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ORIGINAL PAPER

EVALUATION OF THE RELATIONSHIP BETWEEN CAPILLARY WATER ABSORPTION AND PHYSICAL-MECHANICAL PROPERTIES OF SOME SEDIMENTARY ROCKS

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ABSTRACT

Water is an important natural factor affecting the mechanical and physical properties of rock. One of the most important mechanisms that allows water to enter the pores between the grains of the rock is the water absorption potential of the rock. In this study, the relationship between capillary water absorption potential and mechanical and physical properties of limestone, clayey limestone, sandstone, marl and mudstone rock units in an open pit coal mine was evaluated by simple and multiple regression analyses. For this purpose, water absorption, unit volume weight, point loading, uniaxial compressive strength and ultrasonic velocity tests, chemical and petrographic analyses were performed. Capillary water absorption tests were performed at 11 different time intervals between 5 and 7200 minutes. According to the test results, it was determined that the capillary water absorption potential of all rock units significantly affected the physical and mechanical properties of the rock. It was determined that clayey limestone has high, marl has low and other rocks have moderate capillary water absorption values. In simple and multiple regression analyses, it was determined that the most effective parameters in capillary water absorption values were porosity, water absorption by weight, dry density and P wave velocity.

INTRODUCTION

Physical and mechanical properties of rocks underlie the design phase of engineering structures. Rocks continuously expose to different climate conditions and this a fact that cannot be prevented. During the design phase of engineering structures, the rock exposes to climatic and atmospheric conditions and it is necessary to determine how the rock will be affected as a result of these events, and this situation is needed to be evaluated in the design phase. Especially water takes part among the most important parameters that negatively affect the rock. Water accelerates the deterioration of rocks independently or coherently with other environmental factors and negatively affects the physical and mechanical properties of rock.

Capillary absorption is one of the most important factors in evaluating the ingress of water into the rock structure (Peruzzi et al., 2003). The water that penetrates the rock structure by capillary water absorption causes a reduction in the strength, abrasion and freezing resistance of the rock. The rate and amount of capillary water absorption and its retention in pores have an important impact on strength. If capillary water absorption and porosity are high, the negative effect of water on the rock increases. Ice crystallization occurs if the capillary absorbed water is kept under the temperature of 0 °C for a longer time. Strength decreases significantly by means of growing ice crystals and increasing ice volume (Tomašić et al., 2011).

Sedimentary rocks cover broad areas on the earth's surface. Because they are close to the surface, they are more affected by climatic conditions. While surface flow is not important in the rock mass exposed to water for underground drift walls, it is more of an issue in open-pit mining benches. Water penetrates rock at different ratios depending on porosity, time, rock type, clay content and pH value of water (Özdemir et al., 2019; Çelik and Köken, 2023). The activity of water in the rock has to be well known to determine the deterioration status of rock by the effect of water. Water absorption potentials of rock show variability depending on the water movement mechanism in the rock. A porous rock contact with water absorbs water by the effect of capillarity. Rocks show the tendency to take water into their structure when they come into contact with water. This situation depends on the capillary absorption strength that controlled by the pores in the rock. This is a situation that naturally occurs without exposing any external pressure or force. Capillary water absorption mechanism depends on the size of pores that forms the rock and their connection with each other (Cueto et al., 2009; Vázquez et al., 2010).

Capillary water absorption studies generally focus on concrete and natural building stones (Angeli et al., 2006; Çobanoğlu, 2015; Özvan et al., 2015; Sengün et al., 2015; Çelik and Kaçmaz, 2016; Bao and Wang, 2017; Dinçer and Bostancı, 2019; Ünal and Altunok, 2019; Benavente et al., 2020; Çelik and Sert, 2021; İnce, 2021; İnce et al., 2021; Zhang et al., 2022;

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Çelik and Güven, 2024). There are very few studies on the capillary water absorption potential of the rock in engineering structures built in sedimentary rocks. The studies mainly focus on the effect of moisture or potential water absorption (Singh et al., 1999; Kramadibrata et al., 2000; Vasarhelyi, 2003; Sachpazis, 2004; Vasarhelyi and Ván 2006; Duda and Renner, 2013; Wong et al., 2016; Zhou et al., 2016; Rabat et al., 2020; Yasar, 2020; Liu et al., 2021). However, by knowing the capillary water absorption potential of rocks, the movement of water within the rock during the time the rock will be exposed to water will be determined. Engineering structures are built both below and above underground water levels. In structures below the groundwater level, rock masses are generally exposed to water for a long time, while the structures above them may have less contact with water. Particularly, the water carried into pores and capillary cracks may leak from the ground in the rock environments where tunnel work is performed. In other words, water leakage into the structure can be seen from any part of the structure. This situation manifests itself as a complete flow of water or small leaks. However, water negatively affects the structure in both situations. Water that penetrates into the structure as leakage originates from the water moving in pores and capillary cracks located in the rock structure (Khodabandeh and Rozgonyi-Boissinot, 2022; Zhang et al., 2022). The movement of water in this manner depends on the capillary water absorption potential of rocks. Therefore, it is important to know the capillary water absorption potential of rocks in terms of prevention of water that may penetrate into the structure.

Rock units in open-pit mines deteriorate over time under the influence of natural conditions. The most important factor in this deterioration is water. Water settles between the pores of the rock, saturating the rock, and over time, the capillary cracks and pores grow, causing larger cracks to form and ultimately, the mass to become unstable. Water enters the rock structure under the influence of underground water and surface water. Capillary cracks and pores absorb water by absorption or capillary means. Especially water absorbed by the capillary method causes further deterioration of the rock.

Also, constantly standing or flowing of water within the rock structure cause differences from the point of affecting the rock mass. Because of the water trapped in the structure will be under pressure and load constantly, it will cause expansion of existing pores and cracks. However, the water that freely flows through cracks will exhibit this effect less (Huang et al., 2023; Sun et al., 2023). It is important to transfer the water without keeping in the structure. Otherwise, the effect of dominating water will be unfavorable.

Different researchers investigated the effects of different parameters (water content, wave velocity, density, etc.) on capillary water absorption values in igneous, sedimentary, metamorphic and pyroclastic rocks using regression analyses (Benavente et al., 2007; Benavente et al., 2015; Çobanoğlu, 2015; Ünal and Altınok, 2019; İnce, 2021; İnce et al., 2021). In this study, the effects of parameters (porosity, water absorption, density, P-wave velocity, strength and point load index) on capillary water absorption values in 5 sedimentary rocks were evaluated using simple and multiple regression analyses. There are many more sedimentary rocks in geological structures. The results obtained can be further improved with further studies.

This study was carried out in the field of a private coal mine located near Altıntaş district of Kütahya province in Türkiye. The study was conducted on rock units limestone (L), clayey limestone (CL), sandstone (S), marl (M) and mudstone (MS) which are constitutive of the host rock of coal. Capillary water absorption potentials of these rock units and the effect of physical and mechanical properties in these potentials were investigated. For this purpose, capillary water absorption, water absorption, unit weight, point load, uniaxial compressive strength and ultrasonic pulse velocity tests and chemical and petrographical analyses were carried out. The obtained results were interpreted and evaluated with simple and multiple regression analyses.

MATERIALS

The study area was located near Altıntaş district of Kütahya province in Türkiye (Fig. 1). The study area is geologically within the Yeniköy Formation. The Yeniköy formation, which comes unconformably with lateral and vertical transitions in the study area, consists of gravel-sand sized components derived from ophiolitic rocks at the base and yellow sandstone, fine-grained clastics and carbonate levels towards the top. Coal levels are observed within the unit. Middle Miocene aged Karacahisar volcanics, consisting of rhyolite, trachyte, dacite, andesitic pyroclastic, agglomerates and trachyandesites, are laterally transitional with the Neogene formations in the region. Alluvium and slope debris cover all units incompatibly (Fig. 2) (Aydoğan, 2006). The geological complexity of the study area is largely due to the fact that the region is located at the northeastern end of the Menderes Massif on the border of the Torids and Anatolides (Ketin, 1960). Units belonging to Palaeozoic, Mesozoic and Cenozoic periods are exposed in Kütahya and its surroundings located in Central Western Anatolia. The basement rocks are metamorphic units consisting of schist and marble and ophiolitic rocks located tectonically on top of them. Above these, there is a discordant, lake and river environment reflecting the lake and river environment, volcanics, clastic and carbonate thick cover stack (Özburan, 2009). In the study area, a complex series consisting of various rock types of Palaeozoic and Mesozoic age and units consisting of conglomerate-clay-marn-siltstone-sandstone-tuff and silicified limestone and clayey limestones containing coal of Cenozoic age were observed.

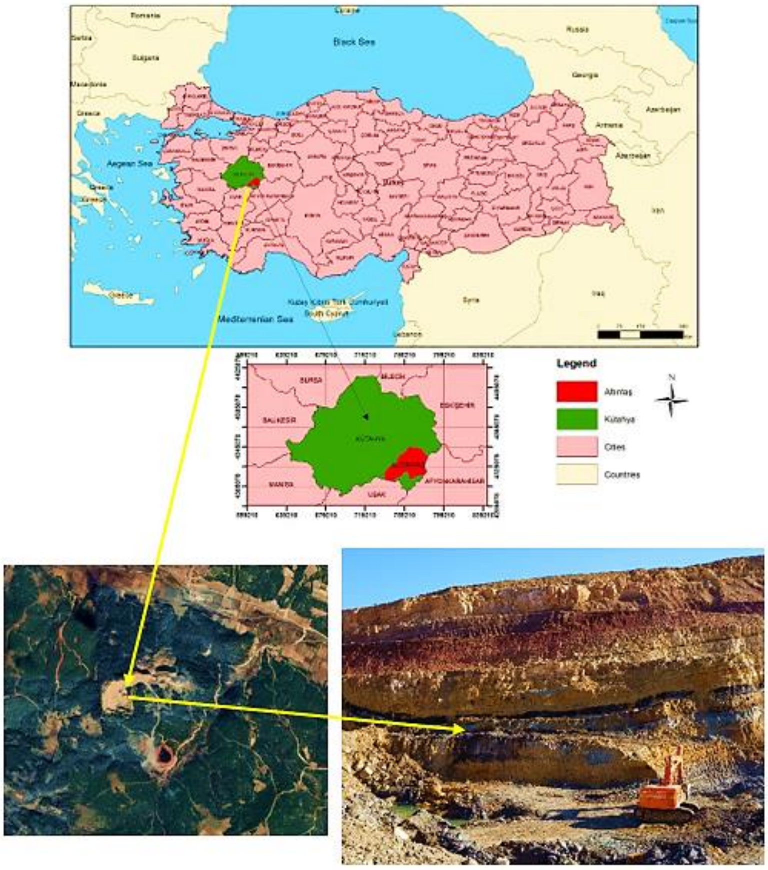


Fig. 1 Location map of the study area and general view of the open-pit mine.

The samples used in the study were obtained from 5 core drillings bored in various parts of the open-pit mine (Fig. 3). Figure 3 shows the clastic and cylindrical samples in the drilling core boxes. M, L and S samples were shown for identificaion in Figure 3. The samples were examined meticulously and care was taken to ensure that there were no structural defects such as fractures, cracks, etc., and they were transported to the laboratory under appropriate conditions. In accordance with the purpose of the study, the samples were cut to appropriate sizes for each experimental study.

METHODS

X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF) analysis and petrographic analyses of rock thin section analyses were performed to determine the chemical, textural and petrographic properties of the materials.

The chemical composition of the samples was determined by XRF. XRF analyses were performed using a representative sample for each rock type. At least 0.9-12 g of solid sample was ground for each sample in the laboratory and XRF tests were performed. The results are given in Table 1 and Results section.

Mineral compositions were determined by performing XRD images with at least 100 mg of ground sample at $2\theta = 0° – 70°$, 2°/min scanning speed. The results are given in Results section and in Figure 6.

Petrographic analysis of rock thin sections was performed for petrographic description and determination of the main and secondary minerals that make up the rock and the rock structure. Nomenclature of Folk (1962) and Folk (1974) have been followed for the petrographic description and determination of limestones and sandstones. The samples were saw cut to approximately 20 x 30 x 8.0 mm and prepared for thin section (petrographic) analysis. The results are given in Results section and in Table 2. Laboratory experiments for physical and mechanical properties were carried out in accordance with ISRM (2007) suggested methods, TS 699 (2009) and TS EN 1925 (2000) standards to determine the physical and mechanical properties of the samples. In the tests, unit weight (γ_d), apparent porosity (n), water absorption by weight (W_a), P-wave velocity (Vp), point load strength (I_c), uniaxial compressive strength (σ_b), $CaCO_3$ content and capillary water absorption coefficient (C) of intact rock samples were determined (Fig. 4). The methods followed in experimental studies are given

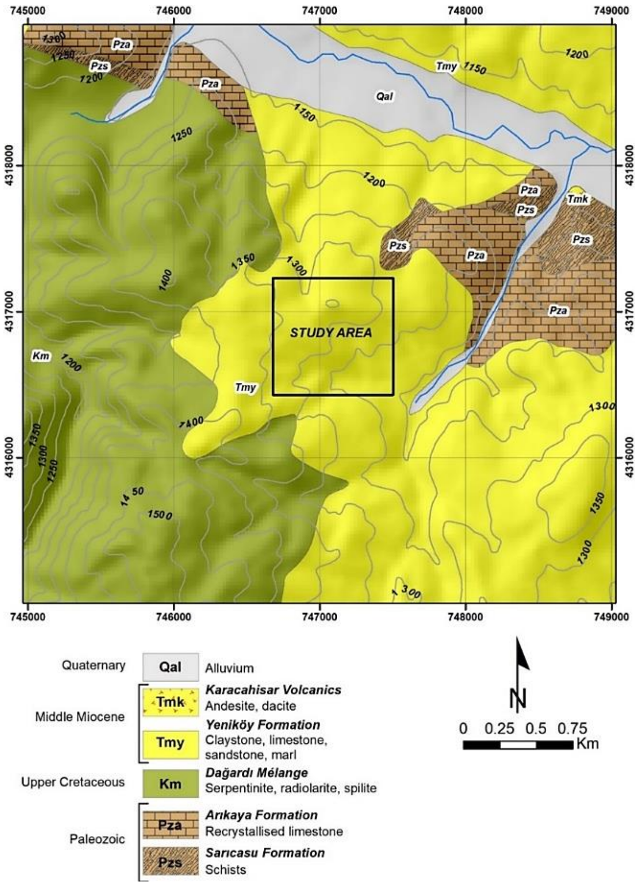


Fig. 2 Geological map of the study area.

Fig. 3 General view of the cores obtained from core drilling in the study area.

below. Cores were obtained from drilling boxes for each test.

Uniaxial compressive strength tests were carried out under dry conditions on samples with an L/D (length/diameter) ratio of 2.5-3. Samples diameters were 47.6 mm (NQ). The core bits were trimmed with cutting devices and made ready for the experiment. A servo-controlled hydraulic press with a capacity of 100 tons was used in the experiment. The suggested method by ISRM (2007) was followed when applying axial loading of 0.5-1.0 MPa/s during the experiments. (Fig. 4a).

An ultrasonic pulse velocity tester was used to determine the sound velocity of rock samples. Devices operating at 54 kHz for the P wave was operated. The suggested method test by ISRM (2007) was applied to dry samples. In the experiment, 47.6 mm (NQ) diameter samples with a L/D ratio of 2.5-3 were used. (Fig. 4d).

Unit weight values were determined using the caliper method. The suggested method by ISRM (2007) for the test was applied to dry samples with 47mm diameter (NQ).

Fig. 4 a) uniaxial compressive strength test, b) Bernard calcimeter, c) point load strength test, d) pundit lab ultrasonic pulse velocity test.

The point load strength index test was applied in two directions, diametrically and axially. The experiment for samples with 47 mm diameter (NQ) was carried out under dry conditions by suggested method ISRM (2007) (Fig. 4c).

The water absorption test was carried out in accordance with the standard (TS EN 1925 (2000)) by keeping the samples (NQ diameter) in water for at least 48 hours until they reached a constant mass.

$CaCO_3$ can produce chemical reactions in engineering structures in different liquid conditions (especially acidic). As a result of the reactions, voids may form in the regions with $CaCO_3$ and the water absorption coefficient may change. Therefore, Bernard Calcimeter was used to determine $CaCO_3$ content in the experiment, the samples ground to 63μm size were used. In the experiment, $CaCO_3$ content was determined with 25 % pure HCl solution (Fig. 4b). It should be noted that this device is not automatic, sensorised and calibrated like the XRF instrument and may give inaccurate $CaCO_3$ results.

CAPILLARITY TEST

The capillary water absorption capacity of a porous rock is defined by its water absorption coefficient (C value). This is a process driven by capillary forces arising from micropores and capillary pores. Rocks with a high amount of capillary pores are expected to have a high C value. This means that they have the capacity to rapidly absorb water through capillary absorption in the pore spaces. The C value of rocks with low capillary water absorption is <0.5 $kg/m^2.h^{0.5}$, the C value range of rocks with medium capillary water absorption is 0.5 $kg/m^2.h^{0.5}$–3.0 $kg/m^2.h^{0.5}$ and the C values of rocks with high capillary water absorption capacity is >3.0 $kg/m^2.h^{0.5}$ (Snethlage, 2005). The C value indicates sufficient water uptake in the pore spaces to keep the rock moist for long periods of time and mobilize existing salts. The importance of this parameter cannot be underestimated, because a strong sorption capacity means that a high amount of pollutant uptake and distribution in the pore spaces simultaneously occur.

One of the important parameters in water absorption is the anisotropy of rocks. Determination of anisotropy in terms of water absorption is applied by proportioning ultrasonic sound velocity tests taken from different directions. The rocks with low anisotropy ratio give more stable results in engineering structures. These rocks generally have lower water absorption values. For this reason, determination of anisotropy of rocks is extremely important and recommended (Fort et al., 2011; Fořt, 2015; Freire et al., 2015). Anisotropy measurements in different directions were not performed in this study.

Capillary water absorption experiments were carried out on core samples with a length/diameter ratio greater than 2. The base of the cylindrical rock samples prepared for this experiment was immersed in water to a depth of 3.0±1 mm. The water level was constantly checked to ensure that the level did not change depending on the ambient temperature. However, the length of some stages of the experiment required adding water to the test container. The capillary water absorption tests were conducted according to TS EN 1925 (2000) standards.

Different time intervals were used when measuring capillarity. Time intervals were chosen as 5, 15, 30, 60, 180, 480, 1440, 2880, 4320, and 7200 minutes for all rock units (Fig. 5). At 1 minute, since the samples did not absorb water, the results were started to be taken at 5 minutes. For this reason, the 5th minute was determined as the first test minute. In capillary water absorption experiments, time intervals of 4320 and 7200 minutes were added, unlike other studies. Thus, it was evaluated in the long-term situation. At each time interval, the samples were weighed with an accuracy of 0.01 g and the amount of water they absorbed was determined. In the last stage of the capillarity test, the amount of water absorbed by the sample (kg) was determined by its ratio to the area of the bottom surface (m^2) and the square root time (h) value. Capillary water absorption was calculated with Equation 1. $kg/m^2h^{0.5}$ is used for classification (low, medium and high) in capillary water absorption tests (Graue et al., 2011).

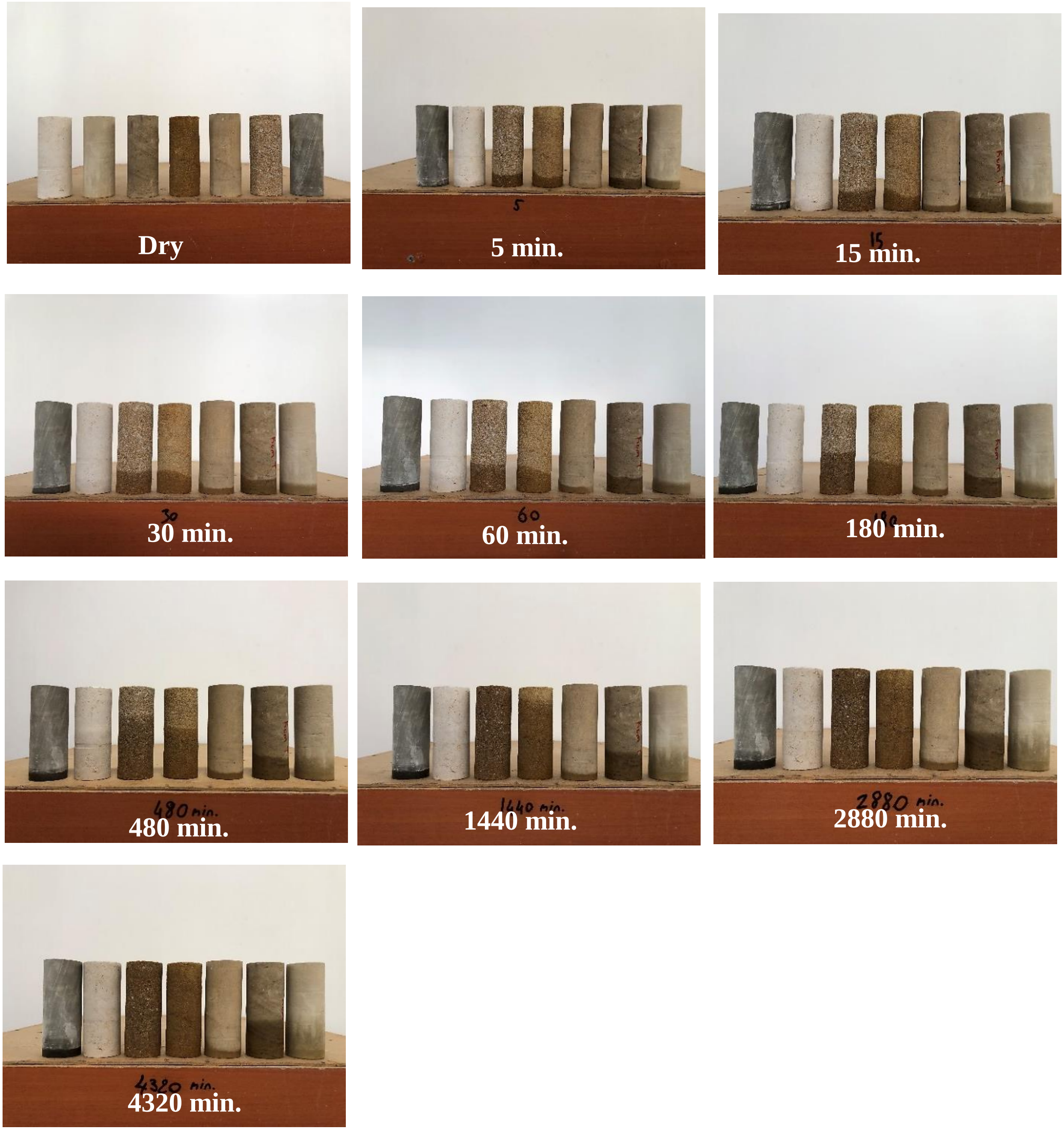


Fig. 5 Capillary water absorption status of samples according to time intervals.

$$C = \frac{m_i - m_d}{A\sqrt{t_i}} \tag{1}$$

where; C is the capillary water absorption coefficient ($kg/m^2h^{0.5}$), m_d is the dry mass before the experiment (kg), m_i is the saturated mass after the experiment (kg), A is the base area of the sample (m^2), t_i is the time (h).

SIMPLE REGRESSION (SR) AND MULTIPLE LINEAR REGRESSION (MLR) ANALYSES

Simple and multiple linear regression analyses were used to determine the parameters affecting the capillary water absorption values. For this purpose, equations with significance values (p) below 0.05 were generated. It is stated that the high F value indicates the success of the equation obtained (Ince et al., 2021). The values of p and F obtained were given for MLR equations in Table 6. The dependent variable parameter was capillary water absorption (C) values and the independent variable parameters were values of porosity (n), density (γ_d), water absorption by weight (W_a), P wave velocity (V_p) uniaxial compressive strength (σ_b), point load strength (I_c) and $CaCO_3$ percentage. The equations were generally linear, exponential, logarithmic and polynomial equations.

Table 1 Chemical composition of the five types of stone expressed in percent.

Rock Type	CL	L	M	S	MS
CaO (%)	39.10	53.85	33.10	14.05	2.75
SiO_2 (%)	22.85	1.56	19.05	54.68	47.17
Al_2O_3 (%)	6.12	0.57	8.85	12.21	13. 80
Fe_2O_3 (%)	2.98	0.78	4.13	3.73	11.09
MgO (%)	0.78	0.32	0.95	1.74	11.65
K_2O (%)	0.77	0.09	1.46	1.86	2.13
TiO_2 (%)	0.47	0.05	0.51	0.58	0.88
Na_2O (%)	0.10	-	0.21	0.36	0.55
SO_3 (%)	0.07	0.04	0.37	0.03	0.22
P_2O_5 (%)	0.06	0.04	0.06	0.08	0.12
MnO (%)	0.05	0.04	0,10	0.07	0.21
LOI (%)	26.47	42.60	31.15	10.60	9.02
Total (%)	99.82	99.94	99.94	99.99	99.59

LOI: Loss on ignition

RESULTS

According to the XRF analysis results (Table 1) of five types of samples, the major oxides percentage for limestone, clayey limestone, marl and sandstone are CaO, SiO_2 and Al_2O_3, while major oxides percentage in percentage for mudstone are SiO_2, Al_2O_3, Fe_2O_3 and MgO. In terms of LOI percentages, the lowest values were for S and MS, whereas the highest percentage values were for L and M.

As a result of petrographic analyses of rock thin sections, petrographic descriptions and determinations were made for each rock sample and given in the sections inside Table 2.

According to XRD graphs, calcite, kaolinite, muscovite and quartz minerals for clayey limestone, sandstone and marl (CL, S and M), calcite and quartz minerals for limestone (L), calcite, clinochlore, muscovite and quartz minerals for mudstone (MS) peaked in rock materials XRD shots (Fig. 6).

The average curves obtained according to the capillary water absorption test results for the rock samples examined within the scope of the study are given in Figure 7. Additionally, the results of the physical and mechanical properties of the rock units are given in Table 3. The C values in Table 3 were obtained for each sample from slope of lines in Figure 7, which corresponds the capillary water absorption per unit area versus the square root of time.

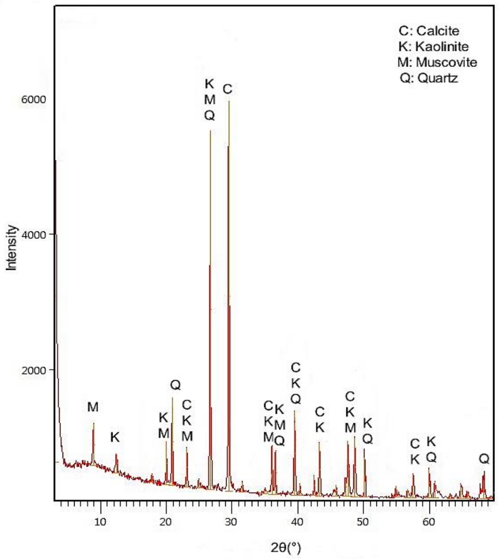
The change of the obtained capillary water absorption coefficient values over time is presented in Table 4. In Table 5, the results and their classifications on the basis of rocks are given according to the classifications determined by Graue et al. (2011).

The relationship between physical and mechanical properties of rock samples (dry density (γ_d), porosity (n), water absorption by weight (W_a), P-wave velocity (V_p), uniaxial compressive strength (σ_b), point load strength (I_c)) and capillary water absorption values was estimated by Simple Regression (linear, exponential, logarithmic and polynomial) (SR) and Multiple Linear Regression (MRL) analyzes (Fig. 8). The moderate and high correlation coefficients (R^2) for SR are 0.6271, 0.5396, 0.6101 and 0.7007, respectively (Fig. 8).

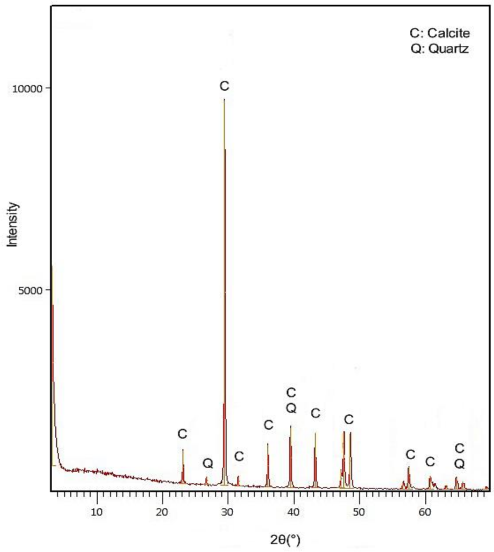
In general, multiple linear regression analysis is one of the most common methods applied to estimate the dependent variable. It helps to comprehend how several parameters work together to affect the output results. Based on the values of the independent variables, it allows to predict the value of the dependent variable. The p and f values of the regression parameters show the degree of accuracy of the equation obtained as a result of the analysis. This technique has been used to estimate the capillary water absorption coefficient independently of two or more independent variables. In this study, capillary water absorption was estimated from n, Wa, ρd, Vp and $CaCO_3$ variables for multiple linear regression analysis. The data obtained are presented in Table 6. The R^2 values of the correlations obtained from MRL analysis are between 0.525 and 1.

DISCUSSION

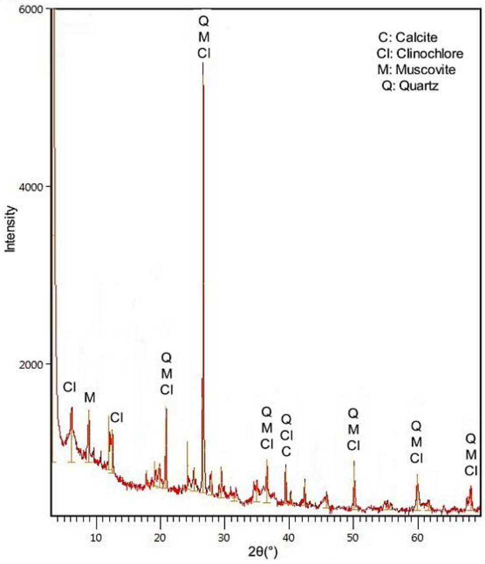
According to the classification of various researchers (Snethlage, 2005; Graue et al., 2011), among the capillary water absorption coefficients of limestone (L), mudstone (MS), sandstone (S), clayey limestone (CL) and marl (M) rocks, it was observed that the highest capillary water absorption coefficient belongs to limestone and the lowest belongs to marl rock (Table 5). Considering the values of water absorption by weight (W_a) and porosity (n), it was determined that the highest was clayey limestone and the lowest was marl. It is thought that this situation is due to the fact that clayey limestone contains more voids. Researchers (Tomašić et al., 2011; Çelik and Kaçmaz, 2016; Dinçer and Bostancı, 2019; Ünal and Altunok, 2019; Çelik and Sert, 2021; Çelik and Köken, 2023) stated that W_a and n values are one of the most important parameters in capillary water absorption values. These parameters are values related to the gaps between rock grains.



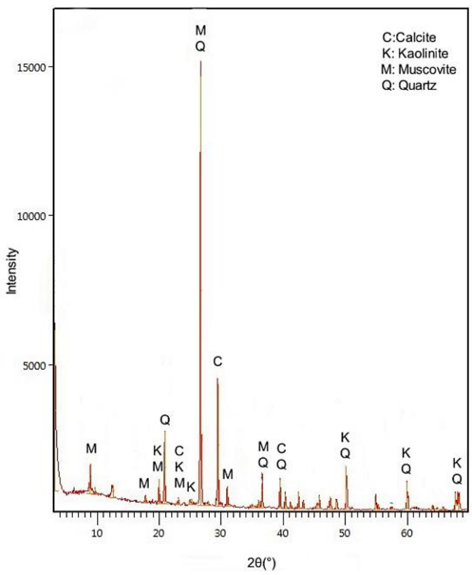
a)



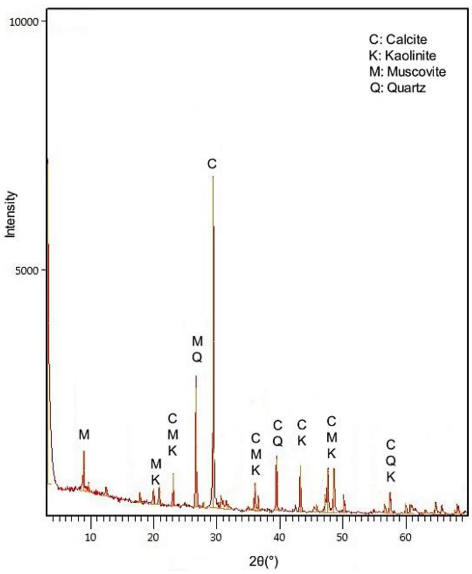
b)



c)



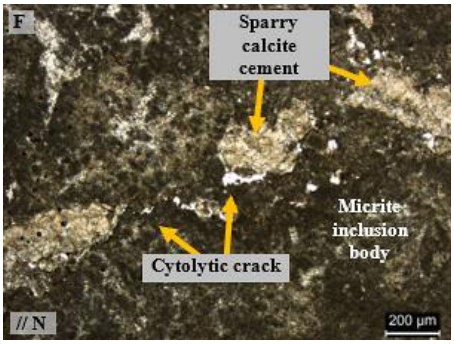
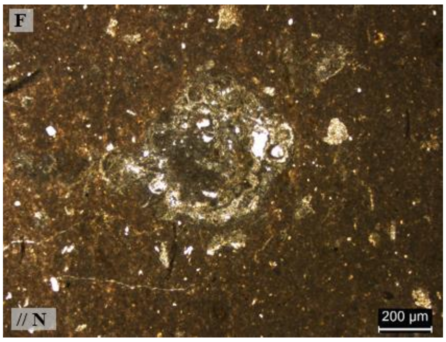
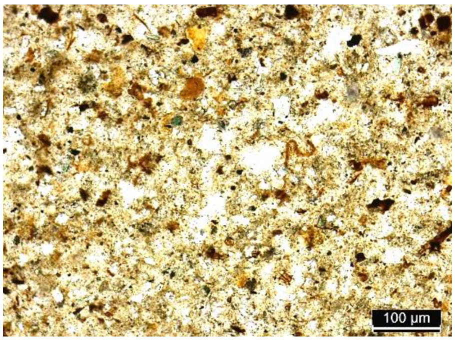
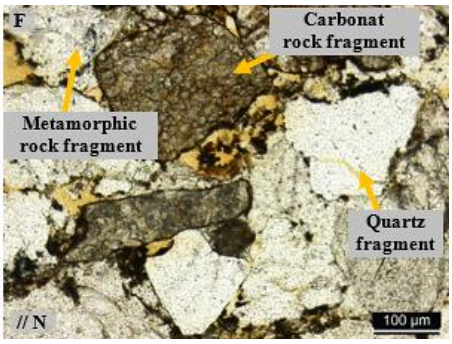
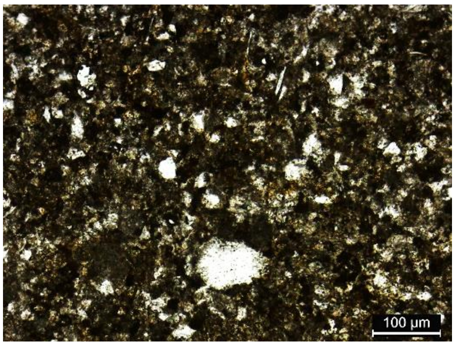
d)



e)

Fig. 6 XRD graphs of rock units a) CL; b) L; c) MS; d) S; e) M.

Table 2 Petrographic analyses of rock thin sections.

Photomicrographs	Petrographic description and determination
	Clayey limestone (Fossiliferous biomicrite): It is composed mainly of matrix supported micrite and less than 10 % allochem. Generally, sporulated allochems contains bivalve and gastropoda shells. Furthermore, spar cements can be followed in the infillings of fractures. -Texture: clastic or non-clastic -Main crystals: differents forms of calcium carbonates ($CaCO_3$) -Crystal shapes: granular, massive, crystalline or clastic -Grain size: from 0.01 mm to larger sizes -Matrix/cement: cemented by a matrix of clayey carbonate.
	Limestone (Micrite): It generally contains sparitic calcite grains (less than % 10) and micrite. Sparitic calcite crystals are also located as fracture infills in micro-fractures. -Texture: clastic or non-clastic -Main crystals: differents forms of calcium carbonates ($CaCO_3$) or dolomites $CaMg(CO_3)_2$ -Crystal shapes: granular, massive, crystalline or clastic -Grain size: from 0.01 mm to larger sizes -Matrix/cement: cemented by a matrix of carbonate mud.
	Mudstone: It generally contains fragments of small sized materials (less than 0,05 mm) together with quartz, altered and often chloritized muscovite and biotite grains. The quantity of silt ranges from 40 % to 50 %. -Texture: clastic -Main crystals: differents forms of clays, silts and muds -Crystal shapes: angular and layered -Grain size: fine grained (smaller than 0.06 mm) -Matrix/cement: cemented by a clayey matrix.
	Sandstone (Litharenite): It consists predominantly of carbonate rock fragments and quartzite and quartz-muscovite schist fragments derived from metamorphic rocks. Rock fragments are interlocked within the well-consolidated sandstone. Fragments were also binded by a clay matrix/cement under the influence of diagenesis. -Texture: granular and rough -Main crystals: differents forms of quartz and feldspar -Crystal shapes: angular and rounded -Grain size: 0.06-2 mm -Matrix/cement: cemented by a clayey matrix.
	Marl: Rock fragments derived mostly from quartzite and muscovite/biotite-schist type metamorphic rocks disseminated in a clay and micritic carbonate were detected. The grain size of rock fragments in carbonate cement is generally below 10 μ, and rarely reaching a size of 500 μ have been observed. -Texture: soft and mud-like -Main crystals: differents forms of carbonate, clay and silt -Crystal shapes: conchoidal fracture -Grain size: Very fine-grained (<0.02 mm) -Matrix/cement: cemented by a clayey matrix

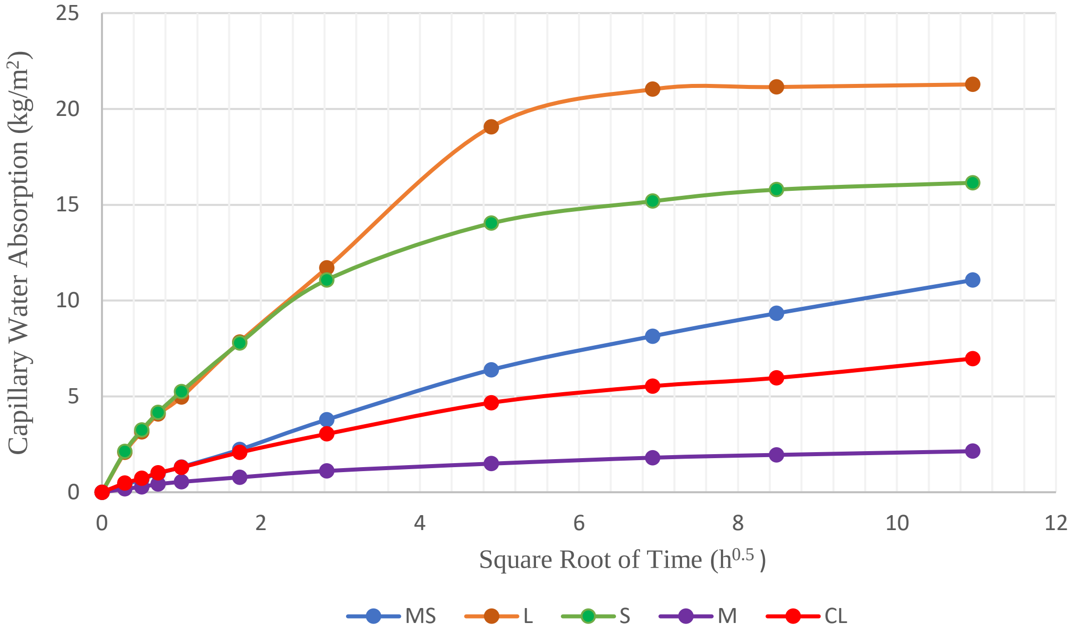


Fig. 7 Average curves obtained from the capillary water absorption test of the examined rock samples.

Table 3 Capillary water absorption coefficients of rock units and some physical-mechanical engineering properties.

Parameters	Rock Units				
	CL	L	MS	S	M
C (kg/m^{2}h$^{0.5}$)	0.64±0.34	3.03±1.69	1.01±0.12	1.86±2.06	0.23±0.16
γ_d (g/cm^3)	2.28±0.05	2.26±0.08	2.54±0.21	2.26±0.05	2.44±0.13
n (%)	13.57±1.98	14.51±2.75	9.33±6.12	12.25±2.15	6.75±2.68
W_a (%)	5.68±0.93	6.27±1.82	4.35±1.91	4.99±0.09	3.88±0.20
V_p (km/sn)	2.634±0.08	4.828±0.23	2.975±0.66	2.891±0.06	3.304±0.14
σ_b (MPa)	48.88±6.85	49.50±13.94	50.67±10.62	16.33±4.00	29.25±5.24
$CaCO_3$ (%)	29.49±11.49	29.66±13.50	7.17±0.90	27.07±6.63	28.21±10.58
I_c (MPa)	3.21±1.19	2.42±1.13	1.20±0.68	0.68±0.72	1.45±1.32

C: capillary water absorption coefficient, γ_d: unit weight, n: porosity, W_a: water absorption by weight, V_p: P-wave velocity, σ_b: uniaxial compressive strength, I_c: point load strength

Table 4 Water absorption coefficient (C) values of rocks depending on time.

Time	Minute	5	15	30	60	180	480	1440	2880	4320	7200
	Hour$^{0.5}$	0.29	0.5	0.71	1	1.73	2.83	4.90	6.93	8.49	10.95
C (kg/m^2.h^{0,5})											
CL		1.64	1.44	1.43	1.30	1.20	1.08	0.95	0.80	0.70	0.64
L		7.21	6.30	5.77	4.97	4.53	4.14	3.89	3.03	2.49	1.94
MS		1.36	1.33	1.38	1.32	1.29	1.34	1.30	1.18	1.10	1.01
S		7.38	6.48	5.89	5.26	4.49	3.92	2.86	2.19	1.86	1.47
M		0.60	0.56	0.60	0.54	0.45	0.39	0.30	0.26	0.23	0.20

Table 5 Classification of the examined rock units according to their capillary water absorption coefficients (Graue et al., 2011).

Sample Name	C (kg/m^{2}h^{0,5})	Classification
L	3.03	High
CL	0.64	
MS	1.01	Medium
S	1.86	
M	0.23	Low

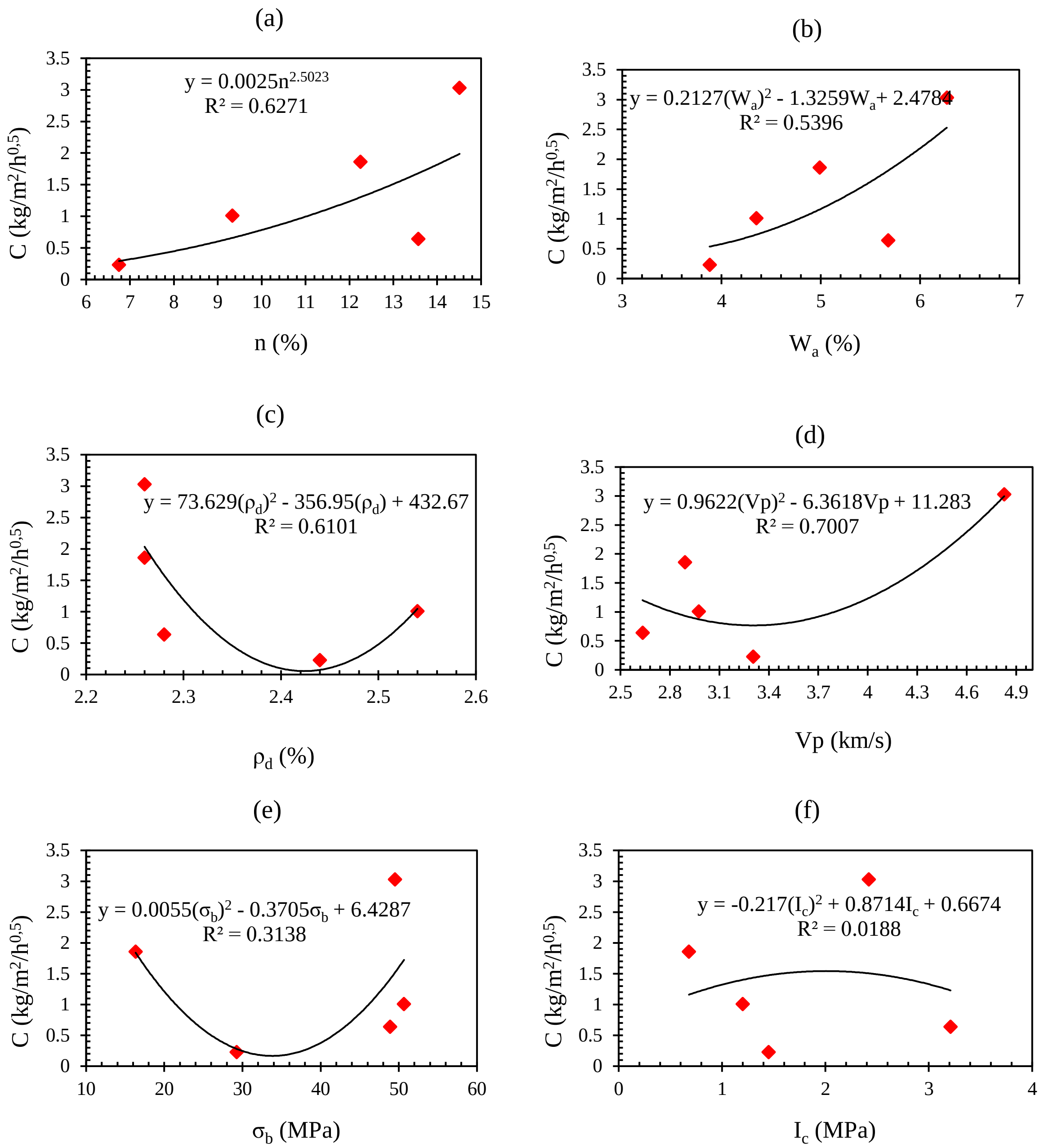


Fig. 8 Relationships between the capillarity values and physical properties of the samples, a) porosity, b) water absorption by weight, c) dry density, d) P-wave velocity, e) uniaxial compressive strength, f) point load strength.

Table 6 Multiple linear regression analysis results.

Independent variables	Equation	R^2	F	P
n, W_a, γ_d	$-3.980 + 0.032n + 0.778W_a + 0.450\gamma_d$	0.525	4.060	0.036
n, W_a, V_p	$0.757 + 1.073n - 3.286W_a + 0.002V_p$	1	9523	<0.01
V_p, W_a, γ_d	$0.077 + 0.001V_p + 0.385W_a - 1.270\,\gamma_d$	0.738	10.326	0.002
n, W_a, γ_d, $CaCO_3$	$134.239 - 2.959n + 7.130W_a - 52.411\gamma_d - 0.490CaCO_3$	1	2.944E+14	<0.01

R^2: correlation coefficient, F: statistical value, p: significance value

Table 7 Regression analysis classifications (Alpar, 2018).

R^2 correlation coefficient	Relationship level
0.00-0.19	No or negligibly low relationship
0.20-0.39	Weak (low level) relationship
0.40-0.69	Moderate relationship
0.70-0.89	High level of relationship
0.90-1.00	Very high level of relationship

When the simple regression analyses in Figure 8 were evaluated, it was determined that there were moderate and high level of relationships between the capillary water absorption coefficient and porosity, water absorption by weight, dry density and P-wave velocity parameters. These parameters have an impact on capillary water absorption values as a result of the voids in the rock. However, no significant relationship was obtained between uniaxial compressive strength, point load strength and capillary water absorption.

In terms of the strength of the rocks, MS has the highest strength. MS, L and CL generally gave the highest strengths and close results to each other. However, MS is thought to give the highest strength due to its low porosity and low water absorption values by weight. The fact that it has less voids compared to other rocks has led to these results. It is assumed that the high clay content of rock M and the coarse-grained structure of rock S caused low strength results compared to other rocks.

According to the multiple regression values in Table 6, it was determined that the most affecting parameters were porosity, water absorption by weight, dry density and P-wave velocity. As in simple regression values, these parameters were more effective than other parameters in multiple regression. According to the classifications in Table 7, it was determined that there was a moderate and high level of correlation between the parameters. Additionally, the significance values (p) of the equations in Table 6 being lower than 0.05 increases the accuracy of the equations (Mendeş et al., 2005).

In our study, porosity, P-wave velocity, density and water absorption by weight parameters produced at least R^2 0.52 correlation value in capillary water absorption results. Different researchers evaluated similar parameters in different rocks by regression analyses. Vázquez et al. (2010) obtained correlation values of at least 0.64 R^2 and higher between capillary water absorption coefficient and P wave for three granite rocks used for ornamentation. It was also stated that anisotropy in different orientations and fracture planes in the rocks were effective in these results. Çobaoğlu (2015) evaluated the effect of porosity, water absorption by weight and density on capillary water absorption values of travertine used as ornamental and building stone by simple and multiple regression. The effects of at least one or more of the parameters gave a correlation coefficient of at least 0.91 R^2 and a high correlation level. Sengun et al. (2014, 2015) obtained at least 0.51 R^2 correlation level of density, porosity, compressive strength, abrasion resistance and P wave velocity values in terms of capillary water absorption values with simple regression in different natural stones. İnce et al. (2021) analysed the effects of porosity, water absorption by weight, P wave velocity and density parameters on the water absorption coefficients of some igneous, sedimentary and metamorphic rocks used as building stones by simple and multiple regressions. R^2 correlation values of at least 0.67 and above were obtained for these parameters. These values provided at least a medium and above relationship level (Table 7). Previous studies support the accuracy of the results obtained in this study.

CONCLUSIONS

The water content of rocks is one of the most important parameters in determining their state in the deterioration process and, therefore, the stability of the engineering structure. Water penetrates into the pores and capillary cracks that form the rock, either directly or through capillary means. This water ingress affects many physical and mechanical properties of the rock. This situation occurs constantly in rocks in the natural environment and cannot be prevented. The aim should be to pre-determine the damage that water will cause to rocks through engineering studies and to take the necessary precautions.

In this study, the relationship between capillary water absorption values and physical and mechanical properties of samples of 5 different rock types located in an open-pit coal mine was evaluated. For this purpose, density, porosity, compressive strength, seismic velocity, water absorption by weight, point load strength, $CaCO_3$ and capillary water absorption coefficient (C) experiments were carried out. Values obtained from SR and MLR approaches were interpreted for capillary water absorption estimation.

The conlusions obtained in this study are presented below:

1. The increase in the amount of water absorbed by the samples was rapid at first and then slowed down over time. Throughout the entire water absorption process, L has higher n, Wa and Vp values than other rocks. This indicates that it has more voids or fractures. For this reason, it is recommended that Scanning Electron Microscope (SEM) and Computed Tomography Scanning (CT-Scan) studies be carried out to be able to learn the surface and void structure of such rocks in more detail.

2. In simple and multiple regression analyses, correlation coefficients showed that the most important parameters were density, P-wave velocity, porosity and water absorption by weight.
3. In future studies, it is suggested that pore diameter graphs and P wave velocity anisotropy ratios at different orientations should be obtained for better evaluation of capillary water absorption values.
4. In terms of engineering structures, in studies to be carried out on rocks with high water absorption capacity, it is thought that it is necessary to first investigate the capillary water absorption coefficient, water absorption by weight, porosity and related physical parameters of the rocks at the design stage of engineering structures, in order to prevent dangerous events that may occur in the future and situations that will create additional costs. Because when water is not drained in rocks, it can create pore pressure and cause the stability of engineering structures to deteriorate over time.

DATA AVAILABILITY

Data is available upon request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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