         | 0.74 | Metamorphic (gypsum) | Greece            | Diamantis et al. (2009)        |
| 20  | \( UCS = 14.63 I_{s(50)} \)        | 60         | 0.88 | Mixed            | India             | Mishra and Basu (2012)          |
| 21  | \( UCS = 16.4 I_{s(50)} \)         | 329        | 0.92 | Mixed            | Japan             | Kohn and Maeda (2012)           |
| 22  | \( UCS = 12.29 I_{s(50)} + 5.892 \)| 40         | 0.96 | Mixed            | Malaysia          | Mohamad et al. (2015)          |
| 23  | \( UCS = 20.7 I_{s(50)} + 4.299 \) | 22         | 0.92 | Mixed            | USA               | Deere and Miller (1966)         |
| 24  | \( UCS = 12.5 I_{s(50)} \)         | 21         | 0.73 | Igneous          | Hong Kong         | Chau and Wong (1996)           |
| 25  | \( UCS = 22.79 I_{s(50)} + 13.295 \)| 35         | 0.88 | Sedimentary      | Pakistan          | Akram and Bakar (2007)          |
| 26  | \( UCS = 11.076 I_{s(50)} \)       | 16         | 0.89 | Sedimentary      | Pakistan          | Akram and Bakar (2007)          |
| 27  | \( UCS = 10.92 I_{s(50)} + 24.24 \)| 52         | 0.56 | Mixed            | Turkey            | Kahraman and Gunaydin (2009)    |
| 28  | \( UCS = 22.8 I_{s(50)} \)         | 7          | 0.99 | Metamorphic (quartzite) | India            | Singh et al. (2012)            |
| 29  | \( UCS = 15.8 I_{s(50)} \)         | 19         | 0.91 | Metamorphic (khondalite) | India            | Singh et al. (2012)            |
| 30  | \( UCS = 22.2 I_{s(50)} \)         | 6          | 0.78 | Metamorphic (quartzite\(e\)) | India            | Singh et al. (2012)            |
| 31  | \( UCS = 21.9 I_{s(50)} \)         | 10         | 0.89 | Sedimentary      | India             | Singh et al. (2012)            |
| 32  | \( UCS = 16.1 I_{s(50)} \)         | 7          | 0.71 | Sedimentary      | India             | Singh et al. (2012)            |
| 33  | \( UCS = 14.4 I_{s(50)} \)         | 6          | 0.82 | Sedimentary (shale) | India            | Singh et al. (2012)            |
Table 14 continued

| S/N | Relationship          | No of data | R²  | Rock types                          | Country of origin | References            |
|-----|-----------------------|------------|-----|-------------------------------------|-------------------|-----------------------|
| 34  | $UCS = 23.3I_s^{(50)}$| 21         | 0.97| Igneous (gabbro)                    | India             | Singh et al. (2012)   |
| 35  | $UCS = 23.5I_s^{(50)}$| 7          | 0.98| Metamorphic (amphibolite)           | India             | Singh et al. (2012)   |
| 36  | $UCS = 24I_s^{(50)}$  | 6          | 0.96| Metamorphic (epidiorite)            | India             | Singh et al. (2012)   |
| 37  | $UCS = 22.3I_s^{(50)}$| 8          | 0.68| Sedimentary (limestone)             | India             | Singh et al. (2012)   |
| 38  | $UCS = 22.7I_s^{(50)}$| 9          | 0.82| Sedimentary (dolomite)              | India             | Singh et al. (2012)   |
| 39  | $UCS = 10.99I_s^{(50)} + 7.042$| 15       | 0.92| Sedimentary<sup>a</sup>              | Iran              | Heidari et al. (2012) |
| 40  | $UCS = 11.96I_s^{(50)} + 10.94$| 15   | 0.94| Sedimentary<sup>a</sup>              | Iran              | Heidari et al. (2012) |
| 41  | $UCS = 13.29I_s^{(50)} + 5.251$| 15        | 0.90| Sedimentary<sup>a</sup>              | Iran              | Heidari et al. (2012) |
| 42  | $UCS = 4.792I_s^{(50)} + 44.37$| 21        | 0.75| Metamorphic                          | India             | Tandon and Gupta (2015) |
| 43  | $UCS = 5.602I_s^{(50)} + 4.380$| 9         | 0.96| Igneous (granitoid)                  | India             | Tandon and Gupta (2015) |
| 44  | $UCS = 3.103I_s^{(50)} + 17.95$| 12        | 0.40| Igneous (gneiss)                     | India             | Tandon and Gupta (2015) |
| 45  | $UCS = 2.479I_s^{(50)} + 24.68$| 12        | 0.37| Metamorphic                          | India             | Tandon and Gupta (2015) |
| 46  | $UCS = 10.53I_s^{(50)} + 7.615$| 6         | 0.91| Sedimentary                          | India             | Tandon and Gupta (2015) |
| 47  | $UCS = 3.125I_s^{(50)} + 40.08$| 60        | 0.41| Mixed                                | India             | Tandon and Gupta (2015) |
| 48  | $UCS = 24I_s$         | 390 NA    | 0.74| Metamorphic                          | Greece            | Diamantis et al. (2009) |
| 49  | $UCS = 21I_s$         | 240 NA    | 0.53| Metamorphic                          | Greece            | Diamantis et al. (2009) |
| 50  | $UCS = 18I_s$         | 255 NA    | 0.52| Metamorphic                          | Greece            | Diamantis et al. (2009) |
| 51  | $UCS = 17.811I_s^{0.86}$| 32        | 0.82| Metamorphic                          | Greece            | Sabatakakis et al. (2008) |
| 52  | $UCS = 16.45exp^{0.391I_s}$| 32        | 0.80| Metamorphic                          | Greece            | Diamantis et al. (2009) |
| 53  | $UCS = 21.54I_s^{(50)} - 6.02$| 32       | 0.74| Metamorphic                          | Greece            | Diamantis et al. (2009) |
| 54  | $UCS = 7.62I_s^{0.74}$| 240        | 0.81| Sedimentary (general)                | Greece            | Sabatakakis et al. (2008) |
| 55  | $UCS = 25.3I_s^{(50)}$| 240        | 0.71| Sedimentary                          | Greece            | Sabatakakis et al. (2008) |
| 56  | $UCS = 13I_s^{(50)}$  | 240        | 0.49| Sedimentary<sup>d</sup>              | Greece            | Sabatakakis et al. (2008) |
| 57  | $UCS = 24I_s^{(50)}$  | 240        | 0.36| Sedimentary<sup>d</sup>              | Greece            | Sabatakakis et al. (2008) |
| 58  | $UCS = 28I_s^{(50)}$  | 240        | 0.53| Sedimentary<sup>d</sup>              | Greece            | Sabatakakis et al. (2008) |
| 59  | $UCS = 15.25I_s^{(50)}$| 19        | 0.98| Igneous                              | Turkey            | Tugrul and Zarif (1999) |
| 60  | $UCS = 56.939ln(I_s^{(50)}) - 1.6551$| 40        | 0.93| Sedimentary                          | Iran              | Azimian et al. (2014) |
| 61  | $UCS = 43.8981I_s^{(50)} - 57.134$| 53      | 0.76| Sedimentary                          | Iran              | Heidari et al. (2018) |
| 62  | $UCS = 90.147^{0.92}$| 143        | 0.91| Igneous                              | USA               | Kallu and Roghanchi (2015) |
| 63  | $UCS = 16.5I_s^{(50)} + 51$| 10        | 0.69| Sedimentary                          | USA               | Gunsallus and Kulhawy (1984) |
| 64  | $UCS = 16I_s^{(50)}$  | 11         | NA | Igneous                              | India             | Ghosh and Srivastava (1991) |
| 65  | $UCS = 23I_s^{(50)}$  | 30         | NA | Sedimentary                          | USA               | Smith (1997)          |
| 66  | $UCS = 9.08I_s^{(50)} + 39.32$| 11        | 0.85| Mixed                                | Turkey            | Fener et al. (2005)   |
| 67  | $UCS = 8.2I_s^{(50)} + 36.43$| 17        | 0.68| Igneous                              | Turkey            | Kahraman and Gunaydin (2009) |
| 68  | $UCS = 18.45I_s^{(50)} - 13.63$| 16        | 0.77| Metamorphic                          | Turkey            | Kahraman and Gunaydin (2009) |
| S/N | Relationship | No of data | $R^2$ | Rock types | Country of origin | References |
|-----|--------------|------------|-------|------------|-------------------|------------|
| 69  | $UCS = 29.77I_s(50) - 51.49$ | 19         | 0.78  | Sedimentary | Turkey            | Kahraman and Gunaydin (2009) |
| 70  | $UCS = 11.103I_s(50) + 37.659$ | 34         | 0.86  | Metamorphic | India             | Basu and Kamran (2010) |
| 71  | $UCS = 17.6I_s(50) + 13.5$ | 7          | 0.88  | Sedimentary | UK, France and Denmark | Aliyu et al. (2019) |
| 72  | $UCS = 24I_s(50)$ | 15         | 0.88  | Igneous     | United Kingdom    | Broch and Franklin (1972) |
| 73  | $UCS = 9.459I_s(50)$ | 419        | 0.68  | Mixed       | United Arab Emirates | Salah et al. (2014) |
| 74  | $UCS = 18.71I_s(50)$ | 35         | 0.60  | Mixed       | Several countries | Thuro et al. (2001) |
| 75  | $UCS = 2.59I_s(50) + 0.21$ | 22         | 0.65  | Sedimentary | UAE               | Elhakim (2015) |
| 76  | $UCS = 2.86I_s(50)$ | 22         | 0.64  | Sedimentary | UAE               | Elhakim (2015) |
| 77  | $UCS = 24.36I_s(50) - 2.14$ | 8          | 0.99  | Metamorphic | Iran              | Fereidooni (2016) |
| 78  | $UCS = 5.575I_s(50) + 21.92$ | 15         | 0.93  | Sedimentary | Iran              | Heidari et al. (2012) |
| 79  | $UCS = 7.557I_s(50) + 23.68$ | 15         | 0.94  | Sedimentary | Iran              | Heidari et al. (2012) |
| 80  | $UCS = 3.495I_s(50) + 24.84$ | 15         | 0.89  | Sedimentary | Iran              | Heidari et al. (2012) |
| 81  | $UCS = 23I_s(54) + 13$ | 14         | 0.94  | Sedimentary (Limestone) | USA   | Cargill and Shakoor (1990) |

*Combination of 54, 48, 42, 30 and 21 mm core diameter sizes

54 mm core diameter size only
48 mm core diameter size only
42 mm core diameter size only
30 mm core diameter size only
21 mm core diameter size only
Rocks with porosity > 1%
Rocks with porosity < 1%
Rocks with Is < 2 MPa
Rocks with Is = 2–5 MPa
Rocks with Is > 5 MPa
Quartzite sample is finer-grained with higher porosity when compared to the other quartzite sample considered in that study
Point load determined axially for saturated state
Point load determined diametrically for saturated state
Point load determined using irregular samples for saturated state
Core diameter size is 54 mm (NX)
Core diameter size is 42 mm (BX)
Core diameter size is 21.5 mm (EX)
Rocks with Is > 5 MPa
Linear correlation with non-zero intercept
Linear correlation with zero intercept
Point load determined axially for air-dried state
Point load determined diametrically for air-dried state
Point load determined using irregular samples for air-dried state
UCS and $I_s(50)$ in MN/m²
5.2 Support Vector Machine

SVM models are supervised learning models with associated learning algorithms that analyse data used for classification and regression analysis (Aboutaleb et al. 2018). It is an approach of artificial intelligence that enables non-linear mapping of an $n$-dimensional input space into a higher-dimensional feature space where, for example, a linear classifier can be used. The method can train non-linear models based on the structural risk minimization principle that seeks to minimize an upper bound of the generalization error rather than minimize the empirical error as implemented in other neural networks (Khandelwal et al. 2010). The approach has been used in rock mechanics to estimate UCS (Ceryan 2014; Ren et al. 2019). Table 18 lists some SVM-based estimation of UCS from other rock properties. The analysis of the $R^2$ of the studies compiled show that SVM models have $R^2$ value ranging from 0.60 to 0.99.

5.3 Fuzzy Inference System

A fuzzy inference system (FIS) is a system that uses fuzzy set theory to map inputs to outputs (Gokceoglu and Zorlu 2004). Fuzzy logic accomplishes machine intelligence by providing a mean for representing and reasoning about human knowledge that is imprecise by nature (Gupta and Kulkami 2013). Fuzzy inference is a method that interprets the values in the input vector and based on some sets of rules, assigns values to the output vector. In fuzzy logic, the truth of any statement becomes a matter of a degree. FIS has been used in rock mechanics to estimate rock properties. Specifically, the technique has been to estimate UCS from other rock properties (Grima and Babuška 1999; Gokceoglu and Zorlu 2004; Karakus and Tutmez 2006; Heidari et al. 2018). Table 19 lists some FIS-based estimation of UCS of different rock types from other rock properties. The analysis of the $R^2$ of the studies compiled show that FIS models have $R^2$ values ranging from 0.64 to 0.98.

5.4 Genetic Programming

Genetic programming (GP) is a technique of evolving programs, starting from a population of usually random programs, fit for a task by applying operations analogous to natural genetic processes to the population of programs. It is a technique for the automatic generation of computer programs by means of natural selection (Beiki et al. 2013). The GP process starts by creating a large initial population of programs that are random combinations of elements from the problem-specific function sets and terminal sets. Improvements are made possible by stochastic variation of programs and selection according to pre-specified criteria for judging the quality of a solution (Brameier and Banzhaf 2001). GP has been used in rock mechanics for estimating UCS from other properties (Canakci et al. 2009; Armaghani et al. 2018). Table 20 lists some studies where GP has been used to estimate UCS from other rock properties. The statistics of the $R^2$ values of the models generated for the studies listed in the table shows a range of 0.63–0.97.

5.5 Hybrid Artificial Neural Network

ANN has several disadvantages such as long training time, unwanted convergence to local instead of global optimal solution, and large number of parameters (Liou et al. 2009). To overcome these drawbacks, there have been attempts to remedy some of these disadvantages by combining ANN with another algorithm that can take care of a specific problem. Hybrid forms of ANN such as ANFIS, PSO-ANN, ICA-ANN, etc., have been developed to overcome these drawbacks.
Table 16  Multiple regression equations for estimating UCS from other rock properties

| S/N | Relationship | No of data | Input parameters | R²    | Rock types | Country of origin | References               |
|-----|--------------|------------|-----------------|-------|------------|-------------------|--------------------------|
| 1   | $UCS = -6.319 + 4.27\rho + 4.418V_p + 0.427\gamma$ | 19         | Density $\rho$, P-wave velocity $V_p$, unit weight $\gamma$ | 0.90  | Sedimentary | Turkey            | Dincer et al. (2008)     |
| 2   | $UCS = 142.47 \times e^{-9.561/\rho V_p}$ | 64         | Density $\rho$, P-wave velocity $V_p$ | 0.56  | Sedimentary | Iran              | Moradian and Behnia (2009) |
| 3   | $UCS = -7.708 + 92.722\nu + 0.866E_d$ | 482        | Poisson ratio ($\nu$), dynamic Young’s modulus ($E_d$) | 0.897 | Sedimentary | Iran              | Aboutaleb et al. (2018)   |
| 4   | $UCS = 0.079e^{-0.039\lambda L_s^{1.1}}$ | 9          | Porosity $n$, equotip hardness number $L_s$ | 0.88  | Mixed       | Japan and Indonesia | Aoki and Matsukura (2008) |
| 5   | $UCS = 69.505\rho_{dry} + 0.025V_p - 0.479Qtz - 1.439Plg - 158.796$ | 45         | Dry density ($\rho_{dry}$), P-wave velocity $V_p$, quartz content ($Qtz$), plagioclase content ($Plg$) | 0.55  | Igneous      | Malaysia            | Armaghani et al. (2015)   |
| 6   | $UCS = 6.24Is_{(50)} + 25.8V_p - 90.3$ | 150        | Point load strength $Is_{(50)}$, P-wave velocity | 0.85  | Sedimentary | Turkey            | Cobanoglu and Celik (2008) |
| 7   | $UCS = 4.14Is_{(50)} + 29.8V_p + 0.54(N) - 116$ | 150        | Point load strength $Is_{(50)}$, P-wave velocity $V_p$, Schmidt hardness rebound ($N$) | 0.99  | Sedimentary | Turkey            | Cobanoglu and Celik (2008) |
| 8   | $UCS = 6.9 \times 10^{0.0087(N+0.16)}$ | 28         | Schmidt hardness rebound ($N$), unit weight $\gamma$ | 0.94  | Mixed       | USA               | Deere and Miller (1966)   |
| 9   | $UCS = 6.9 \times 10^{1.348\log(N)-1.325}$ | 25         | Unit weight $\gamma$, Schmidt hardness number | 0.80  | Mixed       | USA               | Aufmuth (1973)            |
| 10  | $UCS = 12.74e^{(0.185/N)}$ | 20         | Unit weight $\gamma$, Schmidt hardness Rebound ($N$) | NA    | Mixed       | USA               | Beverley et al. (1979)    |
| 11  | $UCS = 0.447e^{(0.045(N+3.5)+\gamma)}$ | 5          | Unit weight $\gamma$, Schmidt hardness rebound ($N$) | 0.94  | Sedimentary | USA               | Kidybinski (1980)         |
| 12  | $UCS = 4.5 \times 10^{-4}(N\gamma)^{2.46}$ | 10         | Unit weight $\gamma$, Schmidt hardness rebound ($N$) | 0.93  | Sedimentary | Turkey            | Kahraman (1996)           |
| 13  | $UCS = -6.319 + 4.418 \times 10^{-3}V_p + 0.427\gamma$ | 19         | P-wave velocity $V_p$, unit weight $\gamma$ | 0.95  | Sedimentary | Turkey            | Dinçer et al. (2008)      |
| 14  | $UCS = 3V_p^2V_s^2-2.85$ | 46         | P-wave $V_p$ and S-wave $V_s$ velocities | NA    | Sedimentary | Turkey            | Uyanik et al. (2019)      |
| 15  | $UCS = 52.214 - 527.77GS + 80.86SF + 0.526Qtz^2$ | 30         | Grain size ($GS$), shape factor ($SF$), quartz content ($Qtz$) | 0.84  | Metamorphic  | China              | Ali et al. (2014)         |
Table 16 continued

| S/N | Relationship | No of data | Input parameters | $R^2$ | Rock types | Country of origin | References |
|-----|--------------|------------|-----------------|------|-------------|-------------------|------------|
| 16  | $UCS = (-25.8 \ln(D) + 153.5) \ln(SCSI) - (83.51 \ln(D) + 310.2)$ | 600 | Particle diameter ($D$), single compressive strength index ($SCSI$) | 0.91 | Sedimentary | Iran | Cheshomi and Sheshde (2013) |
| 17  | $UCS = (-0.3D + 1.92)SCSI + (1.24D + 6.72)$ | 300 | Particle diameter ($D$), single compressive strength index ($SCSI$) | 0.96 | Sedimentary | Iran | Cheshomi et al. (2015) |
| 18  | $UCS = 0.121SCSI - 7.462D + 63.98$ | 10 | Single compressive strength index, particle diameter | 0.66 | Sedimentary | Iran | Ashtari et al. (2019) (D = 3-10 mm) |
| 19  | $UCS = 10.61I_{(50)} + 6.8710^{-2}V_p - 339.48$ | 32 | Point load strength, P-wave velocity | 0.88 | Metamorphic | Greece | Diamantasis et al. (2009) |
| 20  | $UCS = 10.51I_{(50)} + 27.45\gamma_d - 675.50$ | 32 | Point load strength, dry unit weight | 0.86 | Metamorphic | Greece | Diamantasis et al. (2009) |
| 21  | $UCS = 12.15I_{(50)} - 1.78\beta + 169.72$ | 32 | Point load strength, degree of serpentinitization ($\beta$) | 0.83 | Metamorphic | Greece | Diamantasis et al. (2009) |
| 22  | $UCS = 8.0710^{-2}V_p - 0.92\beta - 295.49$ | 32 | P-wave velocity, degree of serpentinitization | 0.82 | Metamorphic | Greece | Diamantasis et al. (2009) |
| 23  | $UCS = 6.5710^{-2}V_p + 17.50\gamma_d - 739.38$ | 32 | P-wave velocity, dry unit weight | 0.81 | Metamorphic | Greece | Diamantasis et al. (2009) |
| 24  | $UCS = 36.31\gamma_d - 0.59\beta - 821.85$ | 32 | Dry unit weight, degree of serpentinitization | 0.80 | Metamorphic | Greece | Diamantasis et al. (2009) |
| 25  | $UCS = 5.01I_{(50)} + 5.52e^{0.0004V_p} - 3.53$ | 85 | Point load strength, P-wave velocity | 0.83 | Igneous (Grade 3 weathering) | Macau | Ng et al. (2009) |
| 26  | $UCS = \exp(-0.08008h + 0.01630e - 0.28813d + 4.12057)$ | 65 | Nail penetration depth ($h$) (mm), NailGun energy ($e$) (J), nail diameter ($d$) (mm) | 0.95 | Mixed | Turkey | Selcuk and Kayabali (2015) |
| 27  | $UCS = 0.88 \times \rho^{2.24} \times SH^{0.22} \times CI^{0.89}$ | 44 | Density, shore hardness ($SH$), cone indenter ($CI$) | 0.55 | Mixed | England and Turkey | Tiryaki (2008) |
| 28  | $\ln UCS = 4.3 \times 10^{-2}(N_{\gamma_d}) + 1.2$ | 7 | Schmidt hardness number, Dry density | 0.93 | Sedimentary (sandstones) | USA | Cargill and Shakoor (1990) |
| 29  | $\ln UCS = 1.8 \times 10^{-2}(N_{\gamma_d}) + 2.9$ | 7 | Schmidt hardness number, Dry density | 0.98 | Sedimentary (carbonates) | USA | Cargill and Shakoor (1990) |
| 30  | $UCS = 0.476PD - 0.017CC - 0.049Q + 0.065$ | 138 | Packing density ($PD$), concavo-convex ($CC$), quartz content ($Q$) | 0.53 | Sedimentary (sandstones) | Turkey | Zorlu et al. (2008) |
Table 16 continued

| S/N | Relationship                                      | No of data | Input parameters                                                                 | $R^2$  | Rock types            | Country of origin | References                  |
|-----|--------------------------------------------------|------------|----------------------------------------------------------------------------------|--------|-----------------------|-------------------|----------------------------|
| 31  | $UCS = 13.244I_{j(50)} + 0.13V_p - 16.987$       | 40         | Point load index, P-wave velocity                                               | 0.94   | Sedimentary (marlstone) | Iran              | Azimian et al. (2014)       |
| 32  | $UCS = 1.277N + 2.186BPII + 16.41I_{j(50)} + 0.011V_p - 82.436$ | 108        | Schmidt hardness number, Block punch index, point load strength, P-wave velocity | 0.91   | Sedimentary           | Iran              | Heidari et al. (2018)       |
| 33  | $UCS = 47.11I_{j(50)} + 0.006i + 1.59JO$        | 5          | Point load strength, asperity angle ($i$), joint orientation ($JO$)              | 0.68   | Mixed                 | India             | Kabilan et al. (2017)       |
| 34  | $UCS = 13.371I_{j(50)} + 0.05i + 0.62JO$        | 5          | Point load strength, asperity angle, joint orientation                           | 0.90   | Mixed                 | India             | Kabilan et al. (2017)       |
| 35  | $UCS = -595.303 - 442.363V_p + 45.338V_p^2 - 6.1n + 0.52n^2 + 28.314I_{j(50)} - 4.061I_{j(50)}^2 + 115.822N - 2.007N^2$ | 30         | P-wave velocity, porosity, point load strength, Schmidt hardness number          | 0.64   | Sedimentary           | Iran              | Dehghan et al. (2010)       |
| 36  | $UCS = 38 - 352.26n - 5.3Cfc + 10.67Cf + 93.15M$ | 44         | Void Percent, ferroan calcitic cement ($Cfc$), ferruginous cement ($Cf$) mica percentage ($M$) | 0.57   | Sedimentary           | Nepal             | Manouchehriyan et al. (2012) |
| 37  | $UCS = 0.035V_p + 3.158I_{j2} - 0.954p - 342.729$ | 94         | P-wave velocity, slake durability index ($2^{nd}$ cycle), density                | 0.94   | Sedimentary (coal)    | India             | Sharma et al. (2017)        |
| 38  | $UCS = -727 + 0.0427UPV + 19.3WA + 33DD + 95SD + 86BD$ | 52         | Ultrasound pulse velocity ($UPV$), water absorption (WA), dry density (DD), saturated density (SD), bulk density (BD) | 0.64   | Igneous               | Turkey            | Canakci et al. (2009)       |
| 39  | $UCS = -229 + 3.74N + 76.2p + 3.24n$            | 93         | Schmidt hardness number, density, porosity                                     | 0.90   | Mixed                 | Iran              | Majdi and Rezaei (2013)     |
| 40  | $UCS = 1.277N + 2.86BPI + 16.41I_{j(50)} + 0.011V_p - 82.436$ | 53         | Schmidt hardness number, Block punch index, point load strength, P-wave velocity | 0.91   | Sedimentary           | Iran              | Jalali et al (2017)         |
| 41  | $UCS = -11.813 - 2.572n + 23.665I_{j(50)} + 41.654n + 12.197p - 0.001V_p$ | 163        | Porosity, point load strength, Poisson’s ratio, density and P-wave velocity     | 0.91   | Sedimentary           | India             | Madhubabu et al. (2016)     |
| 42  | $UCS = 34.186DD + 0.838I_{j2} + 2.308BTS - 109.184$ | 47         | Dry Density, Slake durability Index, Brazilian Tensile Strength                  | 0.93   | Sedimentary           | Malaysia          | Armaghani et al. (2018)     |
### Table 17 ANN-based models for prediction of UCS from other rock properties

| S/ N | Output                          | Input                                                                 | No of data | R²   | Rock types       | Country of origin | References                  |
|------|-------------------------------|----------------------------------------------------------------------|------------|------|------------------|--------------------|----------------------------|
| 1    | UCS                           | Dynamic poisson ratio                                                | 425        | 0.56 | Sedimentary      | Iran               | Aboutaleb et al. (2018)    |
| 2    | UCS                           | Dynamic poisson ratio                                                | 425        | 0.58 | Sedimentary      | Iran               | Aboutaleb et al. (2018)    |
| 3    | UCS                           | Dynamic poisson ratio, Young’s modulus                               | 425        | 0.90 | Sedimentary      | Iran               | Aboutaleb et al. (2018)    |
| 4    | UCS                           | Dynamic poisson ratio, Young’s modulus                               | 425        | 0.92 | Sedimentary      | Iran               | Aboutaleb et al. (2018)    |
| 5    | UCS                           | Equotip number, porosity, density, grain size                        | 33         | 0.97 | Mixed            | Spain              | Meulenkamp and Grima (1999) |
| 6    | UCS                           | Petrography study values (mineral composition, grain size, aspect ratio, form factor, area weighting and orientation of foliation planes of weakness) | 112        | NA   | Metamorphic      | India              | Singh et al. (2001)        |
| 7    | UCS                           | Quartz content, packing density, concavo-convex                      | 138        | 0.87 | Sedimentary      | Turkey             | Zorlu et al. (2008)        |
| 8    | UCS                           | P-wave velocity, point load strength, Schmidt hardness number, porosity | 30         | 0.86 | Sedimentary      | Iran               | Dehghan et al. (2010)      |
| 9    | UCS                           | Porosity, bulk density, water saturation                             | 5000       | 0.98 | Mixed            | Iran               | Rabbani et al. (2012)      |
| 10   | UCS                           | Porosity, slake durability index, P-wave velocity in solid part of the sample, effective porosity, petrography study values | 55         | 0.88 | Sedimentary      | Turkey             | Ceryan et al. (2012)        |
| 11   | UCS                           | Dry density, P-wave velocity, quartz content, plagioclase content   | 45         | 0.99 | Igneous          | Malaysia           | Armaghani et al. (2015)    |
| 12   | UCS                           | Density, shore hardness, cone indenter hardness                     | 0.40       |      | Mixed            | England and Turkey | Tiryaki (2008)             |
| 13   | UCS                           | Effective porosity, slake durability index, point load strength        | 39         | 0.93 | Sedimentary      | Turkey             | Yilmaz and Yuksek (2008)   |
| 14   | UCS                           | Origin of rocks, two/four-cycle slake durability index and clay content | 56         | 0.98 | Sedimentary      | Turkey             | Cevik et al. (2011)        |
| 15   | UCS                           | Unit weight, shore hardness, porosity, P-wave velocity, slake durability index | 54         | 0.50 | Sedimentary      | Turkey             | Yagiz et al. (2012)        |
| 16   | UCS                           | Porosity, density, P-wave Velocity, Poisson ratio, point load strength | NA         | 0.97 | -                | India              | Madhubabu et al. (2016)    |
| 17   | UCS                           | Grain size, shape factor, quartz content                             | 30         | 0.95 | Metamorphic      | China              | Ali et al. (2014)          |
| 18   | UCS                           | Cone indenter, density and Shore hardness                            | 44         | 0.63 | Mixed            | England & Turkey   | Tiryaki (2008)             |
| 19   | UCS                           | Packing density, concavo-convex, quartz content                      | 138        | 0.82 | Sedimentary (sandstones) | Turkey | Zorlu et al. (2008) |
| 20   | UCS                           | Amplitude attenuation coefficient, high and low frequency ratio      | 1614       | 0.99 | Mixed            | China              | Ren et al. (2019)          |
| 21   | UCS                           | P-wave velocity, porosity, point load strength                      | 30         | 0.93 | Sedimentary      | Iran               | Dehghan et al. (2010)      |
| 22   | UCS                           | Void percent, ferroan calcitic cement, ferruginous cement, mica percentage | 44         | 0.77 | Sedimentary      | Nepal              | Manouchehrian et al. (2012) |
and GA-ANN have been used to predict UCS of rocks by many studies (Monjezi et al. 2012; Armaghani et al. 2016; Jalali et al. 2017; Mohamad et al. 2018). Table 21 lists some studies where Hybrid forms of ANN have been used to estimate UCS from other rock properties. The statistics of the $R^2$ values of the models generated for the studies range from 0.60 to 0.99. Compared to other forms of artificial intelligence approaches, the hybrid ANNs produced higher $R^2$ values, indicating that they have more prediction capability compared to those forms of artificial intelligence that are not hybrid.

### 6 Summary and Conclusions

This study made a compilation of empirical relations for estimating UCS from other rock properties reported in the literature for the three types of rock and for cases where different rock types are mixed.
| S/N | Output layer | Input layer | No of data | $R^2$ | Rock types | Country of origin | References |
|-----|--------------|-------------|------------|------|------------|------------------|------------|
| 1   | UCS          | Schmidt hardness number, density, porosity | 93         | 0.95 | Sedimentary | Iran             | Rezaei et al. (2014) |
| 2   | UCS          | Petrographic composition           | 102        | 0.92 | Igneous     | Turkey           | Gokceoglu (2002)     |
| 3   | UCS          | P-wave velocity, block punch index, point load strength, tensile strength | 82         | 0.67 | Sedimentary | Turkey           | Gokceoglu and Zorlu (2004) |
| 4   | UCS          | Petrographic composition           | NA         | 0.64 | Igneous     | Turkey           | Sonmez et al. (2004) |
| 5   | UCS          | Point load strength, shore hardness, P-wave velocity | NA         | 0.97 | Mixed       |                  | Karakus and Tutmez (2006) |
| 6   | UCS          | Clay content, slake durability index | 68         | 0.88 | Sedimentary | Turkey           | Gokceoglu et al. (2009) |
| 7   | UCS          | Block punch index, point load strength, shore hardness, P-wave velocity | 60         | 0.98 | Mixed       | India            | Mishra and Basu (2012) |
| 8   | UCS          | Grain size, shape factor, quartz content | 30         | 0.91 | Metamorphic | China            | Ali et al. (2014)    |
| 9   | UCS          | Block point index, Schmidt hardness number, point load strength, P-wave velocity | 288        | 0.91 | Sedimentary | Iran             | Heidari et al. (2018) |
| 10  | UCS          | Density, Equotip value, porosity       | 226        | NA   | Mixed       |                  | Grima and Babuška (1999) |
| 11  | UCS          | Schmidt hardness number, Block punch index, Point load strength, P-wave velocity | 106        | 0.91 | Sedimentary | Iran             | Jalali et al. (2017) |

| S/N | Output layer | Input layer | No of data | $R^2$ | Rock types | Country of origin | References |
|-----|--------------|-------------|------------|------|------------|------------------|------------|
| 1   | UCS          | Density, porosity, P-wave velocity | 72         | 0.83 | Sedimentary | Iran             | Beiki et al. (2013) |
| 2   | UCS          | P-wave velocity, water absorption, density | 106        | 0.86 | Sedimentary | Turkey           | Baykasoğlu et al. (2008) |
| 3   | UCS          | Quartz content, density, porosity, shore hardness, cone indenter hardness | 44         | 0.63 | Sedimentary | Nepal            | Manouchehrian et al. (2013) |
| 4   | UCS          | Dry density, slake durability index, Brazilian tensile strength | 47         | 0.97 | Sedimentary | Malaysia         | Armaghani et al. (2018) |
| 5   | UCS          | Ultrasound pulse velocity, water absorption, dry density, saturated density, bulk density | 52         | 0.88 | Igneous     | Turkey           | Canakci et al. (2009) |
| 6   | UCS          | Origin of rocks, two-cycle slake durability index and clay content | 56         | 0.96 | Sedimentary | Turkey           | Cevik et al. (2011) |
| 7   | UCS          | Origin of rocks, four-cycle slake durability index and clay content | 56         | 0.97 | Sedimentary | Turkey           | Cevik et al. (2011) |
| 8   | UCS          | Bottom ash dosage, dry unit weight, relative compaction, brittleness index, energy absorption capacity | 70         | 0.85 | Sedimentary | Turkey           | Gülü (2014)         |
Based on the database developed, typical ranges and mean of data used in developing the regressions, and the range and mean of the $R^2$ values of regressions for estimating UCS from other rock properties were evaluated and summarised. The empirical relationships considered in this study include simple
regressions, multiple regressions, and artificial intelligence-based relations for estimating UCS using approaches such as ANN, SVM, FIS, GP, and hybrid ANN like ANFIS, PSO-ANN, ICA-ANN, and GA-ANN.

The database of regression equations between UCS and other rock properties provides a systematic and logical assemblage of empirical relations that can be used in mining engineering practice. The relationships between UCS and other rock properties can be assessed to decide on the regression equation to be used for estimation of UCS at a specific site for a rock type. This will eliminate the problem of overestimation or underestimation of rock properties often encountered when regression equations are used to estimate the UCS. In addition, the database will serve as a useful companion to rock characterization approaches developed for mining and geotechnical application, especially when there is need to perform model selection and when quantifying the variability of UCS at a project site. The database will be particularly beneficial at small to medium-sized project sites, where rock properties data are often too sparse and there is need to estimate UCS of rock for mine planning and design purposes. A future study can investigate the possibility of developing an approach to rank the reliability of the regression equations in the database when they are used for estimation of UCS.

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**Declarations**

**Conflict of interest**  The authors declare that there are no known conflicts of interest.

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