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Estimating the Mechanical Properties of Marble via the Non-Destructive Method

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Abstract:- One of the factors that affect the marketing, price, and field use of marble is its mechanical properties. Therefore, determining the mechanical properties of marble is very important. Usually, these properties are determined via destructive and non-destructive methods. In this study, the mechanical properties of ten types of marble collected from different parts of Turkey have been determined by destructive and non-destructive methods. Then, simple regression analysis was used to investigate the relationship between the mechanical properties and the velocity of p and s waves in saturated and dry states. As a result, to estimate the mechanical properties via p and s wave velocity the between of them equations with high correlation coefficients have been obtained.

Keywords:- *Marble, Mechanical Properties; Destructive Method, Non-Destructive Method.*

I. INTRODUCTION

Natural rocks are the oldest building materials that can be used commercially after extraction. Since time immemorial, humans have been using natural rocks for reasons of attractiveness, strength, and beauty in various places such as public places, mosques, sidewalks, external surfaces of buildings, etc. Marble is one type of natural rock that can be cut and polished, obtained as blocks in suitable sizes, and has commercial value. From ancient Greece until now, marble has been used as a building rock, decoration, and covering for commercial purposes [1].

Marble is one of the metamorphic stones; that consists of calcite, dolomite, or their combination. Its chemical composition contains a large amount of calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$) as well as silicon dioxide (SiO_2) and various metal oxides and silicate minerals[2].

Determining the mechanical properties of marble during extraction and processing, marketing and price level is extremely important in terms of technical and economic factors. Usually, the physical and mechanical properties of marble are determined via destructive methods. However, the mentioned method has a series of shortcomings, such as the high value of laboratory equipment, time-consuming, non-compliance with soft stones, and the possibility of testing only in the laboratory. Therefore, the researchers replaced the non-destructive method instead. The non-destructive method is evaluated by the speed of ultrasound waves (pressure and shear). This method is widely used in the fields of mining and construction engineering due to the cheapness and portability of the device, the possibility of testing in the field and laboratory, and the speed of the test [3].

Several researchers have studied the relationship between the velocity of ultrasound waves and the physical and mechanical properties of different rocks; As a result, they found different equations with high correlation coefficients [4]–[11].

Kahraman and Yeken tested 14 samples of carbonate rocks in terms of density, porosity, void ratio, water absorption, and P wave velocity. To determine the physical properties of carbonate rocks via the speed of P waves, they studied the relationship between them. As a result, obtained equations with high correlation coefficients[4]. Leucci and De Giorgi studied the effects of fractures on the speed of P and S waves in sedimentary rocks. They found that the speed of P and S waves decreases with the increase in the number of fractures[7]. To estimate the velocity of p-waves in saturated rock, via the velocity of p-waves in dry stones, the hero has studied the relationship between them. For this purpose, 41 different types of sedimentary, metamorphic, and magmatic rocks have been tested in saturated and dry states in terms of P wave velocity. As a result, he obtained equations with high correlation coefficients[3].

In this research, to estimate the mechanical properties of marbles via the non-destructive method, the relationship between the p and s wave velocity and the mechanical properties of different marbles that have been obtained by non-destructive methods will be investigated.

II. MATERIALS AND METHOD

The materials of this research were collected from ten marble quarries located in different parts of Turkey. The trade names of the samples and the location of the quarry where they were taken are shown in Table 1.

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Table 1: The Location and Rock Type of Samples

No	Location and Rock Type	
	Trade names	**location**
1	Crema	Hajialani/Mersin
2	Grey marble	Sivas
3	Emperador	Silifke/ Mersin
4	Emperador	Adiyaman
5	Black Marble	Iskenderun
6	Grey marble	Bilecik
7	Grey marble	Karaman
8	Grey marble	Konya
9	Crema	Adana
10	Limestone	Diyarbakir

Fig 1: The Prepared Samples for Testing

In this study, to determine the mechanical properties of marble samples via destructive and non-destructive methods, the testing process is carried out according to the Turkish Standardization Institute (TSE 699)[12]. The rock samples were brought from the field to the laboratory of the Mining Engineering Department of Cukurova University; It has been cut into cubes and rectangular cubes by a cutting machine. Figure 1.

A. *Uniaxial Compressive Strength*

The uniaxial compressive strength (UCS) test is performed by a Universal Testing Machine Figure 1. The samples were cut into cubes with dimensions of 5×5×5 (cm^3). The equipment needed in this test is a caliper and an oven that set in (105 ± 5 (X). The UCS is obtained from the ratio of the force that causes deformation or destruction of the sample and the surface area on which the force is applied.


Fig 2: The Universal UCS Testing Machine

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"Equation (1)" is used to find the uniaxial compressive strength.

$$\sigma_b=p/s \quad (1)$$

Where σ_b is uniaxial compressive strength (kgf/cm^2), p is Compressively force that destroys the sample (kgf) and s is the surface area where the load will be applied (cm^2).

B. Impact Strength

The maximum resistance of rocks against the impact forces is the impact strength. This test was performed by the device shown in Figure 2.

Fig 3: The Impact Testing Machine

For this purpose, the samples are cut with 4x4x4 (cm^3) dimensions. The equipment needed in this test is a caliper and an oven that set in (105 ± 5 °X). "Equation (2)" is used to find the impact strength.

$$D_n=n(n+1) \quad (2)$$

Where D_n is impact strength (kgf/cm^2), n is the number of impacts that destroy the sample, H is the height of impact on the sample ($H=0.04{\cdot}v$, cm), and v is the volume of sample (cm^3).

C. Flexural Strength

Flexural strength; It is the resistance of beam-shaped samples against bending stresses. Marble is generally used in the form of plates with specific sizes and thicknesses in buildings and other places. Therefore, determining the flexural strength is a very important parameter because the thickness and size of the plate, and the distance between the support points can be determined according to the flexural strength. This test was performed by the device shown in Figure 3. For this purpose, the samples are cut with 5x5x30 (cm^3) dimensions.


Fig 4: The Flexural Testing Machine

"Equation (4)" is used to find the impact strength.

$$\sigma_f=(3{\cdot}p{\cdot}l)/(2{\cdot}b{\cdot}h^2) \quad (3)$$

Where σ_f is flexural strength (kgf/cm^2), p is the Compressively force that destroys the sample (kgf), l is the length of the sample (cm), b is with of the sample, and h is the thickness of the sample (cm).

D. Ultrasonic Waves Velocity (Non-Destructive Method)

Ultrasonic wave velocity is a non-destructive method based on the measurement of p-wave (pressure) and s-wave (shear) velocity. The p-wave is faster than the s-wave. The p-wave passes through solids, liquids, and gases directly, while the s-wave passes in a waveform, like a sine graph. In this research, the passing time of these waves through the marble samples was determined by the (Proceq Inc.) model device as shown in Figure 5. This device consists of a transmitter and receiver and a time display screen.

The samples are cut with dimensions of 5x5x5 (cm^3) and 4x4x4 (cm^3) with completely smooth plates. During the test, to ensure the complete contact of the surface of the sample with the receiver and the transmitter, it is smeared by a viscous substance. It should be noted that the samples were tested in a saturated and dry state. The samples were tested after 48 hours in water and after 24 hours in the oven. The equipment needed in this test is a pan of water, a caliper, and set at (105 ± 5 °C).

Fig 5: The Ultrasonic Wave Testing Machine

"Equation (4)" is used to find the velocity of p and s waves.

$$v=l/t \quad (4)$$

Where v is velocity (cm/sec), l is the with of sample (cm), and t is the time (second).

III. RESULTS AND DISCUSSION

A. Destructive Method Test Results

In order to ensure the test results, from each field sample, ten laboratory samples have been prepared. Then the mentioned samples have been tested separately. The average test results of uniaxial compressive strength (σ_b), impact strength (D_n), and flexural strength (σ_f) as megapascal (*Mpa*) are shown in Table 2.

Table 2: The Test Results of Mechanical Properties of Marble

No	Mechanical Properties		
	σ_b (Mpa)	D_n (Mpa)	σ_f (Mpa)
1	107,42	18,40	10,66
2	98,65	16,80	9,55
3	93,98	15,20	9,21
4	84,94	13,60	8,06
5	78,79	9,60	7,40
6	74,61	8,40	7,03
7	70,21	6,40	6,92
8	65,14	4,40	6,82
9	64,41	3,60	6,56
10	55,11	2,80	5,47

B. Non-Destructive Method Test Results

Each sample was tested five times, and as a result, its average value was considered as the result. The samples were tested after being soaked in water for 48 hours and the velocity p and s waves were calculated in a saturated state (vp_s and vs_s). In order to test the samples in a dry state, the mentioned samples were dried for 24 hours in an oven set at (105°C), then the velocity of p and s waves in the dry state was calculated (vp_d and vs_d). The average of p and s waves obtained is shown in Table 3.

Table 3: The Test Results of Ultrasonic Waves Velocity

No	P and S Wave Velocity in Wet State		P and S Wave Velocity in Dry State	
	vp_w (km/sec)	vs_w (km/sec)	vp_d (km/sec)	vs_d (km/sec)
1	6,454	4,246	6,371	4,191
2	6,483	4,210	6,407	4,161
3	6,234	3,996	6,105	3,913
4	6,112	3,893	6,077	3,871
5	6,048	3,828	6,015	3,808
6	5,769	3,651	5,716	3,595
7	5,573	3,527	5,466	3,459
8	5,394	3,414	5,337	3,378
9	5,206	3,295	5,134	3,249
10	4,613	2,920	3,945	2,497

C. Investigating the Relationship Between Mechanical Properties and Ultrasonic Waves Velocity

As mentioned, the purpose of this research is to find a solution to estimate the mechanical properties of marble by a non-destructive method. For this aim, the simple regression analysis was used to examine the relationship between the parameters obtained by destructive and non-destructive methods. Therefore, the mechanical properties are considered as a dependent, and the ultrasonic wave velocity as an independent variable. The relationship between mechanical parameters and ultrasonic wave velocity with different simple regression models such as linear, logarithmic, quadratic, cubic, power, and exponential has been investigated. The model with the least mean square error (MS) is accepted as the final model. Although models with high correlation coefficients (R^2) were received, they were not accepted as the final model due to the highest mean square error.

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The relationship between UCS with p and s wave velocity in saturated and dry situations (vp_s, vp_d, vs_s, and vs_d) is shown in Figure 4. As can be seen, the relationship between them is direct. The power model has been decided as the final model because of the least squared error. In these models, to estimate the uniaxial compressive strength, the following equations have been obtained. In equations: 5, 6, 7, and 8, the correlation coefficients (R^2) is 89.5%, 77.4%, 93.6%, and 82.6%, respectively.

$$\sigma_\beta=3.2\cdot vp_s^{\,1.82} \quad (5)$$
$$\sigma_b=9.0\cdot vp_d^{1.24} \quad (6)$$
$$\sigma_b=8.2\cdot vs_s^{1.72} \quad (7)$$
$$\sigma_b=16.2\cdot vs_s^{1.23} \quad (8)$$

The relationship between impact strength with p and s wave velocity in saturated and dry situations (vp_s, vp_d, vs_s and vs_d) is shown in Figure 4. As can be seen, the relationship between them is direct. The power model has been decided as the final model because of the least squared error. In this model, to estimate the impact strength, the following equations have been obtained. In equations: 9, 10, 11, and 12, the correlation coefficients (R^2) is 93.3%, 98.8%, 94.5%, and 82.4%, respectively.

$$D_n=0.0002\cdot vp_s^{6.1} \quad (9)$$
$$\sigma_\beta=0.006\cdot vp_d^{4.2} \quad (10)$$
$$\sigma_\beta=0.005\cdot vs_s^{5.6} \quad (11)$$
$$\sigma_\beta=0.046\cdot vs_s^{4.07} \quad (12)$$

The relationship between flexural strength with p and s wave velocity in saturated and dry situations (vp_s, vp_d, vs_s and vs_d) is shown in Figure 4. As can be seen, the relationship between them is direct. The exponential and power models have been decided as the final models because of the least squared error. In this model, to estimate the flexural strength, the following equations have been obtained. In equations: 13, 14, 15, and 16, the correlation coefficients (R^2) is 85.8%, 77.4%, 88.8%, and 79.4%, respectively.

$$\sigma_f=1.26\cdot e^{0.31\cdot vp_s} \quad (13)$$
$$\sigma_f=2\cdot e^{0.23\cdot vp_d} \quad (14)$$
$$\sigma_f=0.94\cdot vs_s^{1.6} \quad (15)$$
$$\sigma_f=1.7\cdot vs_d^{1.1} \quad (16)$$

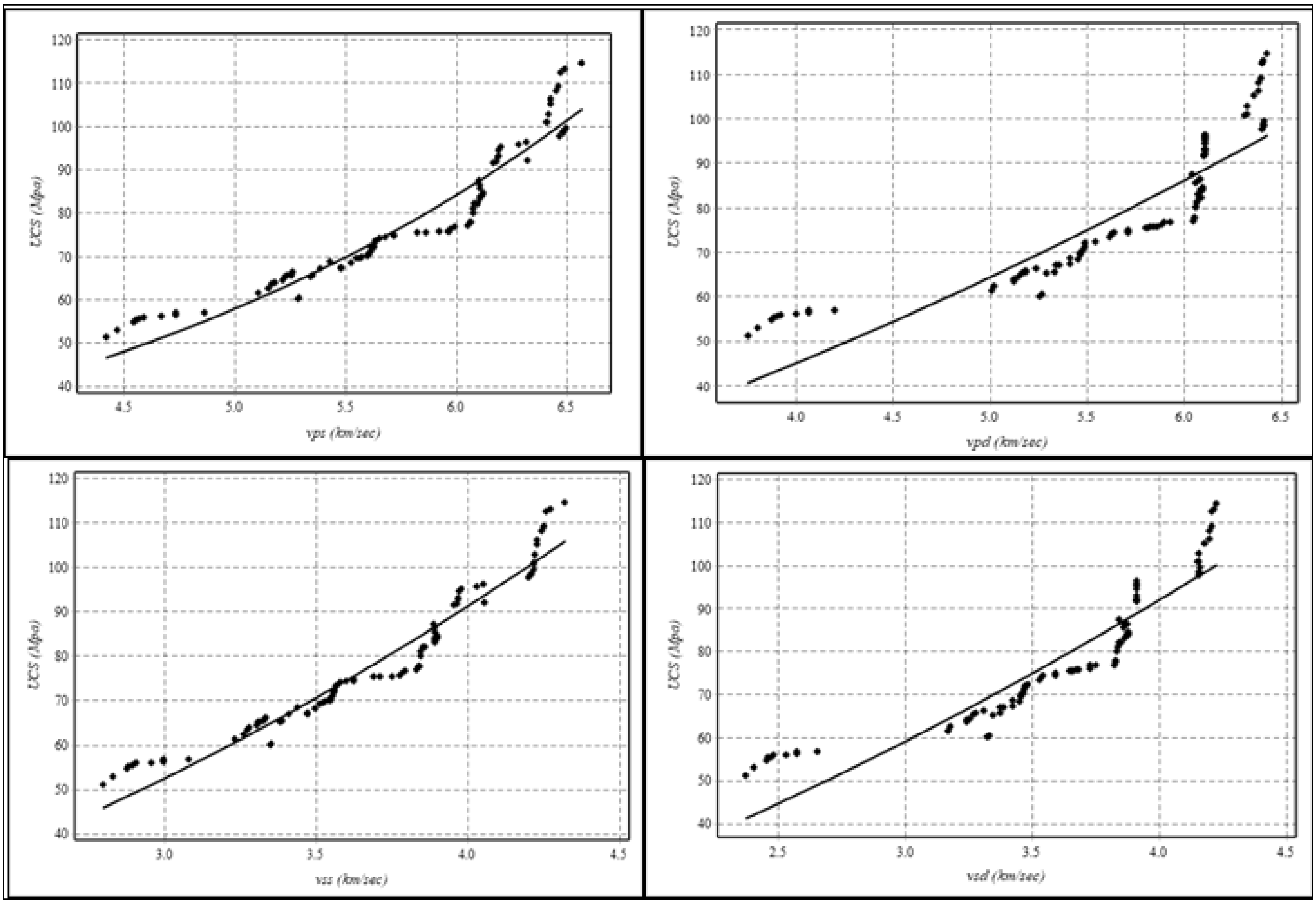

Fig 6: The Relationship between UCS with p and s wave velocity in dry and saturated situations

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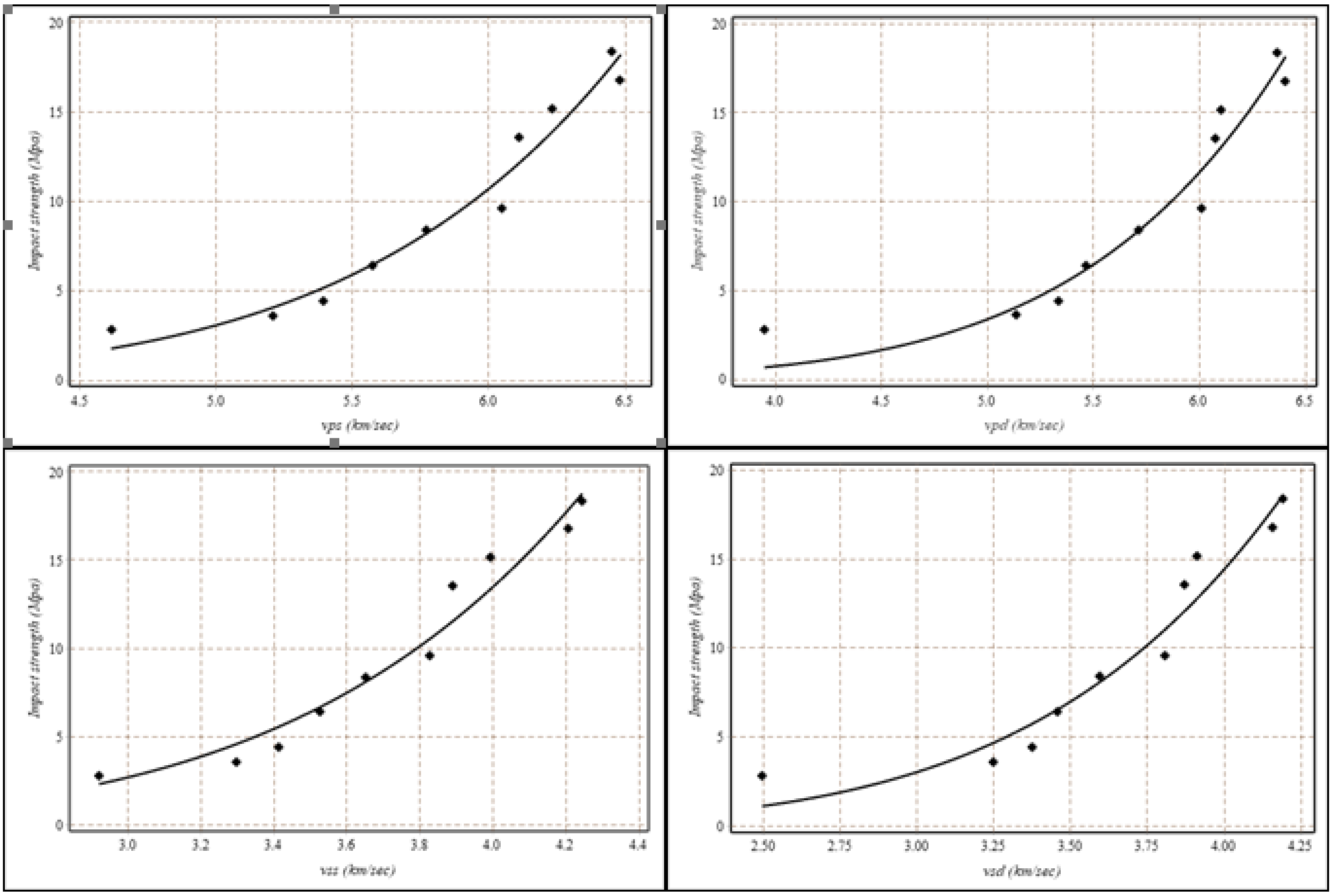

Fig 7: The Relationship Between Impact Strength with P and S Wave Velocity in Dry and Saturated Situations

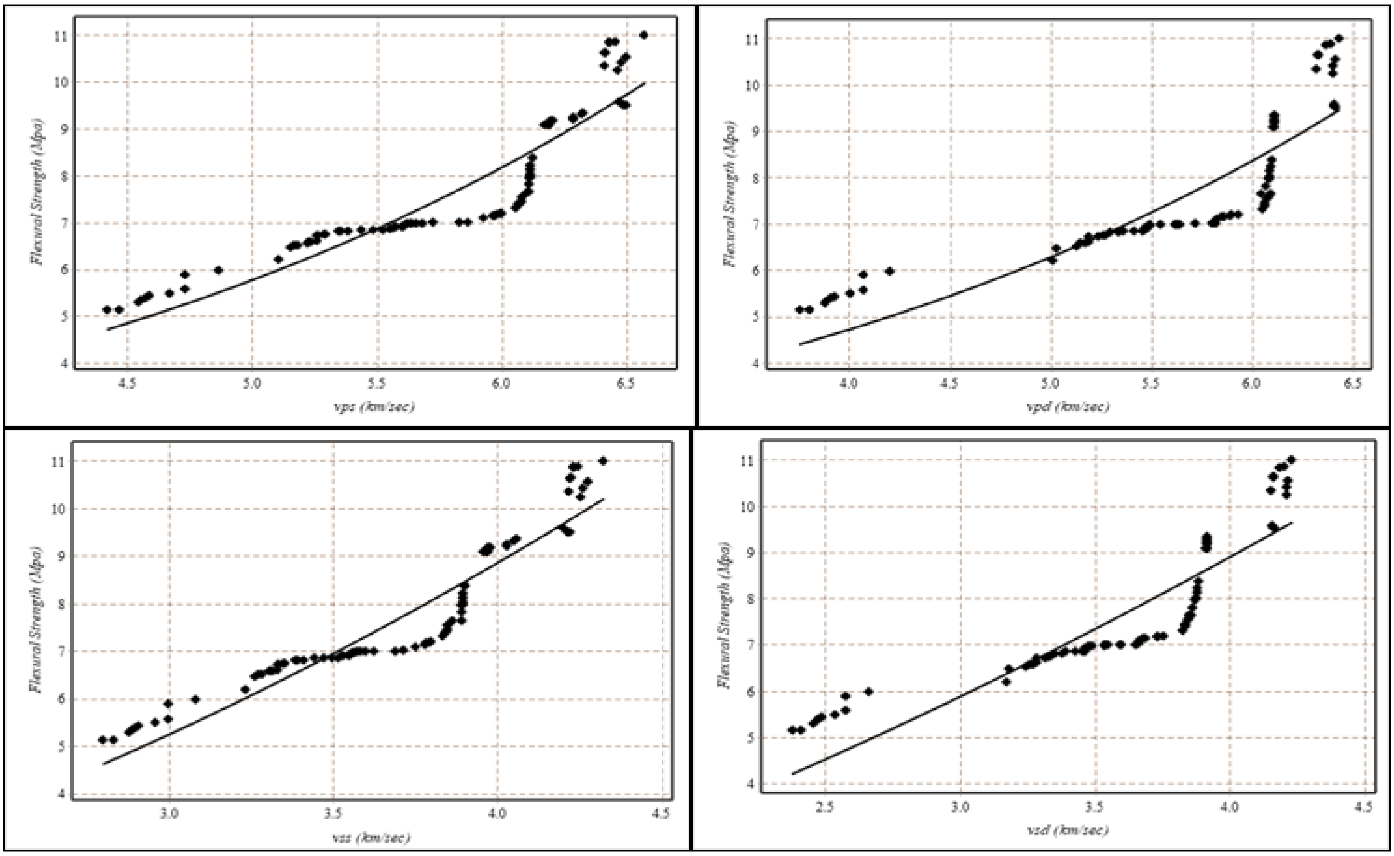

Fig 8: The Relationship Between Flexural Strength with P and S Wave Velocity in Dry and Saturated Situations

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IV. CONCLUSIONS

- After completing this research, the following results can be obtained:
- The marble of Hajialani has the highest resistance against uniaxial compressive, impact, and bending forces, and conversely, the marble of Diyarbakir has the lowest resistance against the mentioned forces.
- The speed of p and s waves is higher in saturated situations than in dry.
- The relationship between the mechanical properties of marbles with the velocity of p and s waves is direct.
- The model is power and exponential equations that have correlation coefficients greater than 80%. Therefore, by these equations, in the case of the existence of the velocity of p and s waves, it is possible to estimate compressive, bending, and impact resistance in marble.

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