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Research Article

Investigation of the Relationship Between Physical and Mechanical Properties of Marble by Regression Analysis

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About Article

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ABSTRACT

Determining the physical and mechanical properties of marble are very important in the design of construction and mining projects. In this study, ten marble samples collected from different parts of Turkey were tested in the laboratory for uniaxial compressive strength, flexural strength, density, water absorption, and porosity. Then, using different simple regression analysis models, the relationship between uniaxial compressive strength and flexural strength with density, water absorption, and porosity was investigated. As a result, equations with strong and very strong correlation coefficients with low standard errors have been obtained, such as R^2=0.81 for UCS-density, R^2=0.66 for UCS-water absorption, R^2=0.65 for UCS-porosity, R^2=0.70 for flexural strength and density, R^2=0.66 for flexural strength–water absorption and R^2=0.68 for flexural strength-porosity.

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1. INTRODUCTION

It is an undeniable fact that natural building stones have been an important material in human life from the past to the present. Natural decorative stones have been widely used throughout human history due to their attractiveness, strength, and beauty. In the past, it was used in the construction of buildings, historical monuments, caravanserais, and porches. Today, it is widely used in the restoration processes of historical monuments, floors, wall coverings, interior and exterior spaces of buildings, landscaping, pedestrian paths, and pavements (Fort *et al.*, 2013; Khandelwal & Ranjith, 2010).

Granite, marble, travertine, basalt, and andesite are natural stones that, after being extracted, are cut and polished to appropriate sizes in processing plants, which have commercial value. Among them, marble is the most well-known and widely used. Scientifically, marble is a metamorphic rock formed by the recrystallization of limestone and dolomite under the influence of heat and pressure. Its chemical composition is mainly composed of calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$), silicon dioxide (SiO_2), and various metal oxides and silicate minerals. When marble is made of pure calcium carbonate, it is white and transparent (Amin *et al.*, 2020; Cinar, 2007).

The physical and mechanical properties of marble are the main parameters that must be considered when selecting machinery and equipment during mining and processing. The physical and mechanical properties of marble, such as specific gravity, porosity, water absorption, color, polish ability, sealing, hardness, compressive strength, impact strength, bending strength, tensile strength, and point strength, have a tremendous impact on technical and economic factors such as the size and number of blocks, the number and thickness of slabs, the place of use, the price level, and demand (Luo *et al.*, 2020; Mohammadi *et al.*, 2024).

Usually, the physical and mechanical properties of stones are determined by destructive methods. This method has some disadvantages, including the high cost of equipment, its time-consuming, and the possibility of testing only in the laboratory (Rahmouni *et al.*, 2013). To solve the aforementioned problems, some researchers studied the relationship between physical and mechanical properties in different stones, in which case, one of the properties can be estimated based on the other properties. In order to estimate the abrasion resistance via porosity, water absorption, and compressive strength, the relationship between them has been studied. As a result, abrasion resistance has a strong relationship with physical properties and a moderate relationship with compressive strength (Adam Mohammed *et al.*, 2021). The relationship between petrographic properties and physical and mechanical properties of granite has been studied by simple regression analysis. It is worth noting that the relationship between the physical and mechanical properties of natural stones and the speed of ultrasound waves has also been studied by several researchers (Kahraman, 2002; Kahraman *et al.*, 2017; Kahraman & Yeken, 2008; Karakul & Ulusay, 2013; Khandelwal & Ranjith, 2010; Rahmouni *et al.*, 2013).

In this study, in order to estimate the uniaxial compressive strength and flexural strength through density, water absorption and porosity in marble, the relationship between them was investigated using simple regression analysis. For this purpose, ten marble samples from different regions of Turkey were collected in the Mining Department Laboratory of Cukurova University.

2. LITERATURE REVIEW

The results show that grain size and shape have a significant effect on engineering properties of granitic rocks such as porosity, water absorption, sound velocity, point, and compressive strength (Tuğrul & Zarif, 1999). The relationship between strength and specific gravity in carbonate and quartz rocks has been studied, and finally equations with high correlation coefficients have been obtained (Smorodinov *et al.*, 2000). The relationship between strength and physical properties in sedimentary rocks has been studied. In this study, 31 empirical equations are summarized that relate unconfined compressive strength and internal friction angle of sedimentary rocks (sandstone, shale, and limestone and dolomite) to physical properties (such as velocity, modulus, and porosity) (Chang *et al.*, 2006)

3. METHODOLOGY

3.1. Sample preparation steps

The materials of this research were collected from ten marble quarries located in different parts of Turkey. Table 1 describes the characteristics of the samples and the location of the areas from which they were sampled. The collected samples were cut into cubes of five centimeters in size according to the Turkish Standard Institute (TSE). To increase the reliability of the work, ten laboratory samples were prepared from each field sample. Figure 1 shows the prepared laboratory samples. The samples were tested for bulk density, water absorption, porosity, and uniaxial compressive strength.

Table 1. Sample specifications and areas from which the sample was taken.

NO	Rock type	Rock class	Location
1	Limestone	Metamorphic	Hajialani/Mersin
2	Grey marble	Metamorphic	Sivas
3	Limestone	Metamorphic	Silifke/ Mersin
4	Limestone	Metamorphic	Adiyaman
5	Black Marble	Metamorphic	Iskenderun
6	Grey marble	Metamorphic	Bilecik
7	Grey marble	Metamorphic	Karaman
8	Grey marble	Metamorphic	Konya
9	Grey marble	Metamorphic	Adana
10	Limestone	Metamorphic	Diyarbakir

Figure 1. Laboratory prepared samples

3.2. Density

With this test, the density of the rock sample is calculated. The necessary equipment for this test is: a digital scale with a sensitivity of 0.1 grams, a caliper, and an oven at a temperature of 105°C. After the test sample is dried in the oven, its mass is determined by weighing it on an accurate scale. Then the volume of the test sample is calculated. The density value is calculated according to (TS 699). Equation 1 is used to determine density.

$$\rho = W/V \quad (1)$$

Where,

ρ is density (gr/cm^3),
W is the mass (gr) and
V is the volume (cm^3).

3.3. Porosity

Porosity is one of the physical properties of rocks and expresses the volume of voids in the rock. When performing a porosity test, the weight of the sample in the dry and wet state is calculated respectively. For this purpose, the samples are placed in water for 48 hours, then their wet weight is calculated and the sample is dried in an oven at 105°C for 24 hours, and its dry weight is calculated (TS 699, 2009). Equation 2 is used to determine porosity.

$$n = (V_V / V)100 \quad (2)$$

Where,

n is the porosity (%),
Vv is the volume of voids (cm^3) which is determined by equation 3, and
V is the volume of simple (cm^3).

$$V_V = (W_w - W_d)/\rho_w \quad (3)$$

Where,

W_w is the wet weight (gr),
W_d is the dry weight (gr), and
ρ_w is the density of water (gr/cm^3).

3.4. Water absorption

This test is performed to determine how much water a rock can hold in its composition. When performing this test, the weight of the sample in the dry and wet state is calculated respectively. For this purpose, the samples are placed in water for 48 hours, then their wet weight is calculated and the sample is dried in an oven at 105°C for 24 hours, and its dry weight is calculated (TS 699, 2009). Equation 4 is used to determine water absorption.

$$c = ((W_w - W_d)/W_d)100 \quad (4)$$

Where,

c is the water absorption (%),
W_w is the wet weight (gr), and
W_d is the dry weight (gr).

3.5. Uniaxial Compressive Strength

Uniaxial compressive strength (UCS) is the maximum resistance of rock against a force that acts parallel to one of the axes. The (UCS) is done by a hydraulic device. In order to perform this test, it is necessary to cut the samples into cubes, rectangular cubes, and cylinders. According to the ASTM standard, the ratio of length and diameter of the cylinder is 2.5-2.5, and its minimum length is 47 millimeters. While this ratio in the ISRM standard is 2.5-3 and the minimum diameter of the cylinder is 54 mm (Teymen, 2005). In this study, the samples were prepared according to (TS 699, 2009) into cubes with dimensions of five centimeters, and the equipment used in the test consisted of a hydraulic machine, caliper, and oven (105±5°C). Equation 1 is used to obtain uniaxial compressive strength.

$$\sigma_c = p/S \quad (5)$$

Where,

σ_c is Uniaxial Compressive strength ($kgrf/cm^2$),
P is the force that causes the destruction of the sample (kgrf),
S is the surface area of the sample on which the force acts (cm^2).

3.6. Flexural Strength

Flexural strength is the maximum resistance of plates to the force that causes them to break. Usually, the building stones that are used as coverings and paving are in the form of plates, the thickness and dimensions of which depend on the flexural strength. Therefore, determining the flexural strength is of particular importance in the design of construction projects (Teymen, 2005). To perform this test, samples were prepared in the form of a prism with dimensions of 5x5x30 cm according to the standard (TS 12372). Figure 2 shows the flexural strength testing apparatus. Equation 1 is used to obtain Flexural strength.

$$\sigma_f = (3 \times P \times l)/(3 \times b \times h^2) \quad (6)$$

Where,

σ_f is Flexural strength (kg/cm^2),
P is the maximum load that causes the sample to break) kgrf),
l is the distance between the support points of the sample (cm),
b is the width of the sample (cm) and
h is the thickness of the sample (cm).

4. RESULTS AND DISCUSSION

4.1. Test Results

The samples have been tested in the laboratory in terms of physical properties such as density, water absorption, and porosity, and also in terms of mechanical properties such as uniaxial compressive strength and flexural strength. In order to increase the accuracy of the work, each sample was tested ten times and the average test results are given in Table 2. The changes in the test results of the physical and mechanical properties of the samples are shown comparatively in Figure 5.

Table 2. Average values of physical and mechanical properties of marble samples obtained as a result of testing.

No	ρ (gr/cm³)	c (%)	n (%)	σ_c (Mpa)	σ_f (Mpa)
1	2.71	0.124	0.217	106.42	10,55
2	2.68	0.26	0.68	97.65	9,44
3	2.69	0.55	1.66	92.98	9,32
4	2.673	0.65	1.74	83.94	8,15
5	2.73	0.15	0.46	77.79	7,51
6	2.66	0.34	0.65	73.61	7,14
7	2.65	0.47	0.89	71.21	6,99
8	2.62	0.52	0.92	66.14	6,88
9	2.61	0.65	0.96	65.41	6,46
10	2.55	2.45	3.51	56.11	5,38

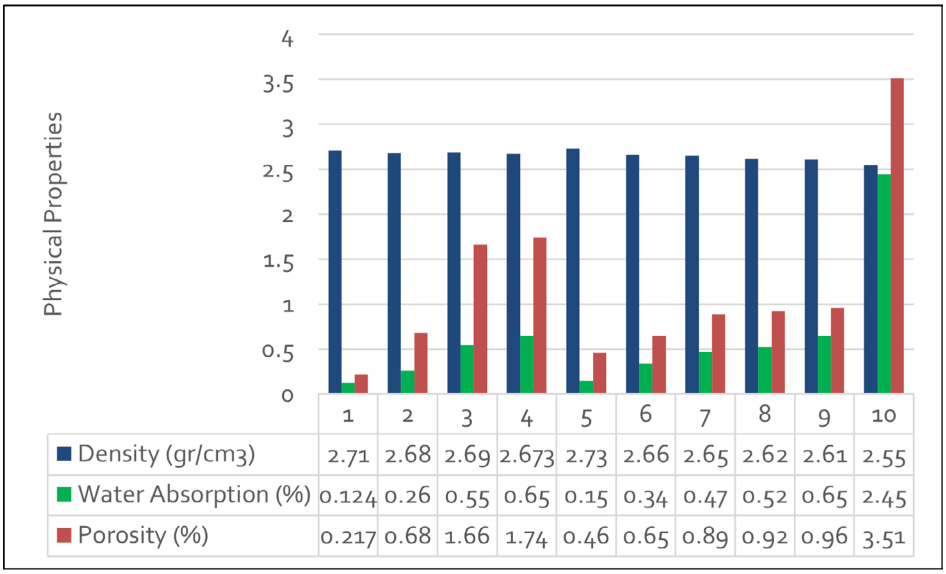

Figure 2. Variations in the values of physical properties of marble samples relative to each other

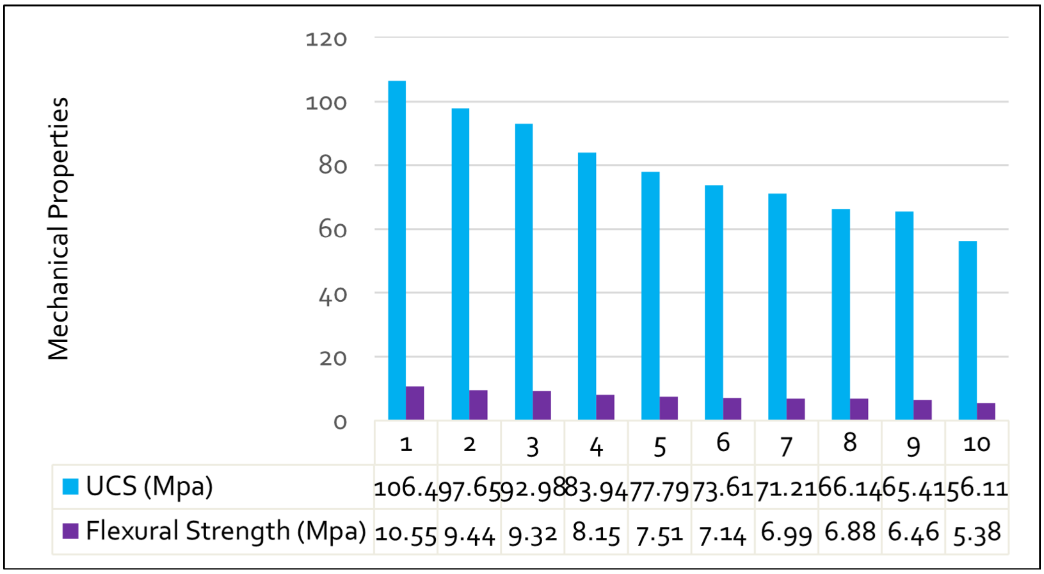

Figure 3. Variations in the values of mechanical properties of marble samples relative to each other

4.2. Investigating the relationship between physical and mechanical properties

In order to estimate the uniaxial compressive strength and flexural strength via density, water absorption, and Porosity, the relationship between them has been investigated by using various simple regression analysis models such as linear, logarithmic, power, and exponential. The mentioned models were compared with each other in terms of correlation coefficient (R^2) and standard error of estimation (SES). The model whose R^2 value is close to 1 and its SES value is close to 0 was selected as the appropriate model.

Table 3-5 show the results of the relationship between uniaxial compressive strength with density, water absorption, and porosity density are obtained by linear, logarithmic, power and exponential regressions.

Tables 3 and 5 show the results of the study of the relationship between uniaxial compressive strength and density and porosity, where the exponential model was selected as the appropriate model due to the high correlation coefficient and low standard error of estimation. Similarly, Table 4 shows the relationship between uniaxial compressive strength and the water absorption, where the Power model was selected as the appropriate model due to the high correlation coefficient and low standard error of estimation. Equations 6-7 are equations that estimate the uniaxial compressive strength by density, water absorption, and porosity.

$\sigma_b = 0.003 \cdot e^{3.8 \cdot \rho}$ (6)

$\sigma_b = 79.84 \cdot c^{0.216}$ (7)

$\sigma_b = 100 \cdot e^{3.8 \cdot n}$ (8)

Where,

σ_c is Uniaxial Compressive strength (Mpa),
e is Euler's number, which value is 2.718,
ρ is density (gr/cm^3),
c is water absorption (%) and
n is porosity (%).

Table 3. Results of investigating the relationship between uniaxial compressive strength and density by different simple regression models

No	Regression Models	Correlation Coefficient	Standard Error of Estimation
1	Linear	0.73	7.82
2	Logarithmic	0.72	7.91
3	Power	0.80	0.080
4	Exponential	0.81	0.078

Table 4. Results of investigating the relationship between uniaxial compressive strength and water absorption by different simple regression models

No	Regression Models	Correlation Coefficient	Standard Error Of Estimation
1	Linear	0.55	10.15
2	Logarithmic	0.65	8.96
3	Power	0.66	0.114
4	Exponential	0.61	0.120

Table 5. Results of investigating the relationship between uniaxial compressive strength and porosity by different simple regression models

No	Regression Models	Correlation Coefficient	Standard Error of Estimation
1	Linear	0.61	9.41
2	Logarithmic	0.66	8.82
3	Power	0.63	0.117
4	Exponential	0.65	0.114

Table 6-8 show the results of the relationship between flexural strength with density, water absorption, and porosity density are obtained by linear, logarithmic, power, and exponential regressions.

Tables 6 show the results of the study of the relationship between flexural strength and density, where the exponential model was selected as the appropriate model due to the high correlation coefficient and low standard error of estimation. Similarly, Tables 7 and 8 show the relationship between flexural strength with water absorption and porosity, where the Power model was selected as the appropriate model due to the high correlation coefficient and low standard error of estimation. Equations 6-7 are equations that estimate the uniaxial compressive strength by density, water absorption, and porosity. Equations 8-10 are equations that estimate the flexural strength by density, water absorption, and porosity.

$\sigma_f = 0.001 \cdot e3.5 \cdot \rho$ (6)

$\sigma_f = 6.3 \cdot c{-}0.238$ (7)

$\sigma_f = 7.84 \cdot c{-}0.22$ (8)

Where,

σ_f is flexural strength (Mpa),
e is Euler's number, which value is 2.718,
ρ is density (gr/cm^3),
c is water absorption (%) and
n is porosity (%).

Table 6. Results of investigating the relationship between flexural strength and density by different simple regression models

No	Regression Models	Correlation Coefficient	Standard Error Of Estimation
1	Linear	0.623	0.929
2	Logarithmic	0.619	0.934
3	Power	0.701	0.105
4	Exponential	0.704	0.104

Table 7. Results of investigating the relationship between flexural strength and water absorption by different simple regression models

No	Regression Models	Correlation Coefficient	Standard Error Of Estimation
1	Linear	0.51	1.055
2	Logarithmic	0.65	0.88
3	Power	0.66	0.111
4	Exponential	0.58	0.124

Table 8. Results of investigating the relationship between flexural strength and porosity by different simple regression models

No	Regression Models	Correlation Coefficient	Standard Error Of Estimation
1	Linear	0.594	0.964
2	Logarithmic	0.707	0.0.818
3	Power	0.68	0.108
4	Exponential	0.645	0.114

4.3. Discussion

The research findings show that there is a direct relationship between uniaxial compressive strength and flexural strength with density, meaning that the more molecules in a rock, the higher its density and strength (Figure4). While The relationship between uniaxial and flexural compressive strength with porosity and water absorption is inverse, indicating that the more empty spaces there are between the rocks, reduces the strength of attraction between the rock molecules and as a result, it will have less resistance to compressive and flexural loads (Figure 5).

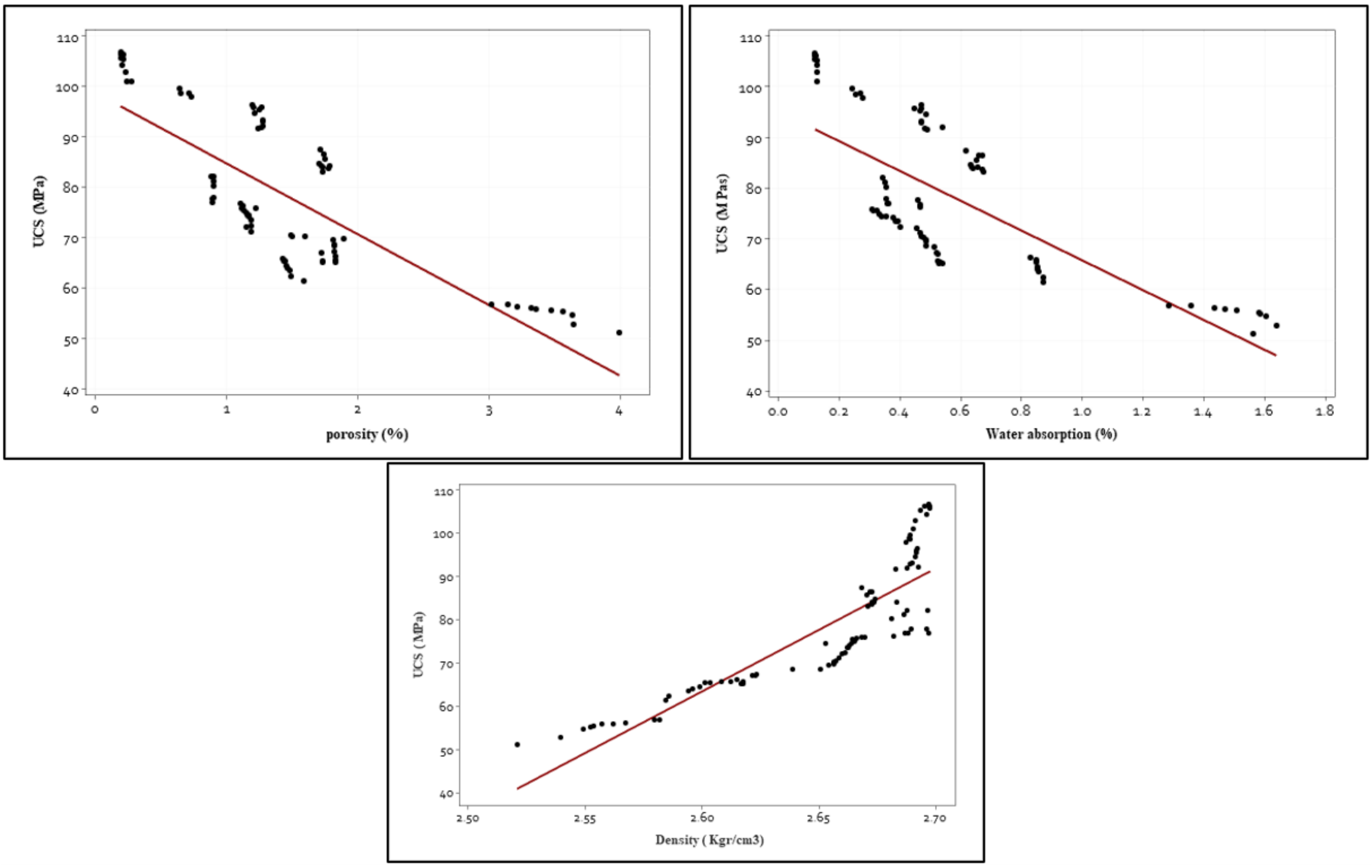

Figure 4. The Relationship between UCS and physical properties of Marbles

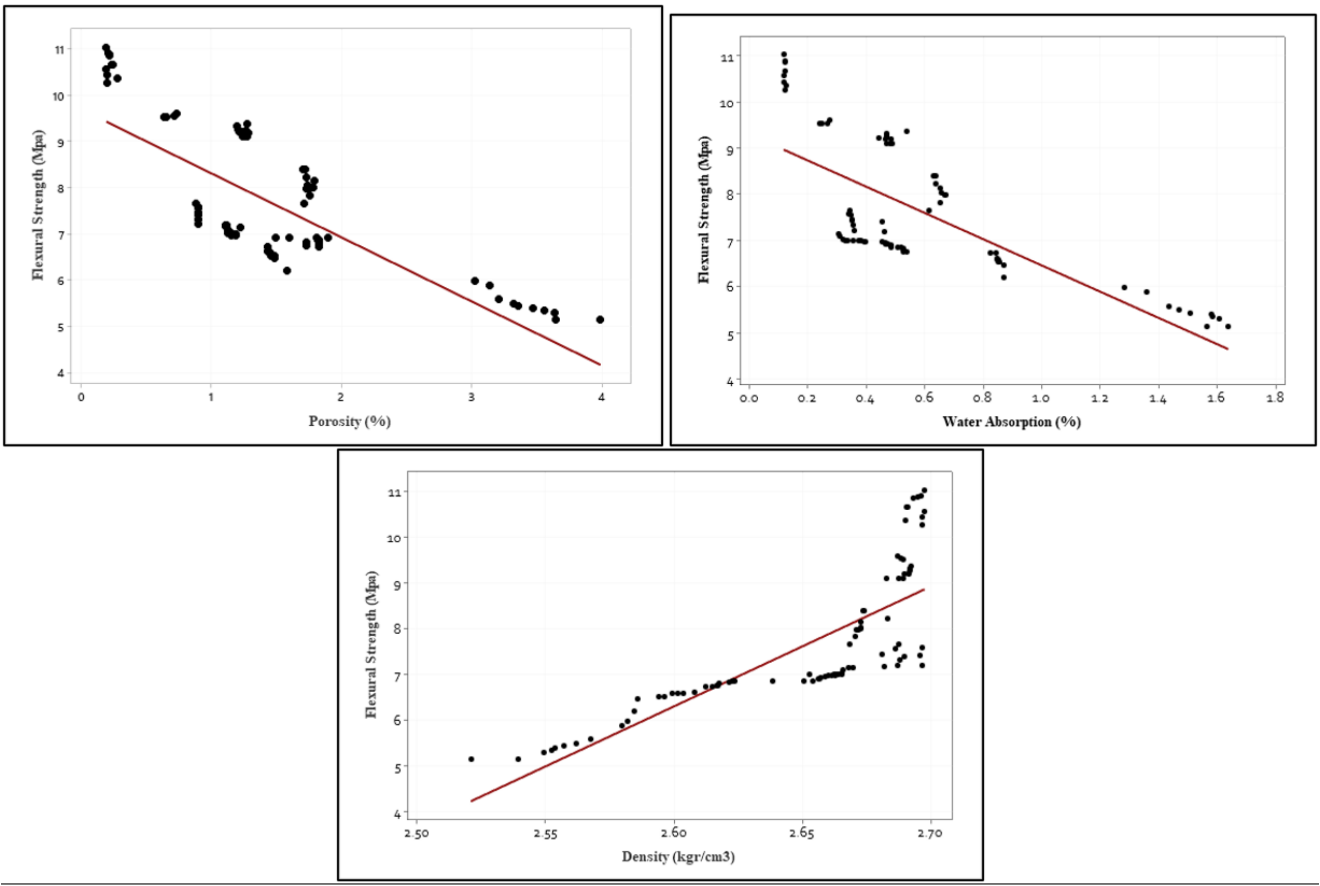

Figure 5. The Relationship between flexural strength and physical properties of marbles

As previously mentioned, in this study, the physical and mechanical properties of marble samples were determined in the laboratory according to the Turkish Standards Institute (TS 699, TS 1097-6, TS 13755, TS 6809, TS 1926, TS 13672 and TS 12372). Tables 9 and 10 show the limits of the required physical and mechanical properties of marble used as decorative material, paving stone, and building material according to TS-1467 and TS-1469 standards(Ozedmir, 2017). From Table 2, it is clear that, except for From Table 2, it is clear that except for Diyarbekir marble, the physical and mechanical properties of other samples are higher than the standard values.

Table 9. Comparison of physical and mechanical properties of marble samples with standard values (Ozedmir, 2017)

Physical Properties	Limit Value	Current Research	Mechanical Properties	Limit Value	Current Research
Density (gr/cm3)	>2.55	>2.55	Uniaxial Compressive Strength (Mpa)	>49	56.11
Water Absorption (%)	<1.80	<0.65	Flexural Strength (Mpa)	>4.9	5.38
Porosity (%)	<2	<1.74			

Table 10 shows the strength values of the correlation coefficient and its type. The strength of correlation coefficients between uniaxial compressive strength and flexural strength with density, water absorption, and porosity has been investigated according to Table 10 and the results are listed in Tables 11 and 12. As can be seen, the relationship between mechanical properties and physical properties has strong correlation coefficients.

Table 10. Categories of correlation coefficients between two variables and their type

Correlation Coefficient (R^2)	Correlation strength	Correlations type
0	Non	Positive
0 – 0.3	Weak	Positive
0.3-0.5	Moderate	Positive
0.5-0.7	Strong	Positive
0.7-1	Very strong	Positive

Table 11. Degree of correlation between uniaxial compressive strength and physical properties (Bhandari, 2023)

Physical properties	Correlation Coefficient (R^2)	Correlations type
Density	0.81	Very strong
Water absorption	0.66	Strong
Porosity	0.65	Strong

Table 12. Degree of correlation between uniaxial compressive strength and physical properties (Bhandari, 2023)

Physical properties	Correlation Coefficient (R^2)	Correlations type
Density	0.70	Very strong
Water absorption	0.66	Strong
Porosity	0.68	Strong

5. CONCLUSION

The results of this research can be summarized as follows.

- All marble samples tested in this study, except of Diyarbakir marble, are of excellent quality.
- Uniaxial compressive strength and flexural strength are strongly related to density, water absorption, and porosity such as R^2=0.81 for UCS-density, R^2=0.66 for UCS-water absorption, R^2=0.65 for UCS-porosity, R^2=0.70 for flexural strength and density, R^2=0.66 for flexural strength–water absorption and R^2=0.68 for flexural strength-porosity.
- Because the equations obtained have strong and very strong correlation coefficients and also have low standard error of estimation, they can be used to estimate uniaxial compressive strength and flexural strength.

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