Assessment of Geo-Mechanical Characteristics of Carbonate Rocks Using Non-destructive Pulse Velocity Measurements

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Abstract. Determining the geomechanical characteristics of the rock formations is critical to the design and analysis of various underground geotechnical structures. This research applied an experimental approach to determining the properties of rock cores based on ultrasonic wave velocities. Three types of carbonate rocks sampled from three different regions were thus experimentally tested and evaluated, with the regions from which the rock samples were collected being located in south-eastern, south-western, and north-eastern areas of Iraq. The geomechanical characteristics of the carbonate rocks were compiled based on ultrasonic pulse velocity tests and uniaxial compressive strength tests implemented under two sets of laboratory testing conditions: dry and saturated. The data are thus reported and discussed for both dry and saturated rock specimens. In general, the results showed a reduction in rock engineering properties with increasing moisture content. The measurements of compressional and shear wave velocities were analysed and correlated with various mechanical properties including: strength, elastic moduli, bulk density, Poisson’s ratio and Lame’s constant; the results of this process revealed that there is a strong correlation between velocity measurements and rock engineering properties. Several statistical relationships with high degrees of regression coefficient are thus proposed to efficiently the evaluate geomechanical properties of carbonate rocks based on compressional and shear wave measurements.

Keywords: Rock Cores, Ultrasonic Methods, Compressional Wave Velocity, Shear Wave Velocity, Uniaxial Compressive Strength, Elastic Modulus, Lame’s Constant.

1. Background
Characterising rocks’ geomechanical properties, such as Young’s modulus, compressive strength, bulk density, and Poisson’s ratio, is a crucial step for evaluating historical building stones, designing proper wellbores, predicting the fracture of rock masses, analysing the stability of underground rock excavations, and studying the lithology of subsurface rock layers [1]. Direct evaluation of rock characteristics requires statically testing rock core specimens in the laboratory, and such core specimens are often tested under compressive loads until failure occurs. The compressive stress-strain response of those rocks is then recorded and analysed to calculate various mechanical parameters [2]. The compression testing procedure has been standardised by the International Society for Rock Mechanics (ISRM), and the American Society for Testing and Materials (ASTM). However, these lab experiments remain time-consuming, limited, wasteful in terms of testing samples, and expensive to perform. Several methodologies have thus been developed to estimate the strength and elastic characteristics of rocks based on non-destructive dynamic
testing methods. These dynamic methods have the advantages of being rapid, reliable, continuous, relatively cheap, and easy to apply [3]. One of the more common dynamic testing methods is the determination of rocks’ characteristics by means of acoustic measurements propagated from ultrasonic pulse transmission techniques [4]. The acoustic measurements utilised in rock evaluation are the shear and compressional wave velocities (Vs and Vp), which are typically determined using the wave propagation theory, and which provide data related to the anisotropy, geomechanical properties, and elasticity of rocks [5].

Ultrasonic testing methods have been utilised for several decades in geoengineering practice and have been used in the laboratory for the evaluation of dynamic characteristics of rocks as well as in the field for geophysical exploration. Many experimental investigations [6, 7, 8, and 9] have presented correlations between the mechanical properties of rocks and sound velocities, indicating generally that geomechanical rock properties are closely correlated to such sound velocities.

Nefeslioglu [10] investigated the statistical correlations between the values of compressional wave velocities and the strength and elastic moduli of weak sedimentary rocks with unconfined compressive strengths ranging from 0.25 to 5.0 MPa. Uniaxial compressive strength tests were carried out on 66 core specimens, and the load-deformation data were recorded to measure the elastic moduli. The laboratory measurements were then statistically analysed to develop the following empirical equations:

\[
UCS = 0.457983 e^{1.504268(V_p)}
\]

\[
E_s = 0.015478 e^{2.135656(V_p)}
\]

where UCS is the uniaxial compressive strength (MPa), Es is the Young’s elastic modulus (GPa), and Vp is the compressional wave velocities (km/sec).

Moradian and Behnia [11] studied the relationships between sedimentary rocks’ characteristics and ultrasonic wave velocities. They used the uniaxial compressive strength test and ultrasonic pulse velocity test to evaluate 64 sedimentary rocks specimens, and the results were analysed to relate the compressive strength and static Young’s elastic modulus with the compressional wave velocity as given below:

\[
UCS = 165.05 \exp \left( \frac{-4451.07}{V_p} \right)
\]

\[
E_s = 2.06 \left( V_p \right)^{2.78}
\]

where the units of UCS, Es and Vp are MPa, GPa, and m/sec, respectively.

Yasar and Erdogan [12] tested various types of carbonate rock to examine the relationships between rocks’ mechanical properties and the measurements of compressional wave velocities. They proposed the following linear correlations:

\[
V_p = 0.0317 \text{UCS} + 2.0195
\]

\[
V_p = 0.0937 \text{Es} + 1.7528
\]

where the units of UCS, Es and Vp are kg/cm², GPa, and km/sec, respectively.

Kahraman [7] developed another nonlinear relationship for 27 various rock formations, based on extensive laboratory testing work:

\[
UCS = 9.95 \left( V_p \right)^{1.12}
\]

where the units of UCS and Vp are MPa and km/sec, respectively.

The objective of the current research was to statistically relate the geomechanical properties of carbonate rocks with the shear and compressional velocities of elastic waves obtained from ultrasonic testing.
techniques. A large number of ultrasonic pulse velocity tests were thus carried out on carbonate rocks in conjunction with determination of their other mechanical parameters, including their uniaxial compressive strength, modulus of elasticity, density, and Poisson’s ratio.

2. Mineralogy of Rock Samples
Three different rock types, collected from various quarries located in south-eastern, south-western and north-eastern Iraq, were employed in the experimental work. Rock samples with no bedding planes were chosen during the sampling process to minimise the effect of anisotropic qualities on the geomechanical measurements. The rock samples were all medium to strong carbonate rocks, composed primarily of calcium carbonates (CaCO$_3$) in the form of calcite, along with other minerals such as silicate, iron, and clay. The rock samples collected from each quarry were tested with respect to their basic chemical composition, as presented in Table 1.

![Table 1. Main chemical components of carbonate rocks.](image)

| Components | Test Results (%) |
|------------|-----------------|
|            | Rocks from south-eastern region | Rocks from south-western region | Rocks from north-eastern region |
| CaO        | 52              | 50.9            | 45                |
| SiO$_2$    | 3.9             | 0.90            | 2.6               |
| Al$_2$O$_3$| 51              | 2.67            | 6.7               |

3. Experimental Laboratory Work
Laboratory experiments were implemented to evaluate the rocks’ geomechanical properties. Cylindrical specimens were cut from larger rock samples using a core cutting machine. All cylindrical specimens had a slenderness ratio (length/diameter) equal to 2, with 60 mm diameter and 120 mm length. The lower and upper heads of each specimen were polished and ground to ensure parallelism and flatness. To determine the effect of water content, both dry and wet testing conditions were investigated. The dry specimens were air-dried at lab temperature for 24 hours, while the wet specimens were prepared by saturating them in water for 24 hours. This period of immersion was selected based on a preliminary laboratory test in which rock samples were left in water and weighed at 6-hour intervals until no change in weight was recorded between two consecutive readings. After the preparation of rock specimens, the experimental work was carried out in three stages: (1) ultrasonic pulse velocity test, (2) bulk density measurements, and (3) uniaxial compressive strength test.

3.1. Ultrasonic Pulse Velocity Test
A non-destructive ultrasonic testing method was applied using Proceq test equipment with a frequency range from 24 kHz to 1 MHz: this test equipment can generate, transmit and receive small-amplitude sonic waves that produce strain energy through the specimen [13]. Based on the upgraded method suggested by Adnan [14], the direct-transmission testing mode using a pair of transducers was utilised in this study. This testing mode is relatively straightforward, depending only on two factors: (1) the travel path, L and (2) the travel time, T, of the wave. Figure 1 shows a typical test setup for direct ultrasonic testing. The velocity of ultrasonic waves propagated through the rock specimen are calculated as the ratio of the travel distance of the wave to its travel time.
Figure 1. Schematic diagram of ultrasonic pulse velocity equipment.

Measurements of both compressional and shear waves are necessary to make a reliable estimation of the rock mechanical characteristics [15,16]. However, the shear wave velocity is often unavailable in practice due to a lack of testing techniques; there can also be difficulties associated with shear wave measurements, as these require firm contact between the end faces of the specimen and the transducers. Many empirical correlations have thus been established to predict shear wave velocity based on compressional wave velocity. In this study, measurements of compressional wave velocity were taken, and the shear wave velocity was then calculated using the following formula:

$$V_s = a_0 V_p^2 + a_1 V_p + a_2$$  \[(8)\]

where the polynomial regression coefficients $a_0$, $a_1$, and $a_2$ are -0.05509, 1.10168, and -1.0305, respectively, and $V_p$ and $V_s$ are given in km/sec. Equation 8 was proposed by [17] and offers a nonlinear correlation derived from an extensive experimental dataset. Many verification studies have also reported that Equation 8 provides the most reliable prediction for carbonate rocks.

3.2. Uniaxial Compressive Strength

Uniaxial compressive strength (UCS) is the most common and important measure of rock capacity to resist compressive loads. This parameter is typically utilised in rock design practice and as an index in the technology of rock excavation [18]. The standard test method, given by ASTM D7012 [19], was followed in this study to determine the rock strength. The intact rock core specimens obtained from the samples collected from three different quarries were continuously tested under an axial compressive load until ultimate load and failure occurred. The maximum compressive load on the specimen was determined as follows:

$$\text{UCS} = \frac{\text{Peak Load}}{\text{Cross Sectional Area}}$$  \[(9)\]

3.3. Bulk Density

Density is a basic physical characteristic of the rocks, defined as the mass per unit volume. The density of rocks varies based on the number of voids (porosity) in the rock mass and the occurrence of water in these voids [20]. In this study, the volume of the core specimens was assessed by measuring the length (L) and
diameter of the core (D); then the mass of the dry and saturated cores was determined. The bulk density was calculated by dividing the mass of the core (m) by its volume (V):

\[ \rho = \frac{m}{(\pi \times L \times D^2/4)} \]  

(10)

4. Methodology

All data collected were analysed for the development of statistical models to predict the geomechanical characteristics of rocks, including strength, density, and other related parameters. The accuracy of the statistical models was then validated using two parameters, the root mean square error (RMSE) and the coefficient of determination (R²).

The coefficient of determination is a statistical parameter that describes how closely the data lie to the fitted regression curve. This coefficient always ranges between 0 and 1, with R² equal to 0, when the regression model displays none of the variability of the fitted data around its mean, and R² equal to 1, if the regression model indicates all variability of the fitted data around its mean. Typically, the higher the R², the better the model fits the response data [21]. R² is determined using the following formula:

\[ R^2 = 1 - \frac{RSS}{CSS} \]  

(11)

where RSS is the residual sum of squares, which indicates the variance between the testing data and that predicted by the model, and CSS is the corrected sum of squares, which represents total variation in the predicted data.

The root mean square error (RMSE) defines the standard deviation of the residuals or the spread of the measured testing point about the fitted regression line. This statistical parameter is determined as follows:

\[ \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \]  

(12)

where:
- \( y_i \): Measured testing data
- \( \hat{y}_i \): Predicted testing data
- \( n \): Number of testing points

The accuracy of the statistical equations was further verified through plotting the data obtained from the experimental tests against the predicted data obtained from each suggested correlation.

5. Results Analysis and Discussion

5.1. Strength

The results obtained from the uniaxial compressive strength test showed that the strengths of dry rock specimens ranged from 41.26 to 92.92 MPa, with an average value of 64.31 MPa, while the strength of saturated rock specimens varied from 36.90 to 70.06 MPa, with an average of 56.88 MPa. It was observed that the existence of moisture content caused an average reduction in rock strength of more than 11%. The compressional and shear wave velocities were correlated with strength data, and Figures 2 and 3 illustrate the relationships between strength and wave velocities for both dry and saturated rock core specimens. The obtained velocities are seen to be well correlated with rock strength characteristics. Table 2 summarises the
correlating equations for the prediction of the rock strength, which offer a reliable estimation of strength, with a low root mean square error (RMSE) and a significant regression coefficient ($R^2$).

![Graph showing the relationship between Vp and UCS](image1)

**Figure 2:** a) Relationship between Vp and UCS, b) Comparison between measured and predicted UCS
Figure 3: a) Relationship between Vs and UCS, b) Comparison between measured and predicted UCS
Table 2: Correlations between Strength and Wave Velocities

| Testing Condition | Model                      | $R^2$ | RMSE |
|-------------------|----------------------------|-------|------|
| Dry               | $\text{UCS} = 2.0693 (V_p)^{2.0861}$ | 0.88  | 5.81 |
|                   | $\text{UCS} = 5.8667 (V_s)^{2.3685}$ | 0.87  | 5.68 |
| Saturated         | $\text{UCS} = 2.2142 (V_p)^{1.0865}$ | 0.81  | 3.71 |
|                   | $\text{UCS} = 4.3517 (V_s)^{2.3956}$ | 0.82  | 3.63 |

Note:
- Units of uniaxial compressive strength are (MPa)
- Units of compressional and shear wave velocity are (km/sec)

5.2. Modulus

Elastic relations between deformations and loads were evaluated through determining three rock moduli: elastic modulus ($E$), shear modulus ($G$), and bulk modulus ($K$). The elastic modulus, also known as Young’s modulus of elasticity, is obtained from the gradient of the straight-line portion of the stress-strain curve. The shear modulus, also called the modulus of rigidity, represents the resistance of rock mass to small shear deformations, and it is obtained from the ratio of shear stress to shear strain. The bulk modulus is defined as the pressure associated with the fractional change in volume of the rocks. The rock moduli were determined using the standard empirical formulae:

$$E = \rho V_s^2 \left( \frac{3V_p^2 - 4V_s^2}{(V_p^2 - 4V_s^2)} \right)$$  \hspace{1cm} (13)

$$G = \rho V_s^2$$  \hspace{1cm} (14)

$$K = \frac{\rho}{3} \left( \frac{3V_p^2 - 4V_s^2}{V_p^2 - 4V_s^2} \right)$$  \hspace{1cm} (15)

where $\rho$ is the rock density in kg/m$^3$; the units of $E$, $G$ and $K$ are Pa, and the units of shear and compressional wave velocity are m/sec. Figures 4 and 5 show that the rock moduli are positively related to shear and compressional wave velocities. The results also indicate the modulus of elasticity ranged from 28.09 to 72.27 GPa, while the shear modulus varied from 10.84 to 27.31 GPa, while the bulk modulus was in the range 22.89 to 68.17 GPa. For simplicity, several linear regression equations, each with one independent parameter (either compressive wave velocity or shear wave velocity), were developed to predict the rock modulus. Table 3 thus outlines the linear regression equations and correlation coefficients.
Figure 4: Relationships between Moduli and Compressional Wave Velocity
Figure 4: Relationships between Moduli and Compressional Wave Velocity (Continued)
Figure 5: Relationships between Moduli and Shear Wave Velocity

Figure 5a: Dry Condition

- Elastic Modulus
- Shear Modulus
- Bulk Modulus

Figure 5b: Dry Condition

- Predicted Modulus (GPa)
- Measured Modulus (GPa)

Figure 5: Relationships between Moduli and Shear Wave Velocity
Figure 5: Relationships between Moduli and Shear Wave Velocity (Continued)
Table 3: Correlations between Moduli and Wave Velocities

| Rock Modulus      | Model                  | Testing Condition | $R^2$ | RMSE |
|-------------------|------------------------|-------------------|-------|------|
| Young's Modulus   | $E = 19.83 \ V_p - 51.21$ | Dry               | 0.99  | 1.06 |
|                   | $E = 42.66 \ V_s - 65.39$ |                   | 0.98  | 1.59 |
|                   | $E = 20.94 \ V_p - 58.10$ | Saturated         | 0.98  | 0.97 |
|                   | $E = 50.39 \ V_s - 88.36$ |                   | 0.98  | 1.10 |
| Shear Modulus     | $G = 7.40 \ V_p - 18.61$ | Dry               | 0.99  | 0.38 |
|                   | $G = 15.93 \ V_s - 23.93$ |                   | 0.98  | 0.55 |
|                   | $G = 7.66 \ V_p - 20.36$ | Saturated         | 0.98  | 0.37 |
|                   | $G = 18.45 \ V_s - 31.47$ |                   | 0.98  | 0.40 |
| Bulk Modulus      | $K = 20.03 \ V_p - 59.31$ | Dry               | 0.97  | 1.72 |
|                   | $K = 42.85 \ V_s - 72.95$ |                   | 0.95  | 2.45 |
|                   | $K = 23.68 \ V_p - 79.98$ | Saturated         | 0.98  | 1.11 |
|                   | $K = 56.77 \ V_s - 113.6$ |                   | 0.97  | 1.50 |

**Note:**
- Units of Young, shear and bulk modulus is (GPa)
- Units of compressional and shear wave velocity is (km/sec)

5.3. Density
The density of rock specimens in both dry and saturated states was evaluated. The results indicate that the dry density of rock specimens varied from 2.33 to 2.76 gm/cm$^3$, with an average value of 2.58 gm/cm$^3$, while the density of saturated specimens varied from 2.39 to 2.78 gm/cm$^3$, with an average value of 2.61 gm/cm$^3$. The test results confirmed that the density increased with any increase in the moisture content of the rocks. The density data for all rocks were well related to the compressional and shear wave velocities, and relatively high correlations were found. The relationships for the dry and saturated rock specimens are illustrated in Figures 6 and 7, while Table 4 presents the statistical relationships used for the prediction of rock density.
Figure 6: Relationship between Density and Compressional Wave Velocity
Figure 7: Relationship between Density and Shear Wave Velocity

Figure 7a: Relationship between Density and Shear Wave Velocity (Vs) in Dry and Saturated Conditions.

Figure 7b: Comparison of Predicted and Measured Density in Dry and Saturated Conditions with Line of Equality.
Table 4: Correlations between Density and Wave Velocities

| Testing Condition | Model                           | R²  | RMSE |
|-------------------|---------------------------------|-----|------|
| Dry               | $\rho = 1.5879 \left( V_p \right)^{0.2968}$ | 0.75 | 0.05 |
|                   | $\rho = 1.8426 \left( V_s \right)^{0.3365}$ | 0.75 | 0.05 |
| Saturated         | $\rho = 1.3269 \left( V_p \right)^{0.3938}$ | 0.76 | 0.04 |
|                   | $\rho = 1.5312 \left( V_s \right)^{0.4981}$ | 0.76 | 0.04 |

Note:
- Units of density is (gm/cm$^3$)
- Units of compressional and shear wave velocity is (km/sec)

5.4. Lame’s Constant

One of the most significant intrinsic characteristics of rocks is Lame’s constant, which offers an indication of the compressibility of a rock mass caused by an associated pressure, as well as being an essential parameter in the discrimination process for rocks in sedimentary basins. On the basis of compressional and shear waves velocities, the value of Lame’s constant can be calculated using the following empirical relationship:

$$\lambda = \rho \left( V_p^2 - 2V_s^2 \right) \quad (16)$$

where $\lambda$ is the Lame’s constant (Pa), $\rho$ is the rock density (kg/m$^3$), and the units of all wave velocities are m/sec. The Lame’s constant was determined for the three different types of rocks under two moisture conditions, dry and saturated. Figure 8 shows the $\lambda$-Vp plots, in which the type of compressional pulse velocity and the effect of moisture conditions (dry or saturated) are considered. Figure 9 displays the relationship between the shear wave velocity and the Lame’s constant. The results show that the value of Lame’s constant increases progressively with increases in both compressional and shear wave velocities. The results also reveal that dry rock specimens have slightly lower Lame’s constants than saturated rock specimens when Vp and Vs are greater than 5.0 and 2.7 km/sec, respectively. The results further show that the dry Lame’s constant ranged from 15.7 to 47.3 GPa, with an average value of 30.8 GPa, while the Lame’s constant of saturated specimens ranged from 21.3 to 49.9 GPa with an average value of 37.1 GPa. The best fit regression curve was drawn for each set of testing data, and a correlation model for each curve was built based on either shear or compressional wave velocity. Table 5 lists the correlations of the Lame’s constant under saturated and dry testing conditions.
Figure 8: Relationship between Lame’s Constant and Compressional Wave Velocity
Figure 9: Relationship between Lame’s Constant and Shear Wave Velocity
Table 5: Correlations between Lame’s Constant and Wave Velocities

| Testing Condition | Model                  | $R^2$ | RMSE |
|-------------------|------------------------|-------|------|
| Dry               | $\lambda = 0.415 (V_p)^{2.613}$ | 0.99  | 0.89 |
|                   | $\lambda = 1.538 (V_s)^{2.961}$ | 0.98  | 1.43 |
| Saturated         | $\lambda = 0.248 (V_p)^{2.906}$ | 0.98  | 0.66 |
|                   | $\lambda = 0.728 (V_s)^{3.657}$ | 0.99  | 0.82 |

Note:
- Units of Lame’s constant is (GPa)
- Units of compressional and shear wave velocity is (km/sec)

5.5. Poisson’s Ratio

Poisson’s ratio is an elastic parameter that represents the ratio of the lateral deformation to the longitudinal deformation of a mass under tensile or compressive stress. This parameter plays an important role in defining the elastic deformation of rocks subjected to various static and dynamic loads. Although the Poisson’s ratio of rocks varies in only a narrow range (typically from 0.15 to 0.40), various empirical relationships have been developed to predict this parameter. The following formula was utilised in this work to measure the Poisson’s ratio based on compressional and shear wave velocities:

$$\nu = \left(\frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}\right)$$  \hspace{1cm} (17)

where $\nu$ is the Poisson’s ratio, $V_p$ is the compressional wave velocity (m/sec), and $V_s$ is the shear wave velocity (m/sec). Applying Equation 17, the estimated Poisson’s ratio varied from 0.29 to 0.32, with an average value of 0.30. The results show that Poisson’s ratio increases with an increase in both compressional and shear wave velocity. As part of the current work, one-independent variable linear regression equations were generated to predict this elastic property as a function of either compressional velocity or shear velocity, and Figures 10 and 11 show the best fit-lines developed between Poisson’s ratio and shear and compressional velocity. Good agreement was found between Poisson’s ratio and these wave velocities. Table 6 outlines the statistical correlations for determining the Poisson’s ratio.
Figure 10: Relationship between Poisson’s Ratio and Compressional Wave Velocity
Figure 11: Relationship between Poisson’s Ratio and Shear Wave Velocity
Table 6: Correlations between Poisson’s Ratio and Wave Velocities

| Testing Condition | Model          | $R^2$ | RMSE |
|-------------------|----------------|-------|------|
| Dry               | $\nu = 0.014 V_p + 0.234$ | 0.90  | 0.003|
|                   | $\nu = 0.029 V_s + 0.226$ | 0.85  | 0.003|
| Saturated         | $\nu = 0.020 V_p + 0.198$ | 0.98  | 0.001|
|                   | $\nu = 0.048 V_s + 0.170$ | 0.97  | 0.002|

Note: Units of compressional and shear wave velocity is (km/sec)

6. Conclusions
In this paper, experimental research work was carried out to evaluate the geomechanical properties of carbonate rocks based on ultrasonic pulse velocity in combination with uniaxial compressive strength testing. Based on the results of the experimental work, the following conclusions were drawn:

1) The measurements of shear wave velocity can be directly determined from compressional wave velocities. Based on an inclusive literature search, the relationship proposed by Castagna et al. [17] gives the most reliable estimation of shear wave velocities for carbonate rocks.

2) Strong correlations were identified between the data for uniaxial compressive strength and that for ultrasonic wave velocity. These correlations can be used to efficiently predict the strength of both dry and saturated carbonate rocks.

3) The rocks’ elastic moduli, including the Young ($E$), shear ($G$), and bulk ($K$) measures, can be estimated from the values of compressional and shear waves velocities using simple linear regression equations.

4) Lame’s constant and Poisson’s ratio were found to be significantly related to ultrasonic wave velocities. The value of the Lame’s parameter also increases with increases in both shear and compressional wave velocity.

5) The ultrasonic pulse velocity test is an effective testing technique that can be employed in a wide range of rock engineering applications to predict essential rock characteristics.

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