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STATISTICAL MODELS FOR PREDICTING THE MECHANICAL PROPERTIES OF LIMESTONE AGGREGATE BY SIMPLE TEST METHODS

The prediction of strength properties is a topic of interest in many engineering fields. The common tests used to evaluate rock strength include the uniaxial compressive strength test (*UCS*), Brazilian tensile strength (*BTS*) and flexural strength (*FS*). These tests can only be carried out in the laboratory and involve some difficulties such as preparation of the samples according to standards, amount of samples, and the long duration of test phases. This article aims to suggest equations for the prediction of mechanical properties of aggregates as a function of the P-wave velocity (*Vp*) and Schmidt hammer hardness (*SHH*) value of intact or in-situ rocks using regression analyses. Within the scope of the study, 90 samples were collected in the south of Türkiye. The mechanical properties, such as uniaxial compressive strength, Brazilian tensile strength and flexural strength of specimens, were determined in the laboratory and investigated in relation to P-wave velocity, and Schmidt hardness. Using regression techniques, various models were developed, and comparisons were made to find the optimum models using a coefficient of determination (R^2) and p value (sig) performance indexes. Simple and multiple regression analysis found powerful correlations between mechanical properties and P-wave velocity and Schmidt hammer hardness. In addition, the prediction equations were compared with previous studies. The results obtained from this study indicate that the results of simple test methods, such as *Vp* or *SHH* values, of rock used for aggregate could be used to predict some mechanical properties. Thus, it will be possible to obtain information about the mechanical properties of aggregates in the study area in a faster and more practical way by using predictive models.

Keywords: Aggregate; P-Wave Velocity; Schmidt Hardness; Regression; Mechanical Properties

1. Introduction

Aggregates are the main raw material of engineering builds such as roads, tunnels, bridges, and seaports, so it is crucial to know the mechanical properties of aggregates for the strength

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and usage time of the structure in which they are used. Classic test methods require a series of operations, such as a collection of rock samples by drilling in the study area, transporting the collected samples to the laboratory and preparing them following the standards. This situation causes losses of the workforce, energy and time during the determination of physico-mechanical properties. Contrary to standard methods, fast and reliable results obtained using practical and portable alternative simple methods will provide both in-situ and faster results. In addition, the most crucial advantage is that it does not cause deformations in the study area or rock mass. Studies have found that non-destructive and in situ testing methods, such as acoustic emission, seismic wave velocity, and certain hardness tests, can provide considerable benefits in mining, natural stone, and construction projects [1-14].

In previous studies, various indirect testing methods were employed by researchers for reliable estimation of physical and mechanical properties. However, currently, the Schmidt hammer hardness test (*SHH*) and P-wave velocity (*Vp*) methods are regular tests to predict the mechanical properties of limestone aggregate samples. *Vp* is a powerful variable, correlated with different physico-mechanical and index properties for rocks with various origins in many studies [4-19]. *SHH* was applied to estimate the empirical correlations between the mechanical properties obtained from classical tests for concrete and rocks [20-24].

Many studies proposed different models to estimate mechanical properties based on index tests such as ultrasonic wave velocity and various hardness tests because these mechanical properties are crucial for the evaluation of the use of rocks. But generally, researchers focused on statistical approaches for predicting *UCS*. Azimian et al. [5] showed there were strong relationships between *UCS* with point load index and *Vp* for marly rocks. Altindag [25] performed regression analysis to investigate the relationships between *Vp* and the physico-mechanical properties of sedimentary rocks. The relationships, such as *UCS*-*Vp*, *SHH*-*Vp*, point load index-*Vp*, *TS*-*Vp*, porosity-*Vp* and unit weight-*Vp*, were determined by using simple and multiple regression analyses. Yasar and Erdogan [26] improved empirical equations based on *Vp*. They correlated the *Vp*-density, *Vp*-*UCS* and *Vp*-Young's modulus of carbonate rocks. Yagiz [17] aimed to estimate *UCS* and some physico-mechanical properties by using the *Vp* value of rocks. Many researchers used *SHH* to estimate the relationships with mechanical properties obtained from standard tests for concrete and rocks [20-23]. Kahraman [27] correlated *UCS* with parameters such as point load index, *SHH* and *Vp* tests. *SHH* tests were used to estimate the empirical correlations between *SHH* values and *UCS* values obtained from standard tests for concrete and rocks [20-23].

This study focused on evaluating some in situ and simple methods, such as the Schmidt hardness test (*SHH*) and P-wave velocity (*Vp*) and utilised statistical techniques to estimate the uniaxial compressive strength (*UCS*), Brazilian tensile strength (*BTS*) and flexural strength (*FS*) of limestone aggregates. The studied limestone aggregate samples were collected from Mersin, Adana, and Osmaniye cities in the south of Türkiye. Simple and multiple regression analysis was applied to define the relationships between *UCS*, *BTS* and *FS* and *Vp*, as well as *SHH*. In addition, the obtained estimation equations were associated with previous studies. The analyses showed the existence of crucial and meaningful relationships between the investigated parameters. Thus, this study enables the determination of the mechanical properties of limestones from the study regions in a more practical way, economically and in a shorter time.

This paper covers previous studies on predictive models for mechanical properties. In section 3, sampling and experimental studies are introduced. In Section 4, the statistical analysis is discussed. In Section 5, comparisons with previous studies are made. Finally, the conclusions are drawn in Section 6.

2. Previous studies about predictive models for mechanical properties

Researchers proposed various models to estimate mechanical properties such as *UCS*, *BTS* and *FS* based on simple and in-situ tests because of their importance. In general terms, researchers focused on *BTS* and *UCS* parameters. However, studies about the estimation of *FS* are limited. Some of the most used correlations between mechanical properties and *SHH* or *Vp* are summarised in TABLE 1.

TABLE 1

Equations correlating some mechanical properties using *SHH* and *Vp*

Equation	R^2	Rock Type	References	Comment
$UCS = 35.54V_p - 55$ $UCS = 8.36SHH - 416$	0.80 0.87	19 different granite	Tugrul and Zarif [24]	*UCS* in MPa and *Vp* in km/s
$UCS = 4.24e0.059SHH$	0.81	Igneous, metamorphic and sedimentary rocks	Fener et al. [28]	*UCS* in MPa
$UCS = 64.2V_p - 1179.9$	0.90	Sandstone, coal, quartz mica schist, phyllite, basalt	Sharma and Singh [29]	*UCS* in MPa and *Vp* is m/s
$UCS = 0.026V_p - 20.47$	0.91	Marly rocks	Azimian and Ajalloeian [30]	*UCS* in MPa and *Vp* is m/s
$UCS = 4.53V_p^{2.23}$ $FS = 1.1V_p^{1.55}$	0.68 0.80	Tuffs	Teymen [31]	*USC* and *FS* in MPa and *Vp* in km/s
$UCS = 0.25SHH^{1.77}$ $\ln UCS = 3.94\ln V_p - 28.12$ $BTS = 0.15SHH^{1.33}$	0.88 0.92 0.83	Basalt and rhyolite	Kallu and Roghanchi [32]	*UCS* and *BTS* in MPa
$UCS = 0.1383SHH^{1.743}$	0.91	47 Different rock samples	Karaman and Kesimal [33]	*UCS* in MPa
$UCS = 2.304V_p^{2.43}$ $UCS = 0.0137SHH^{2.27}$ $BTS = 0.49V_p^{1.8723}$ $BTS = 0.10087SHH^{1.77}$	0.94 0.93 0.92 0.95	19 different Rock	Kılıç and Teymen, [34]	*UCS* and *BTS* in MPa and *Vp* in km/s
$BTS = 0.1722SHH^{1.4182}$ $BTS = 1.687V_p^{1.7271}$	0.80 0.68	Different types of limestone rocks	Mohammed et al. [35]	*BTS* in MPa and *Vp* in km/s
$UCS = 0.009V_p^{1.105}$ $UCS = 2.664SHH - 35.22$	0.92 0.92	Limestone rocks	Azimian [36]	*UCS* in MPa and *Vp* in m/s
$UCS = 0.033V_p - 34.63$ $BTS = 0.001V_p + 0.662$	0.87 0.88	Quartzite, Granite, Dolomite, Marble, Shale	Khandelwal [37]	*UCS* in MPa and *Vp* in m/s

TABLE 1. Continued

$BTS = 0.2182SHH - 0.5659$ $BTS = 0.0015V_p - 0.3164$	0.70 0.63	Different types of rocks	Parsajoo et al. [38]	*BTS* in MPa and *Vp* in m/s
$UCS = 0.03467V_p - 85.246$ $BTS = 0.003078V_p - 7.873$	0.85 0.85	basaltic rocks	Karakuş and Akatay [39]	*UCS* and *BTS* in MPa and *Vp* in m/s
$BTS = 2\times10^{-5}V_p^{1.5343}$	0.93	Granite	Francisco et al. [40]	*BTS* in MPa and *Vp* in m/s
$FS = 2.67e^{0.0023SHH}$	0.96	Concrete	Murthi et al. [41]	*FS* in MPa
$FS = 0.0041V_p - 9.6345$	0.72	Granite	Noor-E-Khuda et al. [42]	*FS* in MPa and *Vp* in m/s

Previous studies have shown that equations were estimated for *UCS*. This study focused on generating the prediction equations of the main mechanical tests such as *UCS*, *BTS* and *FS* by using some in situ and simple methods such as *SHH* and *Vp*.

3. Sampling And Experimental Studies

Sampling

In this paper, a total of 90 limestone samples were studied using materials taken from the south of Türkiye as aggregate. These limestone aggregate samples are from seven different localities that represent the limestone properties of the region (Fig. 1). Seven separate locations represent almost half of the Mediterranean region. At least 10 samples were obtained from each location, taking into account the structural changes. Samples were prepared from massive, discontinuous and unaltered parts by using wet abrasive cut-off machine and wet drilling machine.

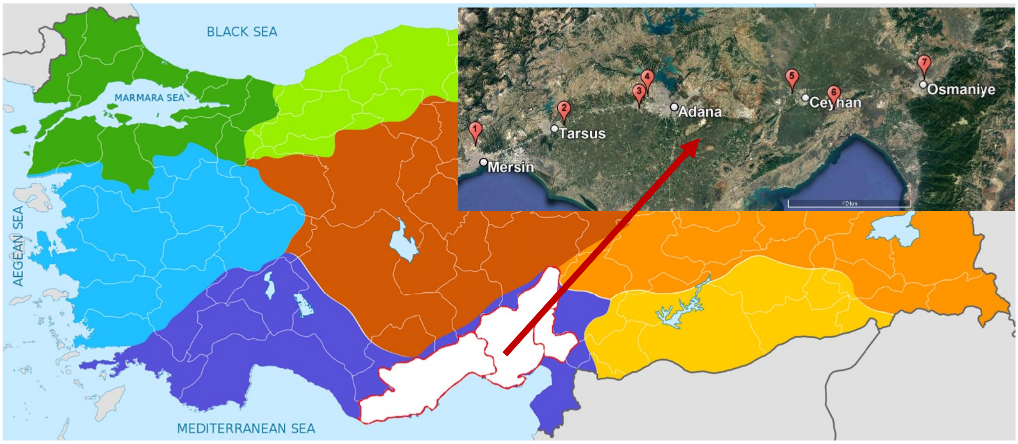

Fig. 1. Location of sample areas

Experiment studies

With the aim of the study, all limestone aggregate samples underwent physico-mechanical tests. These tests were uniaxial compressive strength (*UCS*), Brazilian tensile strength (*BTS*), flexural strength (*FS*), P-wave velocity (*Vp*) and Schmidt hammer hardness (*SHH*). The experiments were performed following the American Society for Testing Materials (ASTM) and the International Society for Rock Mechanics (ISRM) standards (TABLE 2).

TABLE 2

Applied tests and standards

Applied experiments	Standards
Uniaxial Compressive Strength (*UCS*)	ASTM D2938–95 [43]
Brazilian Tensile Strength (*BTS*)	ASTM D3967-16 [44]
Flexural Strength (*FS*)	ASTM C 880-89 [45]
Schmidt Hardness Test (*SHH*)	ISRM (1981b) [46]
P-Wave Velocity (*Vp*)	ISRM (1978) [47]

In experimental studies, a digital calliper (Accud 0-300 mm measuring range), drying oven (Memmert UN55 +5°C / 300°C measuring range), *BTS* test apparatus, *FS* test machine (ELE), pundit (Proceq PL-200), *UCS* machine (ELE-3000 kN capacity) and N-type *SHH* were used for physico-mechanical tests (Fig. 2).

A total of 90 tests were performed on samples obtained from 7 different regions. The average values obtained from these tests are given in TABLE 3. Also, the histograms of the *UCS*, *BTS*, *FS*, *Vp* and *SHH* values for the specimens are illustrated in Fig. 3.

Fig. 2. Physico-mechanical test machines and apparatus

TABLE 3

Ranges of experimental data

Variable	N	Minimum	Maximum	Mean	SD	Variance	Skewness	Kurtosis
USC (MPa)	90	17.57	68.25	41.35	15.23	231.86	0.08	–1.36
BTS (MPa)	90	1.19	11.63	7.56	2.81	7.91	–0.90	–0.37
FS (MPa)	90	0.82	12.53	6.27	3.75	14.08	0.38	–1.50
SHH	90	10.30	36.12	22.91	7.62	58.10	0.17	–1.31
Vp (km/s)	90	2.96	6.48	5.01	0.91	0.83	–0.47	–0.23

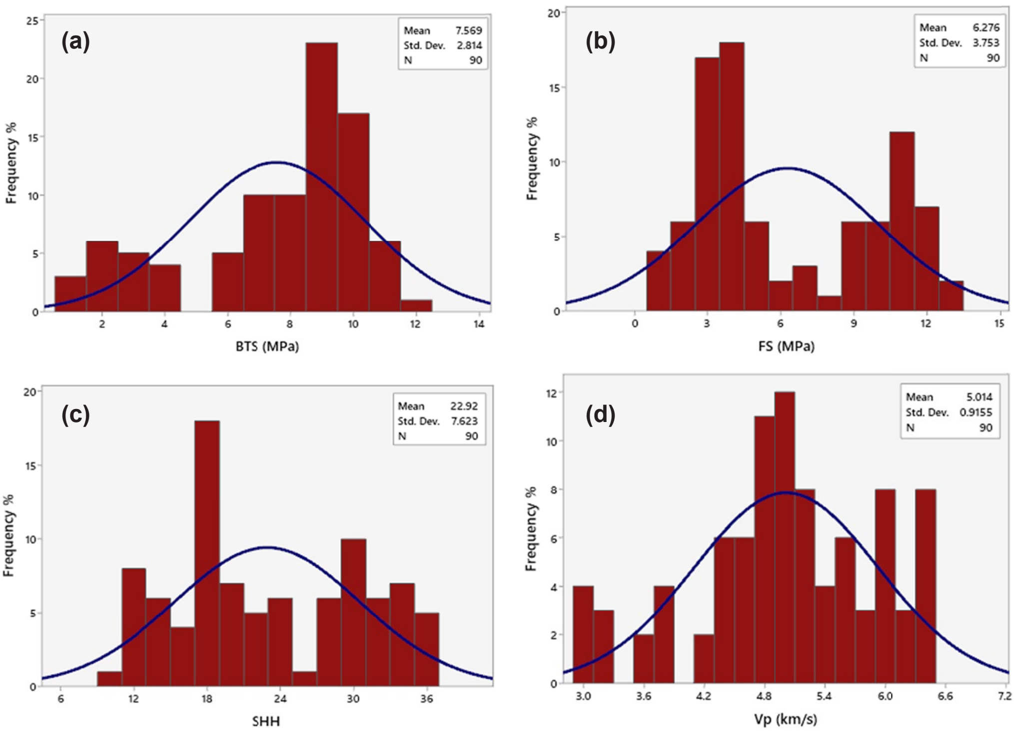

Fig. 3. Histograms of (a) *UCS*, (b) *BTS*, (c) *FS*, (d) *SHH* and (e) *Vp*

4. Statistical Analysis

This study utilised simple and multiple regression analyses, which are commonly used methods for estimating rock properties. The statistical analysis was performed using Minitab 19 statistical software, including ANOVA test results.

Simple regression analysis

SHH and *Vp* values were correlated with *UCS*, *BTS* and *FS* by weight using the method of least squares regression. Simple regression analyses were performed, and the equations of the best-fit line, the determination coefficient (R^2) and the 95% confidence and prediction limits were determined for each regression. Simple regression analysis was performed to examine the relationship. Linear, logarithmic, exponential, and power curve fitting approximations were applied, and the highest correlation coefficient was determined for each regression. The ANOVA test results are detailed in TABLE 4 for the simple regression analyses. The p value was used to determine the significance level of the R^2 values of regression equations, and p values were below 0.005.

TABLE 4

ANOVA test results for simple regression analyses

Equation No	Dependent variable	Independent variables	B (Coeff.)	Standard Error	R^2	ItI value	*F*-value	*p* value
1 Power	UCS	*SHH* Constant	1.064 1.465	0.040 0.454	0.83	26.374 8.021	695.610	0.000 0.000
2 Power		V_p Constant	1.827 2.090	0.086 0.289	0,84	21.232 7.237	450,788	0.000 0.000
3 Power	BTS	*SHH* Constant	1.367 0.102	0.080 0.025	0.76	17.028 4.033	289.956	0.000 0.000
4 Power		V_p Constant	2.609 0.106	0.095 0.016	0.89	27.338 6.524	747.387	0.000 0.000
5 Power	FS	*SHH* Constant	1.857 0.017	0.052 0.003	0.93	35.897 6.257	1288.625	0.000 0.000
6 Exponential		V_p Constant	0.661 0.186	0.035 0.033	0.89	19.079 5.668	363.990	0.000 0.000

A power correlation was found between *UCS* and *SHH* for all data (Fig. 4(a)). The correlation coefficient of the relationship was 0.83. Eq. (1) for the curve is:

$$UCS = 1.465 \times SHH^{1.064} \qquad (R^2 = 0.83) \tag{1}$$

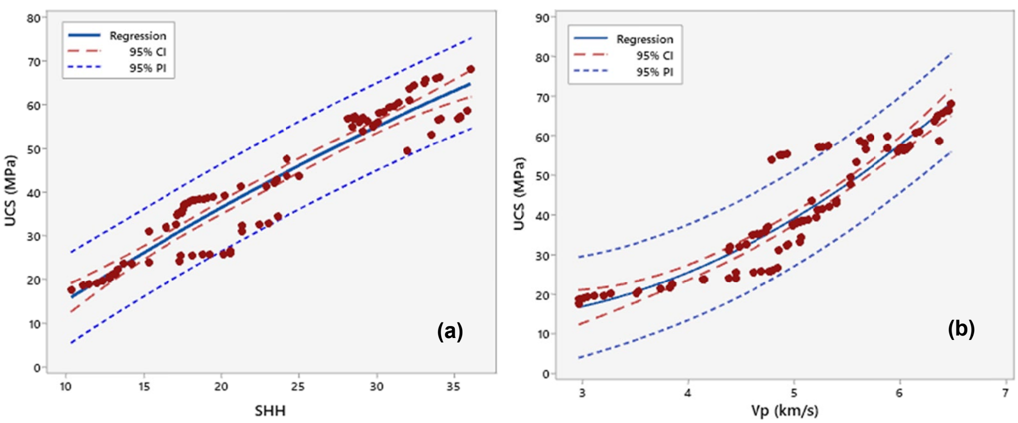

Fig. 4. Relationship between (a) *SHH-UCS* and (b) *Vp-UCS* of limestone aggregates

An exponential relationship was found between *UCS* and *Vp* for all data (Fig. 4(b)). The correlation coefficient of the relationship was 0.85. Eq. (2) for the curve is:

$$UCS = 2.090 \times Vp^{1.827} \qquad (R^2 = 0.85) \tag{2}$$

As visible from Fig. 5(a) and Fig. 5(b), *BTS* demonstrated a power relationship with *SHH* and *Vp*, respectively. The correlation coefficient of the relationship between *BTS* and *SHH* was 0.76, and the correlation coefficient of the relationship between *BTS* and *Vp* was 0.89. Eq. (3) and Eq. (4) for the curve are

$$BTS = 0.102 \times SHH^{1.367} \qquad (R^2 = 0.76) \tag{3}$$

$$BTS = 0.106 \times Vp^{2.609} \qquad (R^2 = 0.89) \tag{4}$$

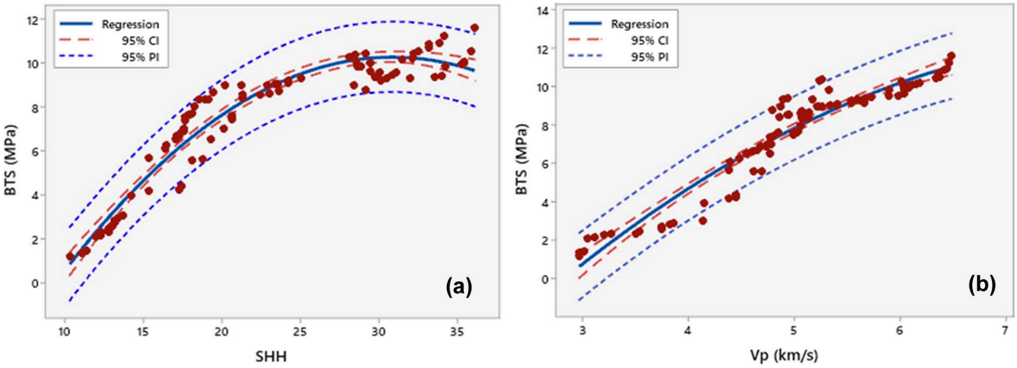

Fig. 5. The relationships between (a) *SHH-BTS* and (b) *Vp-BTS* of limestone aggregates

A power relationship was found between *FS* and *SHH* for the entire dataset (Fig. 6(a)). The correlation coefficient of the relationship was 0.93. Eq. (5) for the curve is:

$$FS = 0.017 \times SHH^{1.857} \qquad (R^2 = 0.93) \tag{5}$$

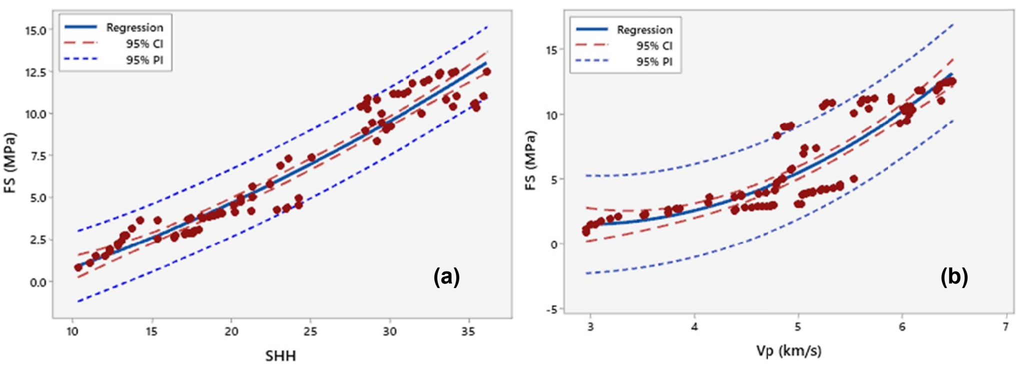

Fig. 6. The relationships between (a) *SHH-FS* and (b) *Vp-FS* of limestone aggregates

An exponential relationship was found between *FS* and *SHH* for the dataset (Fig. 6(b)). The correlation coefficient of the relationship was 0.89. Eq. (6) for the curve is:

$$FS = 0.186 \times e^{0.661Vp} \qquad (R^2 = 0.89) \tag{6}$$

Multiple Regression Analyses

In the next stage of the regression analyses, a series of multiple regression analyses were performed using *SHH* and *Vp*. The ANOVA test results for the multiple regression models to predict the *UCS*, *BTS* and *FS* are summarised in TABLE 5.

TABLE 5

ANOVA test results for multiple regression analyses

Equation No	Independent variables	B (Coeff.)	Standard Error	R^2	ItI value	F-value	*p* value
7 *UCS*	Constant *SHH* *Vp*	–13.99 1.374 4.76	3.50 0.149 1.24	0.91	3.99 9.24 3.84	436.49	0.000 0.000 0.000
8 *BTS*	Constant *SHH* V_p	–6.117 0.061 2.451	0.677 0.028 0.239	0.90	19.079 5.668	363.990	0.000 0.037 0.000
9 *FS*	Constant *SHH* *Vp*	–3.466 0.521 –0.440	0.769 0.032 0.272	0.92	4.51 15.97 1.62	561.390	0.000 0.000 0.109

The equations derived to estimate *UCS*, *BTS* and *FS* of limestone aggregates can be listed as follows:

$$UCS = -13.99 + 1.374SHH + 4.76Vp \tag{7}$$

$$BTS = -6.117 + 0.061SHH + 2.451Vp \tag{8}$$

$$FS = -3.466 + 0.5214SHH - 0.44Vp \tag{9}$$

The relationships between the measured and predicted values are illustrated in Figs. 7-9. As can be seen, the prediction models appear to be more reliable than those obtained by simple regression analysis.

5. Comparison with previous researches

A comparison with the previous studies was done to verify the limitations of the various prediction models. Here, P-wave velocity and Schmidt hammer hardness values were placed in the prediction equations for *UCS*, *BTS* and *FS* and plotted against observed *UCS*, *BTS* and *FS*. There were significant changes between the predicted data and our observed data in each case because of sample differences.

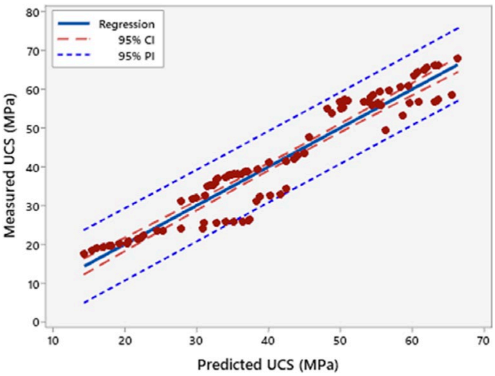

Fig. 7. The relationship between the measured and predicted *USC* from multiple regression

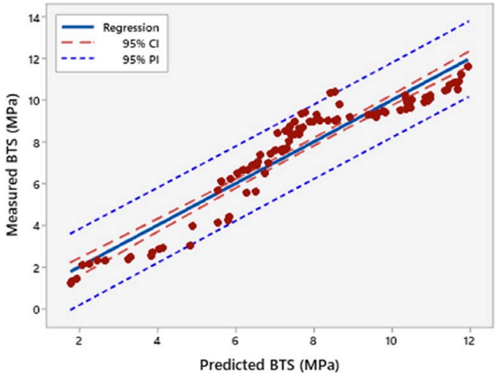

Fig. 8. The relationship between the measured and predicted *BTS* from multiple regression

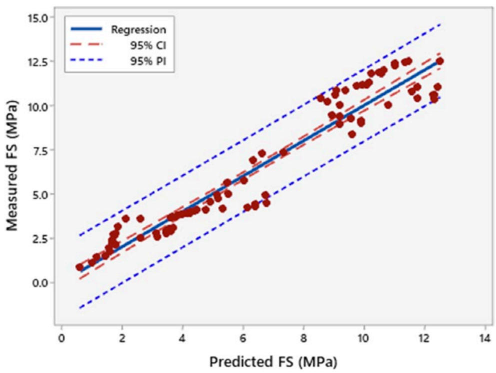

Fig. 9. The relationship between the measured and predicted *FS* from multiple regression

Fig. 10(a) shows *UCS* predicted using *SHH* by Fener et al. [28], Kallu and Roghanchi [32], Karaman and Kesimal [33] and Kilic and Teymen [34] with the observed dataset. The prediction equation suggested for *UCS* using *SHH* in this study differs from those suggested in other studies. However, a close relationship was observed to the prediction equation proposed by Karaman and Kesimal [33].

In Fig. 10(b), there are meaningful differences for *UCS* predicted using *Vp* by Yasar and Erdogan [26], Sharma and Singh [29], Kilic and Teymen [34] and Khandelwal [37]. The closest equation to the data obtained in this study was the one proposed by Kilic and Teymen [34].

As illustrated in Fig. 11(a), there were meaningful differences between *BTS* predicted using *SHH* by Kilic and Teymen [34], Kallu and Roghanchi [32], and Parsajoo et al. [38] with the observed dataset. Among the past studies, the closest to the results of the study was the study by Kallu and Roghanchi [32].

Fig. 11(b) shows *BTS* predicted using *Vp* by Kilic and Teymen [34], Khandelwal [37], Karakus and Akatay [39], and Francisco et al. [40] with the observed dataset. Overall, there are similar relationships observed except for the study conducted by Khandelwal [37].

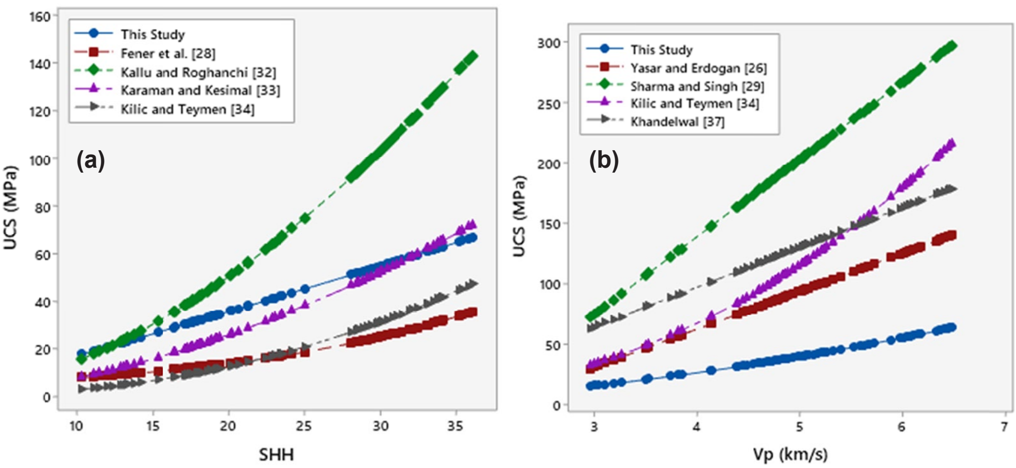

Fig. 10. Comparison of the derived equations with previous equations used to predict *UCS* using *SHH* (a) and (b) *Vp*

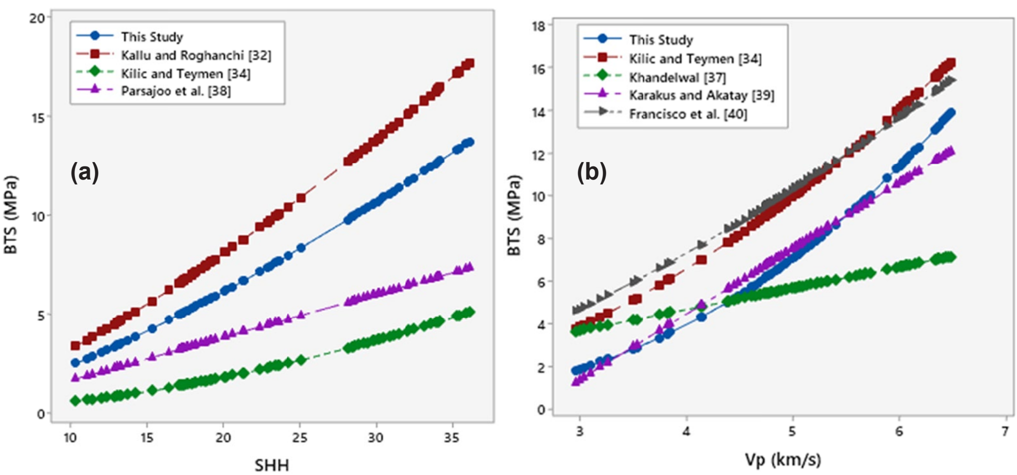

Fig. 11. Comparison of the derived equations with previous equations used to predict *BTS* using *SHH* (a) and (b) *Vp*

When previous studies are reviewed, few studies were identified using *SHH* and *Vp* for the estimation of *FS*.

Fig. 12(a) shows *FS* predicted using *SHH* by Teymen [31] and Noor-E-Khuda et al. [41], and Fig. 12(b) shows *FS* predicted using *Vp* by Murthi et al. [42].

The studies investigated are related to rocks and concrete with different origins. This situation creates differences between the obtained equations. In addition, since the intervals of the data obtained as a result of the experiments are variable, the accuracy of the estimation will decrease for higher and lower values.

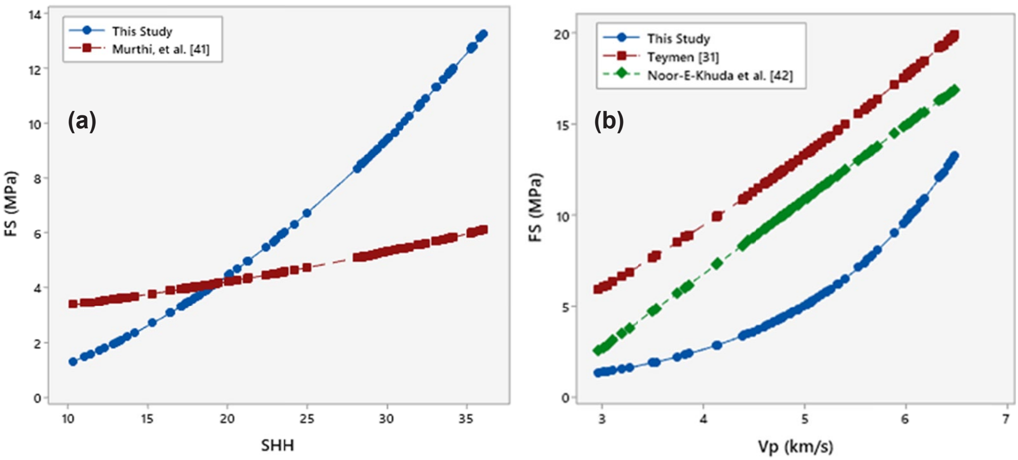

Fig. 12. Comparison of the derived equations with previous equations used to predict *FS* with *SHH* (a) and (b) *Vp*

This study took into account the specific characteristics of rocks in the region. Estimated equations created for the study region can be used. However, the evaluation of a larger study area will require a more comprehensive evaluation in future studies. Because the rock physico-mechanic properties of different places and environments are different.

6. Conclusion

In this study, simple test methods (*Vp* and *SHH*) and mechanical properties (*UCS*-*BTS* and *FS*) of the rocks used for limestone aggregate were determined for 90 limestone aggregate samples. Secondly, regression analysis was used to correlate the obtained parameters, and regression equations were established for the studied properties. In addition, multiple regression analysis showed high prediction performance for the prediction of *UCS*, *BTS* and *FS*. Furthermore, the study's estimation equations were compared to those of previous studies.

In conclusion, *Vp* and *SHH* methods have significant statistical correlations with the mechanical properties of limestone aggregates due to high correlation coefficients. The results of this study indicate that *UCS*, *BTS* and *FS* values can be predicted by determining *SHH* and *Vp*, which are simple, practical, less time-consuming and economical methods. The suggestion is that Schmidt hardness and P-wave velocity may be used most confidently for prediction of mechanical properties. It is suggested that the experimental investigation should be repeated with a number of different rock types in order to universalise these statistical relations. Further study is required to see how varying the rock type affects the correlations.

Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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