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ULTRASOUND STUDY OF LIMESTONE ROCK PHYSICAL AND MECHANICAL PROPERTIES

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Regressive analysis was used to determine empirical correlations between the velocity of an elastic P-wave (compressional pulse) and a number of physical, strength, and deformation characteristics of limestone rock collected at quarries in Turkey. The results may be used to determine the properties of limestone rock formations for engineering purposes.

Introduction

Ultrasonic pulse velocity has been widely used to determine properties and states of rocks. Determination of correlation dependences between P-wave velocity and rock properties may, in the absence of other information, aid in determining the quality of rock, in the first approximation. P-wave velocity was used to determine the homogeneity of rock, as well as its strength and the extent of its deformation [1-8]. Evaluating soil properties using standard methods approved by the ASTM and ISRM is too expensive and time-consuming.

Determining uniaxial compression strength (UCS) under laboratory conditions in accordance with [9, 10] is time-consuming and requires the availability of rock specimens that are identical as defined in standards [11-14]. Determining uniaxial tensile strength τ most often uses the Brazilian test [15-19], providing for *laboratory tests for rupture tests, when measurements are made not along one compression or tension axis, but along previously specified perpendicular directions*.

An alternative to the UCS is the point load strength $I_{s(50)}$, which provides similar results at much lower cost [20-24].

The aim of this study is to investigate the relationship between P-wave velocity and some physical and mechanical rock properties such as dry and saturated density, bulk density ρ_b, porosity n, water absorption, UCS, $I_{s(50)}$, Brazilian tensile strength, and Schmidt hardness.

Limestone was studied from different areas of Turkey (Cebecikoy, Hereke, Akveren, Soğucak, and Bakirköy).

Cebecikoy limestone is of self-edge bioclastic carbonate type and is of Carboniferous age. It contains subordinate shales and dolomite, and is about 50 m thick [25].

Hereke rock is represented by a 950-m thick Lower Triassic stratigraphic section with recrystallized, dolomitic, sandy, and other limestone [26].

Late Eocene rock from the Akveren quarry, lying directly on Triassic rock, is represented by intercalated mudrock ranging from calcareous to limy, in a 250-300-m thick layer.

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Soğucak limestone from the Middle to Upper Eocene and Oligocene [27] is represented by block outcrops of up to 100 m in size, containing fossilized corals, algae, etc.

Upper Miocene deposits at Bakirköy quarries are of lacustrine origin, and are represented by intercalated limestone, clay, and algae 25-30 m thick [28].

Experimental investigations

Homogeneous blocks of rock specimens were collected for testing: three from the Cebecikoy and Soğucak districts, eight from Hereke and Bakirköy, and ten from Akveren. Cylindrical specimens 110-115 mm long, 54 mm in diameter, and having a mass of at least 50 kg were used to determine the UCS, the elasticity modulus E, and the ultrasound pulse velocity (UPV) [9,10]. In accordance with [10], the physical properties of the specimens, such as dry and saturated density ρ_{dry} and ρ_{sat}, respectively, water absorption W_{abs} and porosity n were determined for each specimen. Thirty-two water-saturated specimens were placed in a vacuum of less than 800 Pa for at least one hour to remove air. The specimens were then saturated with water by immersion. Original specimen mass (M_{sub}), water saturated mass (M_{sat}), and mass after being dried in a furnace at +105°C and then cooled to room temperature (M_s) were determined. The volume of the soil particles V_b and of pores V_v were calculated.

$$V_b = \frac{M_{sat} - M_{sub}}{\rho_{dry}}; \quad V_v = \frac{M_{sat} - M_s}{\rho_{dry}};$$

$$\rho_{dry} = M_s / V_t; \quad \rho_{sat} = M_{sat} / V_t;$$

$$W_{abs} = \frac{M_{sat} - M_s}{M_s} 100\%; \quad n = \frac{V_v}{V_t} 100,$$

where ρ_{dry} is the dry density; ρ_{sat} is the water-saturated density; W_{abs} is the water absorption; n is porosity.

The uniaxial compressive strength was determined by subjecting each specimen to additional loading at a nearly constant rate with the help of a hydraulic testing machine rated at 150 kN, in accordance with [9]. The point load index $I_{s(50)}$ of each cylindrical specimen was determined in accordance with [29]. The Brazilian tensile test was performed for 32 specimens in accordance with [30]. Indirect determination of tensile strength was carried out in accordance with [31].

The elasticity modulus was determined in accordance with [29]. UPV was measured using a DT-Quist-120t ultrasonic pulse generator operating at 54 kHz. The Los Angeles abrasion test was carried out using an ASTM method.

Test results

Obtained data for density, porosity, and water absorption, as well as UPV, UCS, $I_{s(50)}$, the Poisson ratio v, tensile strength τ, and elasticity modulus E are presented in Table 1.

The results of the Los Angeles abrasion test are presented in Table 2.

Statistical analysis

A regression analysis using the least squares method was performed to describe the relationships between dry density ρ_{dry}, saturation density ρ_{sat}, bulk density ρ_b, water absorption W_{abs}, porosity n, Poisson's ratio v, tensile strength τ, uniaxial compressive strength UCS, point load index $I_{s(50)}$, and elasticity modulus E [1, 2, 16, 19, 32-45]. Plots of the dependencies of these indices were made as a function of ultrasound pulse velocity (Figs. 1-3).

Analysis of results shows that UPV increases as ρ_{dry}, ρ_{sat}, ρ_b, USC, $I_{s(50)}$, E, and τ increase, as n, W_{abs}, and v decrease.

Empirical relationships between UPV and these characteristics and correlation coefficients R^2 are presented in Table 3.

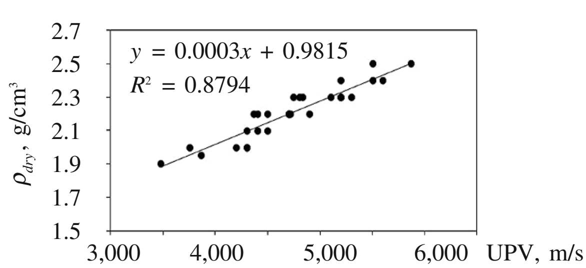
TABLE 1

Formation	Specimen number	P_{dry}, kN/m²	ρ_{sat}, kN/m²	ρ_b, kN/m²	*n*, %	W_{abs}, %	*UPV*, m/s	*v*	*τ*, MPa	*UCS*, MPa	$I_{s(50)}$, MPa	*E*, GPa	*RN*
Cebecikoy	1	22.563	23.544	23.544	2.10	1.30	5,300	0.32	7.40	38	3.44	64.36	42
	2	22.563	23.740	23.740	2.30	1.40	5,100	0.34	7.10	36	3.18	60.22	41
	3	21.582	23.348	23.054	2.20	1.50	4,900	0.33	6.40	34	3.21	59.44	41
Soğucak	4	23.544	24.035	25.016	2.10	1.30	5,600	0.29	7.80	42	3.71	62.44	43
	5	20.601	22.563	21.582	2.50	1.70	4,400	0.38	5.30	28	2.92	52.20	40
	6	23.544	23.740	23.838	2.00	1.30	5,500	0.30	7.50	45	3.65	62.46	43
Hereke	7	24.525	23.838	24.525	2.00	1.40	5,500	0.29	7.70	40	3.48	63.00	43
	8	22.563	22.857	22.857	2.10	1.50	4,800	0.35	6.30	33	3.11	58.44	42
	9	23.544	24.035	23.936	2.10	1.40	5,200	0.31	7.00	36	3.25	61.74	43
	10	22.563	23.740	23.740	2.20	1.40	5,200	0.32	7.20	38	3.52	65.32	43
	11	22.563	23.348	24.035	2.10	1.40	5,200	0.31	7.70	37	3.33	65.00	43
	12	22.563	23.152	23.642	2.10	1.40	5,200	0.32	7.10	38	3.46	62.70	42
	13	22.563	23.544	24.133	2.20	1.50	5,200	0.30	7.00	38	3.44	63.25	41
	14	22.563	23.152	23.348	2.30	1.40	5,200	0.30	6.50	38	3.35	60.34	43
Bakirköy	15	18.639	21.582	20.797	2.89	1.90	3,478	0.39	3.90	19	2.50	38.32	37
	16	19.620	21.582	20.012	2.75	1.80	3,752	0.40	4.10	24	2.40	43.64	39
	17	19.130	22.759	20.601	2.74	1.90	3,864	0.39	3.90	20	2.80	44.28	40
	18	21.582	22.857	21.876	2.40	1.70	4,714	0.34	5.90	33	3.10	58.11	41
	19	22.563	23.544	22.465	2.26	1.60	4,835	0.31	5.46	35	3.50	54.30	42
	20	21.582	23.054	21.974	2.46	1.60	4,365	0.34	5.75	33	2.80	58.20	40
	21	22.563	23.642	22.367	2.23	1.40	4,747	0.35	6.25	30	3.20	59.36	41
	22	24.525	24.329	24.525	1.90	1.20	5,865	0.28	7.55	46	3.90	69.14	44
Akveren	23	21.582	22.857	22.367	2.40	1.70	4,500	0.36	5.80	33	2.97	55.00	41
	24	19.620	22.563	21.778	2.60	1.90	4,300	0.37	5.40	29	3.24	49.24	42
	25	21.582	22.563	22.759	2.30	1.70	4,700	0.33	6.20	30	3.15	58.69	40
	26	21.582	23.054	22.857	2.20	1.50	4,700	0.37	5.80	31	3.32	55.70	41
	27	21.582	22.563	22.171	2.50	1.70	4,400	0.35	5.20	28	2.95	53.68	39
	28	21.582	22.857	22.661	2.30	1.70	4,700	0.34	5.70	33	3.27	65.00	42
	29	20.601	22.955	22.367	2.30	1.60	4,500	0.34	5.00	31	3.22	52.43	41
	30	20.601	22.465	21.876	2.40	1.80	4,300	0.36	6.00	28	2.97	54.00	42
	31	19.620	22.269	22.367	2.60	1.70	4,200	0.38	5.40	28	2.88	49.00	41
	32	19.620	22.367	21.876	2.50	1.90	4,300	0.38	5.50	29	3.21	51.34	40

TABLE 2

Formation	Abrasion losses, %
Cebecikoy	27.30
Soğucak	25.20
Hereke	26.40
Bakirköy	28.90
Akveren	26.70

a



b

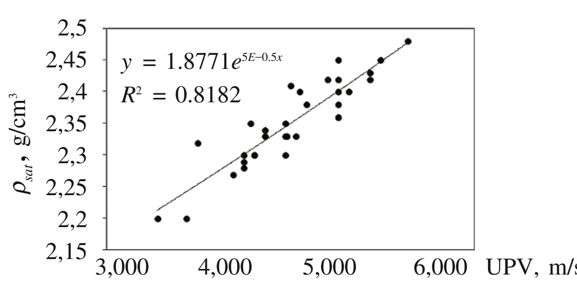


Fig. 1. Correlation dependence of ultrasound pulse velocity and density (a) when dry and (b) when saturated with water or for cylindrical specimens.

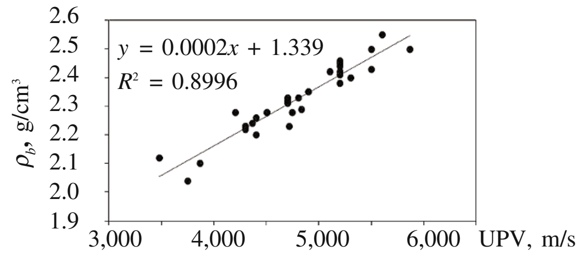


Fig. 2. Correlation dependence of ultrasound pulse velocity and volumetric density for cylindrical specimens.

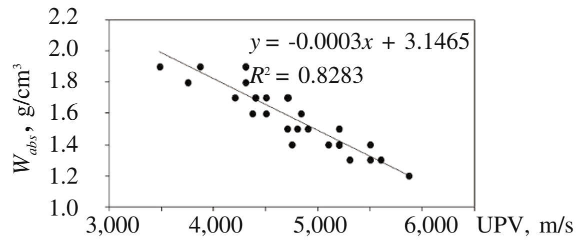


Fig. 3. Correlation dependence of ultrasound pulse velocity and water absorption for cylindrical specimens.

TABLE 3

Empirical dependences	R^2
ρ_{dry} = 0.003UPV + 0.9815	0.88
ρ_{sat} = 1.8771$^{e5E-0.5UPV}$	0.82
ρ_b = 0.002UPV + 1.339	0.90
W_{abs} = -0.0003UPV + 3.1465	0.83
n = -0.004UPV + 3.1465	0.85
v = -5E − 0.5UPV + 0.6	0.85
τ = 0.0019UPV − 2.6545	0.90
UCS = 0.018UPV − 18.405	0.93
$I_{s(50)}$ = 0.0005UPV + 0.659	0.83
E = 0.0114UPV + 3.7059	0.76
$I_{s(50)}$ = 0.022UPV + 30.631	0.70

As is seen from Table 3, ρ_b, τ, and UCS exhibit a strong linear dependence on UPV with a correlation coefficient R^2 = 0.90-0.93. At the same time, ρ_b, W_{abs}, n, and $I_{s(50)}$, as well as ρ_{sat} and v are nonlinear with R^2 = 0.90; 0.83; 0.85; and 0.83, respetively.

Maximum abrasion loss was observed in Bakirköy formation specimens; minimum loss, in Soğucak formation specimens (Table 3). Abrasion losses for all rock ranged from 25.2% to 28.9%.

The conducted tests led to the determination of P-wave velocity in unloaded specimens and discovery of a strict dependence, on this velocity, of the Poisson ratio, tensile strength, axial compressive strength, point load index and static elasticity modulus, density in the dry and saturated states, and porosity.

The studied rocks exhibit rather low porosity and insignificant water content. This condition is associated with high UPV values, as UPV increases as porosity decreases. The P-wave velocity varied between 3,478 m/sec and 5,865 m/sec, while the elasticity modulus varied between 38.32 GPa and 69.14 GPa. Rocks exhibiting such characteristics are considered medium strength rocks.

TABLE 4

Authors	Equations	R^2	Rock	UCS, MPa	V_p, km/s
[38]	$UCS = 35.54V_p - 55$	0.80	Limestone	100-200	4.5-6.5
[46]	$UCS = 9.95V_p^{1.21}$	0.83	Limestone, marble	10-160	1.2-6.4
[47]	$UCS = (V_p - 0.0195)/0.032$ $\rho = (V_p+7.707)/4.3183$	0.81 0.80	Limestone, marble, dolomite	38-120 2.43-2.97	2.9-5.6 2.9-5.6
[39]	$UCS = 0.0642V_p - 117.99$ $Id_2 = 0.069V_p + 78.577$	0.90 0.88	7 types	10-1970	2-3.2
[40]	$\rho = 0.213V_p + 1.256$	0.82	Carbonate soil	2.0-2.6	3.6-6.1
[41]	$UCS = 0.258V_p 3.543$ $UCS = 49.4V_p - 167$ $\rho = 0.19V_p + 1.61$ $Id_2 = 0.71V_p + 95.7$	0.92 0.89 0.58 0.69	9 types	20-125 – 2.15-2.85 –	1.89-6.1 – 1.86-6.1 –
[42]	$UCS = 218.8V_p - 1423$ $UCS = 0.003e^{1.455Vp}$ $UCS = V_p 10.6\times10^{-7}$	0.62 0.58 0.58	Dolerite		
This study	$UCS = 0.018V_p - 18.405$ $\rho_b = 0.0002V_p + 1.339$	0.93 0.90	5 types	19-46 2.0-2.5	3.48-5.87 3.48-5.87

Conclusions

1. The results of the study show that as the ultrasonic pulse velocity increases, dry density, saturated density, bulk density, uniaxial compressive strength, point load strength, Brazilian tensile strength, Schmidt rebound number, and elasticity modulus increase, and water absorption, Poisson ratio, and porosity decrease.

Thus, the ultrasonic pulse velocity may be used as an objective parameter for estimating these characteristics.

2. Laboratory tests show that the studied limestone may be classified by sensitivity index [46. 47] as rocks of medium strength and low porosity, in accordance with the classification in [46]. The uniaxial compressive strength and point load strength turned out to be lower than might be expected given their elastic characteristics [24, 34].

3. The correlation dependencies between ultrasonic pulse velocity and density, as well as uniaxial compression strength, are linear, which agrees with the data of previous researchers (Table 4).

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