

Correlating physico-mechanical properties of intact rocks with P-wave velocity

C. Kurtuluş¹ · F. Sertçelik¹ · I. Sertçelik¹

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Abstract The physico-mechanical properties of five different intact rock types including sandstone, arkoses and limestone were determined through standardized laboratory tests. Ninety six specimens were tested to obtain the relationships between P-wave velocity (V_p), dry unit weight (DUW), uniaxial compressive strength (UCS), point load index $Is(50)$, Brazilian tensile strength (TS), porosity (Φ), and Schmidt hardness (RN). This study also reviews some recent correlations between P-wave velocity and physico-mechanical properties as well as investigates the reliability of these correlations. Findings show the results of the experimental tests are in good agreement with previous studies. Statistical equations have been determined for estimating the physico-mechanical properties of rocks using nondestructive and indirect test methods. Results of regression analysis showed satisfactory correlations. Based on the results, new strong correlation with correlation coefficients above ($R^2 > 0.80$) are introduced for predicting the UCS, $Is(50)$, Φ and RN and reasonable good correlations ($R^2 \geq 0.78$) are introduced to predict TS and DUW from P-wave velocity of different intact rock core samples. There is a discrepancy between P-wave velocity (V_p) in situ values with laboratory results. The large reductions in V_p in situ values are clearly the functions of fractures and natural joints.

Keywords Physico-mechanical properties · Kocaeli (Turkey) · P-wave velocity · Dry unit weight · Porosity

✉ F. Sertçelik
fasert@kocaeli.edu.tr

C. Kurtuluş
cengizk@kocaeli.edu.tr

I. Sertçelik
isert@kocaeli.edu.tr

¹ Department of Geophysics, Kocaeli University, Kocaeli, Turkey

1 Introduction

Construction of projects such as foundation on rocks, underground structures, infrastructure works, tunnels, dams etc. is substantially influenced by physical and mechanical properties of rocks. The reason of the most of the hazards is the inaccurate evaluation of these rock properties. Especially specimen preparation for laboratory testing to determine the mechanical properties are expensive, difficult to be carried out and time consuming. In addition, the accuracy is mostly dependent on the specimen dimension, human errors, instrument calibration and internal factors. For these difficulties, indirect methods are often applied for preliminary studies. Indirect methods are simple do not require specimen preparation. The physico-mechanical properties of rocks are determined according to both the American Society for Testing and Materials ASTM (1986a) and International Society for Rock Mechanics ISRM (1987) and other common standards.

The P-wave velocity which depends on density and elastic properties of rocks has been used for many years to determine the physico-mechanical properties of different rocks by various authors. Many authors have studied the relations between physico-mechanical properties and P-wave velocity of rocks. Smorodinov et al. (1970) established empirical relation between uniaxial compressive strength (UCS) and density/porosity. Inoue and Ohomi (1981) determined the relations between UCS and P-wave velocity of soft rocks. Gaviglio (1989) investigated the relation between P-wave velocity and density. Boadu (2000) found the transport properties of fractured rocks from seismic waves. Kahraman (2001a) made correlations between P-wave velocity and number of joints and Schmidt rebound number (RN). Kahraman (2001b) evaluated the correlations between UCS, point load index ($Is(50)$), RN, P-wave velocity and impact strength index. Kahraman (2002) estimated the P-wave velocity of intact rock from indirect laboratory measurements. Ozkahraman et al. (2004) obtained the thermal conductivity of rocks from P-wave velocity. Yasar and Erdogan (2004) correlated P-wave velocity with density, Young's modulus and UCS of carbonate rocks. Sharma and Singh (2008) studied on the correlations between the P-wave velocity, impact strength index, slake durability index and UCS. Khandelwal and Singh (2009) correlated the P-wave velocity with different physico-mechanical properties of coal measure rocks. Khandelwal and Ranjith (2010) made correlations of P-wave velocity with index properties of different rock types. Kurtulus et al. (2010) evaluated the physical and mechanical properties of Gokceada: Imbroz (NE AegeanSea) Island andesites. Kurtulus et al. (2011a) studied the physical and mechanical properties of serpentinized ultra basic rocks in NW Turkey. Kurtulus et al. (2011b) studied the seismic anisotropy of Devonian limestone. Empirical relationships proposed in literature between P-wave velocity and uniaxial compressive strength (UCS), point load index $Is(50)$, porosity (Φ), Brazilian tensile strength (TS) and Schmidt rebound number (RN) are shown in Table 1. The differences determined could be related to the mineralogical composition and texture of the rock materials or the different methods used for sampling and performing the tests.

This paper aims to evaluate the physico-mechanical properties of intact rocks and the correlation of P-wave velocity with the dry unit weight, uniaxial compressive strength (UCS), Point Load Index ($Is(50)$), Brazilian Tensile Strength (TS), porosity (Φ) and Schmidt Rebound Number (RN), with the intention of providing detailed documentation about intact rocks.

Table 1 Equations correlating the UCS, $Is(50)$, Φ , and RN to P-wave velocity for several areas in the world and references

Equations		References
$UCS = 56.71 V_p - 192.93$		Cobanglu and Celik (2008)
$UCS = 0.11V_p - 515.56$		
$UCS = 0.78e^{0.88V_p}$		Entwisle et al. (2005)
$UCS = 0.78V_p^{0.88}$		
$UCS = 9.95V_p^{1.21}$		Kahraman (2001b)
$UCS = 0.133V_p - 227.19$		Khandelwal and Singh (2009)
$\rho = 0.0002(UPV) + 1.8745$		Kurtulus et al. (2010)
$Is(50) = 0.0018(UPV) - 1.9906$		
$UCS = 0.1581(UPV) - 643.2$		
$RN = 0.0319(UPV) - 92.442$		
$n = -6.10 - 0.5(UPV) + 0.0366$		
$UCS = 0.0675(UPV) - 245.13$	Across foliation	Kurtulus et al. (2011a)
$Is(50) = 0.0042(UPV) - 14.602$	“	
$DUW = 0.0002(UPV) + 1.7752$	“	
$n = -0.0031(UPV) + 16.736$	“	
$UCS = 0.0188(UPV) - 71.04$	Along foliation	
$Is(50) = 0.0013(UPV) - 4.819$	“	
$DUW = 0.0001(UPV) + 1.7937$	“	
$n = -0.0029(UPV) + 16.733$	“	
$Is(50) = 0.0033(UPV) - 7.7876$	Across foliation	Kurtulus et al. (2011b)
$UCS = 0.0533(UPV) - 1326.29$	“	
$n = -0.0011(UPV) + 5.6858$	“	
$d = 0.0002(UPV) + 1.6769$	“	
$Is(50) = 0.0016(UPV) - 2.4235$	Along foliation	
$UCS = 0.0207(UPV) - 24.729$	“	
$n = -0.0005(UPV) - 3.3089$	“	
$d = 8E-05(UPV) + 2.0858$	“	
$UCS = 165.05e^{(-4.452/v)_p}$		Moradian and Behnia (2009)
$UCS = 0.0642V_p - 117.99$		Sharma and Singh (2008)
$SV = 4.3183.9\rho - 7.5071$		Yasar and Erdogan (2004)

Where (V_p and SV) P-wave velocity, (DUW , d , ρ) dry unit weight, (UCS) uniaxial compressive strength, $Is(50)$ point load index, (Φ , n) porosity, (RN , SCH) Schmidt rebound number

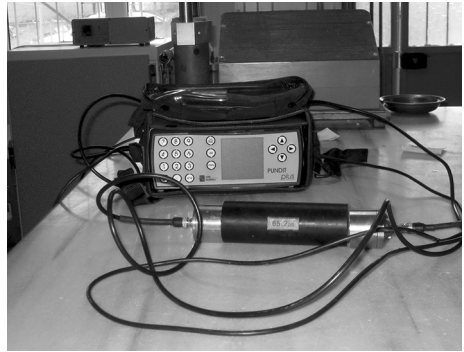
2 Research methodology

2.1 Sample collection

The rock samples were collected from five areas in Kocaeli area (Fig. 1).

Laboratory tests were performed on 96 rock specimens, including 10 of which are volcanic and 86 of them are sedimentary rocks (Table 2).

Fig. 2 Ultrasonic pulse tester instruments



As seen from Table 3, the velocity of Kızderbent volcanite specimens ranges from 5800.0 to 6340.0 m/s with the mean 6370.0 m/s, whereas that of Sopalı arkose specimens vary between 2544.0 and 3300.0 m/s with the mean 2922.0 m/s. The velocity of Körfez sandstone specimens change between 2968.0 and 6010.0 m/s with the mean 4489.0 m/s and that of Akveren limestone specimens ranges from 4300.0 and 5800.0 m/s with the mean 5050.0 m/s. The velocity of Derince sandstone specimens vary between 1890.0 and 3300.0 m/s with the mean 2595.0 m/s.

2.4 Determination of different physico-mechanical properties

The effective porosity of rock specimens were determined using saturation method. Dry unit weights and effective porosity of the rock specimens were determined in accordance with ISRM (2007). The uniaxial compressive strength (UCS) were obtained by subjecting each specimen to H incremental loading at about constant rate using a hydraulic testing machine of 150.0 KN capacity in accordance with ASTM (1986b). The I_s (50) of the specimens was determined by mounting each specimen between two platens of a point load tester of 50.0 KN capacities in accordance with ASTM (2005). Schmidt hardness of the specimens was determined according to ASTM D5873 (2014) standard recommendations on cylindrical specimens using a Schmidt hammer type NR of impact energy of 2.207 Nm. The Brazilian tensile strength of the specimens of NX diameter were determined using Brazilian test apparatus equipped with digital display unit for displaying maximum load. Rock specimens were loaded diametrically between the loading platens of the apparatus as per ISRM (1978) standards.

2.5 Geophysical survey

The seismic refraction surveys were conducted at Kızderbent volcanites, Sopalı Arkose, Körfez sandstone, Akveren limestone and Derince sandstone in the investigation area to correlate the ultrasonic pulse velocities of rock specimens with dynamic P-wave velocities. The seismic refraction data were recorded using a 12 channel Geometrics Seismic Enhancement (Smart Seis) seismograph. The first arrival phases assumed to be refracted from the same interface, the P-wave velocities were calculated from the slope of the line connecting the first arrival phases using GeoSeis computer program. The determined average P-velocities are given in Table 4.

The discrepancy increases notably when comparing V_p in situ values with laboratory results. The large reductions in V_p in situ values are clearly the functions of fractures and

Table 3 V_p , DUW, UCS, $I_s(50)$, TS, Φ , and RN test results

B	DUW (g/cm ³)	UCS (MPa)	$I_s(50)$ (MPa)	TS (MPa)	Φ (%)	RN	Formation
5800	2.68	172.0	13.5	57.0	0.048	51.0	Kızderbent volcanites
5910	2.77	177.0	14.3	60.0	0.045	52.0	Kızderbent volcanites
5957	2.78	184.0	13.46	62.0	0.04	53.0	Kızderbent volcanites
6150	2.82	189.0	14.68	63.5	0.038	56.0	Kızderbent volcanites
6245	2.89	198.0	15.23	65.0	0.034	58.0	Kızderbent volcanites
6274	2.85	198.0	16.2	60.0	0.034	55.0	Kızderbent volcanites
6185	2.88	185.0	15.36	59.0	0.041	55.0	Kızderbent volcanites
6318	2.9	199.0	15.9	61.0	0.033	57.0	Kızderbent volcanites
6324	2.84	195.0	15.8	53.0	0.035	56.0	Kızderbent volcanites
6340	2.95	202.0	16.32	62.0	0.032	60.0	Kızderbent volcanites
3153	2.43	18.0	1.86	29.0	0.278	32.0	Sopalı Arkose
3159	2.38	18.0	1.76	25.0	0.276	32.0	Sopalı Arkose
2544	2.31	11.6	0.93	29.0	0.24	24.0	Sopalı Arkose
3160	2.32	23.5	1.88	35.0	0.249	32.0	Sopalı Arkose
2668	2.25	12.35	1.13	23.0	0.26	29.0	Sopalı Arkose
2918	2.18	15.375	1.23	33.0	0.23	31.0	Sopalı Arkose
3255	2.51	23.5	2.1	38.0	0.25	32.0	Sopalı Arkose
3300	2.46	28.0	2.24	38.0	0.23	32.0	Sopalı Arkose
5150	2.63	102.34	8.19	55.0	0.1	49.0	Körfez sandstone
4968	2.58	119.32	9.55	45.0	0.085	35.0	Körfez sandstone
3874	2.25	59.52	4.76	37.0	0.156	35.0	Körfez sandstone
6010	2.89	164.34	13.15	58.0	0.058	54.0	Körfez sandstone
5246	2.66	126.34	10.11	55.0	0.079	44.0	Körfez sandstone
4870	2.55	100.45	8.04	41.0	0.1	41.0	Körfez sandstone
4338	2.39	101.32	8.11	39.0	0.1	35.0	Körfez sandstone
3200	2.05	46.75	3.74	37.0	0.18	34.0	Körfez sandstone
3345	2.09	52.37	4.19	40.0	0.17	34.0	Körfez sandstone
2968	1.98	53.96	4.32	22.0	0.165	34.0	Körfez sandstone
3610	2.17	73.65	5.89	30.0	0.14	34.0	Körfez sandstone
4535	2.45	89.33	7.14	40.0	0.11	35.0	Körfez sandstone
4380	2.4	89.63	7.17	51.0	0.113	35.0	Körfez sandstone
3800	2.23	82.55	6.6	33.0	0.12	34.0	Körfez sandstone
5380	2.7	127.45	10.2	50.0	0.078	35.0	Körfez sandstone
4925	2.66	117.44	9.4	35.0	0.086	35.0	Körfez sandstone
4360	2.4	84.86	6.79	30.0	0.12	35.0	Körfez sandstone
3990	2.29	86.79	6.94	48.0	0.12	41.0	Körfez sandstone
2950	1.97	55.32	4.43	24.0	0.16	34.0	Körfez sandstone
4640	2.48	98.35	7.87	37.0	0.1	35.0	Körfez sandstone
4409	2.52	37.69	3.67	48.0	0.18	41.0	Körfez sandstone
4667	2.54	72.0	3.66	51.0	0.14	47.0	Körfez sandstone
5455	2.61	135.0	12.2	50.0	0.073	49.0	Körfez sandstone
5070	2.62	129.0	11.5	57.0	0.077	50.0	Körfez sandstone
4876	2.56	99.0	3.98	44.0	0.1	39.0	Körfez sandstone

Table 3 continued

B	DUW (g/cm ³)	UCS (MPa)	Is(50) (MPa)	TS (MPa)	Φ (%)	RN	Formation
4964	2.56	116.0	7.2	45.0	0.088	40.0	Körfez sandstone
4746	2.55	127.0	7.7	56.0	0.078	41.0	Körfez sandstone
4680	2.55	82.0	3.9	49.0	0.12	39.0	Körfez sandstone
4576	2.54	80.0	3.24	44.0	0.125	33.0	Körfez sandstone
4943	2.58	96.0	7.8	42.0	0.1	40.0	Körfez sandstone
4595	2.53	82.0	3.73	48.0	0.12	38.0	Körfez sandstone
4560	2.55	91.0	3.55	44.0	0.11	38.0	Körfez sandstone
4826	2.55	111.0	7.3	55.0	0.092	45.0	Körfez sandstone
4799	2.57	87.0	5.7	57.0	0.12	40.0	Körfez sandstone
5160	2.83	70.0	6.8	59.0	0.14	51.0	Körfez sandstone
5146	2.55	79.0	8.5	60.0	0.13	48.0	Körfez sandstone
5300	2.4	126.0	9.6	55.0	0.08	51.0	Akveren limestone
5100	2.21	118.0	10.4	38.0	0.086	51.0	Akveren limestone
4900	2.3	102.0	9.7	36.0	0.1	35.0	Akveren limestone
5600	2.55	140.0	11.4	48.0	0.069	53.0	Akveren limestone
4400	2.2	28.0	7.4	35.0	0.23	41.0	Akveren limestone
5500	2.43	118.0	13.2	41.0	0.086	55.0	Akveren limestone
5500	2.5	132.0	14.2	43.0	0.074	54.0	Akveren limestone
4800	2.1	160.0	11.3	56.0	0.055	40.0	Akveren limestone
5200	2.44	36.0	13.6	55.0	0.2	44.0	Akveren limestone
5200	2.54	138.0	12.3	53.0	0.07	40.0	Akveren limestone
5200	2.45	142.0	11.6	56.0	0.067	38.0	Akveren limestone
5200	2.41	110.0	12.2	49.0	0.09	40.0	Akveren limestone
5200	2.46	122.0	11.5	43.0	0.08	38.0	Akveren limestone
5200	2.43	128.0	12.2	53.0	0.078	36.0	Akveren limestone
4300	2.11	88.0	5.2	40.0	0.012	41.0	Akveren limestone
5800	2.6	127.0	12.6	53.0	0.079	53.0	Akveren limestone
5200	2.54	115.0	11.5	58.0	0.089	38.0	Akveren limestone
4900	2.78	89.0	10.3	42.0	0.11	48.0	Akveren limestone
4800	2.74	82.0	8.3	40.0	0.12	45.0	Akveren limestone
5600	2.55	110.0	7.2	51.0	0.093	45.0	Akveren limestone
5100	2.43	98.0	6.6	54.0	0.1	45.0	Akveren limestone
4800	2.44	92.0	8.8	44.0	0.11	45.0	Akveren limestone
2210	1.68	13.86	1.11	27.0	0.29	23.0	Derince sandstone
2100	1.57	10.69	0.86	23.0	0.26	29.0	Derince sandstone
1890	1.66	9.65	0.77	15.0	0.31	23.0	Derince sandstone
2400	1.9	18.5	1.48	28.0	0.27	29.0	Derince sandstone
2365	1.87	18.42	1.47	21.0	0.21	27.0	Derince sandstone
2390	1.92	19.17	1.53	27.0	0.23	25.0	Derince sandstone
2340	1.68	14.55	1.64	32.0	0.21	29.0	Derince sandstone
2580	1.69	22.48	1.8	30.0	0.25	32.0	Derince sandstone
2389	1.55	20.68	1.65	28.0	0.26	27.0	Derince sandstone
2725	1.8	26.86	2.15	32.0	0.28	31.0	Derince sandstone

Table 3 continued

B	DUW (g/cm ³)	UCS (MPa)	Is(50) (MPa)	TS (MPa)	Φ (%)	RN	Formation
2640	1.72	24.64	1.97	36.0	0.19	29.0	Derince sandstone
3145	1.82	32.65	2.61	38.0	0.22	33.0	Derince sandstone
3050	1.69	30.69	2.46	31.0	0.22	29.0	Derince sandstone
2480	1.68	19.66	1.58	20.0	0.24	25.0	Derince sandstone
2590	1.87	23.55	1.88	27.0	0.21	32.0	Derince sandstone
2867	1.86	27.45	2.2	33.0	0.23	29.0	Derince sandstone
3100	1.92	31.65	2.53	35.0	0.22	27.0	Derince sandstone
2462	1.76	21.18	1.69	16.0	0.26	21.0	Derince sandstone
2380	1.8	19.66	1.57	25.0	0.23	22.0	Derince sandstone
3268	1.96	33.54	1.68	33.0	0.21	38.0	Derince sandstone

Table 4 Average P-wave velocities of rocks obtained from seismic refraction surveys in the investigation areas

Investigation area	Average P-wave velocity (m/s)
Kızderbent volcanites	4560.0
Sopalı Arkoz	1500.0
Körfez sandstone	1701.0
Akveren limestone	1483.0
Derince sandstone	1493.0

natural joints. P-wave velocity depends on mineralogical composition, micro cracks and pores of the rocks and on the physical parameters, such as absorption by weight, density or porosity.

2.6 Result and discussion

Results of laboratory tests on 96 specimens are listed in Table 3. As can be seen in this table, volcanic rocks give higher uniaxial compressive strength (UCS) values (172–202 MPa) and point load index Is(50) compared to sedimentary rocks.

The previous literatures show that our results are in acceptable ranges (Cobanglu and Celik 2008; Entwisle et al. 2005; Kahraman 2001a; Khandelwal and Singh 2009; Kurtulus et al. 2010; Kurtulus et al. 2011a; Kurtulus et al. 2011b; Moradian and Behnia 2009; Sharma and Singh 2008).

In order to describe the relationships between P-wave velocity and physico-mechanical properties of rocks a regression analysis was carried out. The equation of the best fit line and the coefficient of determination (R^2) were determined for each test result (Figs. 3, 4, 5, 6, 7, 8). It can be seen from the figures that, in all cases, the best fit relationships were found to be the best.

There is an exponential relation between P-wave velocity and dry unit weight with a strong correlation of ($R^2 = 0.795$) (Fig. 3). The equation of this relation is given as;

$$DUW = 0.52V_p^{0.45} \quad (R^2 = 0.795) \quad (1)$$

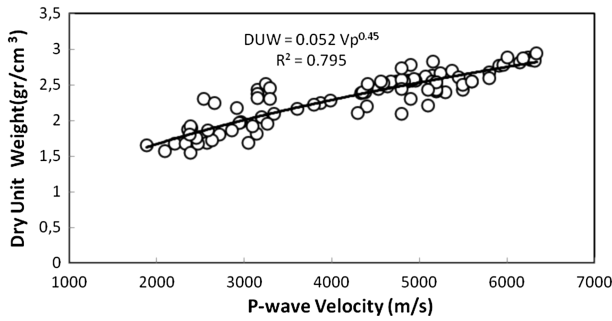


Fig. 3 Graph of dry unit weight (DUW) and P-wave velocity (V_p)

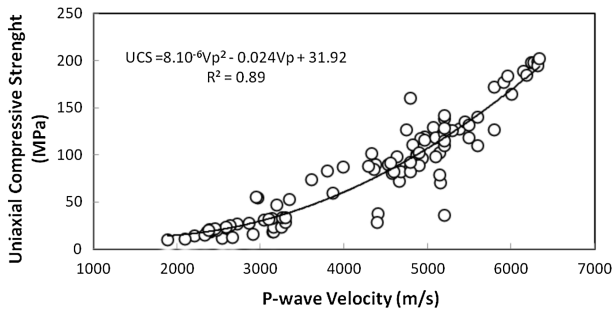


Fig. 4 Graph of uniaxial compressive strength (UCS) and P-wave velocity (V_p)

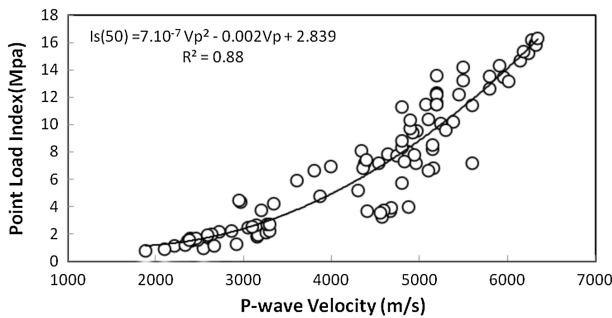


Fig. 5 Graph of point load index ($I_s(50)$) and P-wave velocity (V_p)

Polynomial relations have been observed between P-wave velocity and UCS and $I_s(50)$ (Figs. 4, 5). The equations are given below:

$$UCS = 8.10^{-6}V_p^2 - 0.024V_p + 31.92 \quad (R^2 = 0.89) \quad (2)$$

$$I_s(50) = 7.10^{-7}V_p^2 - 0.002V_p + 2.839 \quad (R^2 = 0.88) \quad (3)$$

A very good correlation ($R^2 = 0.89$) was found between V_p and UCS, and also ($R^2 = 0.88$) between V_p and $I_s(50)$ for P-wave velocity and the tensile strength, effective porosity and Schmidt rebound number show linear relationships (Figs. 6, 7, 8).

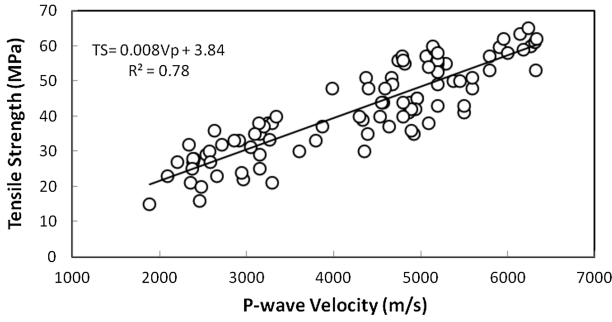


Fig. 6 Graph of tensile strength (TS) and P-wave velocity (V_p)

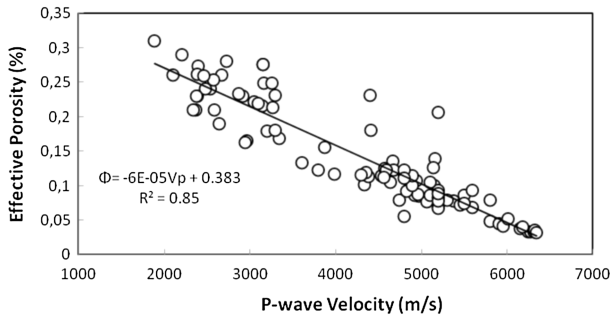


Fig. 7 Graph of effective porosity (Φ) and P-wave velocity (V_p)

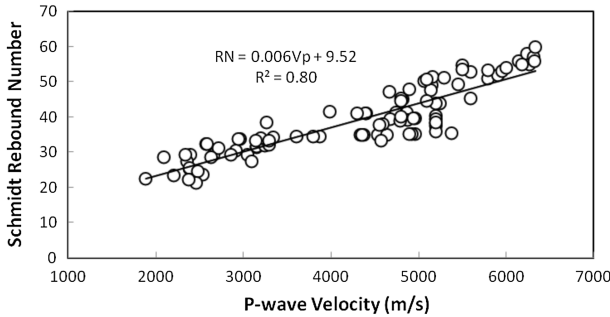


Fig. 8 Graph of Schmidt rebound number (RN) and P-wave velocity (V_p)

$$TS = 0.008V_p + 3.84 \quad (R^2 = 0.78) \tag{4}$$

$$\varnothing = -6E - 05V_p + 0.383 \quad (R^2 = 0.85) \tag{5}$$

$$RN = 0.006V_p + 9.52 \quad (R^2 = 0.80) \tag{6}$$

A good correlation ($R^2 = 0.78$) was found between P-wave velocity and Brazilian tensile strength, ($R^2 = 0.85$) between V_p and \varnothing , and ($R^2 = 0.80$) between V_p and RN.

From Fig. 7, it may be seen that when, the P- wave velocity increases the porosity decreases. However, from Figs. 3, 4, 5, 6, and 8 it can be observed that when the P- wave velocity increases, dry unit weight, uniaxial compressive strength, point load index, tensile strength and Schmidt rebound number increase. Kızderbent volcanites have the highest P-wave velocities range between 5800.0 and 6340.0 m/s with the mean 6370.0 m/s and for physico-mechanical properties wherein dry unit weights (DUW) vary between 2.68 and 2.95 gr/cm³ with the mean 2.815 gr/cm³, uniaxial compressive strengths (UCS) range from 172.0 to 202.0 MPa with the mean 187.0 MPa, Point load index (Is (50)) change between 13.6 and 16.32 MPa with the mean 14.96 MPa, Brazilian tensile strengths range between 53.0 and 65.0 MPa with the mean 59.0 MPa and Schmidt rebound numbers vary from 51.0 to 60.0 with the mean 55.5. Kızderbent volcanites have the lowest effective porosity values (Φ) vary between 0.032 and 0.048 % with the mean 0.04 %. Sopali Arkoses have the lowest P-wave velocities ranging from 2544.0 to 3300.0 m/s with the mean 2922.0 m/s. Their (DUW) vary between 2.18 and 2.46 gr/cm³ with the mean 2.32 gr/cm³, (UCS) range between 11.6 and 28 MPa with the mean 19.8 MPa, (Is (50)) change between 0.93 and 2.24 MPa with the mean 1.585 MPa, (TS) range from 25.0 to 38.0 MPa with the mean 31.5 MPa, (RN) change between 24.0 and 32.0 with the mean 28.0. Sopali arkoses have the highest effective porosities (Φ) vary between 0.23 and 0.278 % with the mean 0.254 %. P-wave velocities and physico-mechanical properties of Körfez sandstone, Akveren limestone and Derince sandstone follow the Kızderbent volcanites respectively. In general, the correlation coefficients (R^2) were lower for the DUW and TS than for the UCS, Is (50), Φ and RN (Figs. 3, 4, 5, 6, 7, 8) in this study.

The relation between DUW and V_p is similar to relationship given by Kurtulus et al. (2011b), but its correlation coefficient ($R^2 = 0.795$) higher than proposed by Kurtulus et al. (2011b). The proposed relationship between UCS and V_p is similar to suggested relationships given by Cobanglu and Celik (2008) and Kurtulus et al. (2010), but correlation coefficient is 0.89 which is relatively higher than their suggested correlation coefficients. However, it is relatively lower than correlation coefficients given by Khandelwal and Singh (2009), Kurtulus et al. (2011a), Sharma and Singh (2008). Our relationship between Is (50) and V_p is similar to relationships given by Kurtulus et al. (2010), Kurtulus et al. (2011a), Kurtulus et al. (2011b), but its correlation coefficient ($R^2 = 0.88$) is lower than that given by Kurtulus et al. (2010), very close to that of others. Relation between RN and V_p is similar to relationship proposed by Kurtulus et al. (2010), however, its correlation ($R^2 = 0.80$) is higher than their suggested correlation.

3 Conclusions

In this study, the physico-mechanical properties including P-wave velocity, dry unit weight, uniaxial compressive strength, point load index, indirect tensile strength, effective porosity, and Schmidt hardness of the intact rocks were determined in the laboratory. The test results were interpreted statistically and reasonable good relationships were determined with P-wave velocity (ranging between 1890.0 and 6340.0 m/s) to the physico-mechanical properties. This result denotes that P-wave velocities could be used in determination of the physico-mechanical properties of intact rocks.

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