Correlation between *P*-wave velocity and some mechanical properties for sedimentary rocks

by R. Altindag*

Synopsis

Engineers and researchers need to estimate the mechanical properties of rocks from *P*-wave velocity. In previous studies, the researchers have investigated either the limited values or all the data belonging to sedimentary, igneous, and metamorphic rocks together in the same statistical analysis. In this study, the raw data pertaining to only sedimentary rocks was taken from previous studies and evaluated. For this purpose, a total of 97 samples of sedimentary rock types were subjected to statistical analysis. First, the relationships between *P*-wave velocity and physical-mechanical properties were investigated by simple regression analysis. All the data were then subjected to multi-regression analysis. Some empirical equations with high correlation coefficients were derived for rock engineers. The equations obtained from the analyses are compared with previous equations found in literature.

Keywords
P-wave velocity, mechanical properties, sedimentary rocks, mechanical properties, brittleness.

Introduction

Seismic techniques, which are known as non-destructive geophysical methods, are commonly used by engineers working in various fields such as mining, civil, and geotechnical engineering. They are frequently employed to investigate certain properties of rocks. Ultrasonic measurements can be applied in various application areas such as rockbolt reinforcement[1], blasting efficiencies in the rock mass[2], the determination of degree of rock weathering[3], determination of deformation and stress on rock masses[4,5], and rock mass characterization[6,7]. A number of studies[8–13] investigating ultrasonic propagation in fractured rock have been carried out. Some researchers[14–16] used the *P*-wave velocity for the estimation of weathering depth of building stones. Many researchers have found that *P*-wave velocity is closely related to physical and mechanical properties of rocks[17–25].

The main factors that influence *P*-wave velocity in rocks are lithology, texture, density, porosity, anisotropy, grain size and shape, water contact, stress, temperature, weathering, alteration zones, pores and microcracks, bedding planes, and joint properties (roughness, filling materials, water, dip and strike, etc.).

The relationships between *P*-wave velocity and rock density have been investigated by various researchers[26–28] who have reported an increase in the density as the velocity increased. The influence of microcracks on *P*-wave velocity distribution has been studied by Babuska *et al.*[29] and Jech *et al.*[30]. The effect of crystallographic preferred orientation of rock-forming minerals on *P*-wave velocities was examined by various researchers. The effects of fracture roughness on *P*-wave velocity for granite, marble, and travertine was studied by Kahraman[31], who stated that *P*-wave velocity decreased as the fracture roughness coefficient values increased. Kahraman[32] derived empirical equations in order to predict *P*-wave velocity of wet rock from the *P*-wave velocity of dry rock.

Singh and Kripamoy[33] revealed that *P*-wave velocity and uniaxial compressive strength (UCS) decreased as the quartz content increased, and decreased as the moisture content increased. They also reported a decrease in *P*-wave velocity as the silica content increased. Some of the empirical relationships between *P*-wave velocity and the UCS for different rock types found in the literature are summarized in Table I.

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Table I

Some empirical relationships between UCS and *P*-wave velocity from previous studies

Equations	Correlation coefficient (r)	Units and notations	Rock type	Number of data	References
$UCS = ax + b$	0.85	--	Sandstones	--	[64]
$UCS = 0.0642\,Vp - 117.99$, (MPa)	0.90	Vp: m/s	Sandstone, coal, quartz mica schist, phyllite, basalt	43	[65]
$UCS = 35.54\,Vp - 55$	0.80	--	Granitic rocks	19	[66]
$UCS = 56.71\,Vp - 192.93$, (MPa)	very small	--	Cement mortar, sandstone, limestone	75	[67]
$UCS = a\,Vp^{b}$	0.94	--	A wide range of British rock types	150	[68]
$UCS = 9.95\,Vp^{1.21}$, (MPa)	0.83	Vp: km/s	Marl, limestone, dolomite, sandstone, hematite, serpantine, diabase, tuff	48	[15]
$Vp = 0.00317\,UCS + 2.0195$	0.80		--	--	[24]
$UCS = 0.78\,e^{0.88Vp}$	0.73	Vp: km/s	Volcanic group	--	[69]
$UCS = 0.78\,Vp^{0.88}$	0.73	Vp: km/s	Volcanic group	--	
$UCS = 0.0407\,Vp - 36.31$, (N/mm^2)	0.85		--	19	[70]
$UCS = 0.004\,Vp^{1.247}$, (MPa)	0.85	Vp: m/s	Granites	9	[71]
$UCS = k\,\rho\,Vp^2 + A$, (kg/cm^2)		ρ: g/cm^3, Vp: km/s	--	--	[22]
$UCS = 0.036\,Vp - 31.18$, (MPa)		Vp: m/s	--	--	[72]
$UCS = 0.1564\,Vp - 692.41$, (MPa)	0.90	Vp: m/s	Sandstones	9	[73]
$UCS = 0.0144\,Vp - 24.856$, (MPa)	0.71	Vp: m/s	Sandstones	24	
$UCS = 7.1912\,Vp + 26.258$, (MPa)	0.57	Vp: km/s	Sandstone, gravel stone, limestone, mudstone, shale	8	[74]
$UCS = 21.677\,Vp + 21.427$	0.95	Vp: km/s	Limestone, marble, dolomitic limestone, tuff, basalt	8	[75]
$UCS = 0.0188\,Vp + 0.0648$	0.95	Vp: km/s	Sandstone	--	[76]
$UCS = 2{,}304\,Vp^{2.4315}$	0.97	Vp: km/s	Diorite, quartzite, sandstone, limestone, marble, granadiorite, basalt, travertine, trachyte, tuff, andesite.	19	[77]
$UCS = 12.746\,Vp^{1.194}$	0.79	Vp: km/s	Limestone, sandstone, travertine, marl, dolomite, mudrock-shale, slate, siltstone	97	This Study
$UCS = -7.155 + 6.194\,Vp + 9.774\,TS$	0.88	Vp: km/s		43	
$UCS = -10.029 + 5.734\,Vp + 10.876\,TS - 2.408\,Is$	0.90	Vp: km/s		26	

The goal of this study is to investigate the relationships between *P*-wave velocity and certain physico-mechanical rock properties such as unit weight, porosity, shore hardness, brittleness, UCS, tensile strength, point load index, and modulus of elasticity, considering the sedimentary rocks only.

Sampling of data

It was noticed in some of the previous studies that the rocks had all been subjected to the same statistical analysis, regardless of the differences in their geological origins. However, in this study, only the raw data of sedimentary rocks obtained from previous studies was taken into account in the statistical analysis. The properties of the rock samples employed in statistical analyses are illustrated in Table II.

Brittleness concepts

Brittleness has become an important rock property. Nevertheless, no standardized and universally accepted brittleness concept or measurement method defining or measuring the rock brittleness has yet been stated. Different researchers mean, express, and use the concept differently for different purposes.

The ratio H/K_c, where H is the hardness (resistance to deformation) and K_c is the toughness (resistance to fracture), is proposed as the index of brittleness[34]. Quinn and Quinn[35] have studied on ceramics and proposed an index of brittleness, $B \equiv (HE)/K_{Ic}^2$, using hardness, Young's modulus, and fracture toughness. Determination of brittleness is largely empirical. Usually, brittleness measures the relative susceptibility of a material to two competing mechanical responses.

Morley[36] and Hetenyi[37] define brittleness as the lack of ductility. Ramsey[38] expresses brittleness as follows: 'When the internal cohesion of rocks is broken, the rocks are said to be brittle'. Obert and Duvall[39] described brittleness as follows: 'materials such as cast iron and many rocks usually terminate by fracture at or only slightly beyond the yield stress'. Brittleness is defined as the property of materials that rupture or fracture with little or no plastic flow[40]. However, it may be stated that following phenomena may be observed[41] as the brittleness increases:

- Low values of elongation
- Fracture failure
- Formation of fines
- Higher ratio of compressive to tensile strength
- Higher resilience
- Higher angle of internal friction
- Formation of cracks in indentation.

Some brittleness index definitions obtained from stress-strain curves were introduced and used in literature[42–44]. A simple index of brittleness is the ratio of compressive strength to tensile strength, ($B_1 = \sigma_c/\sigma_t$). This definition is

Table II

Physical and mechanical properties of rocks

Rock type	UCS (MPa)	TS (MPa)	Point load index, Is (MPa)	*Vp* (km/s)	Modulus of elastisity (GPa)	Brittleness*			References
						B_1	B_2	B_3	
Sandstone	58.14	3.04		2.69	6.08	19.13	0,90	9.40	[78]
Sandstone	63.82	4.31		2.42	5.41	14.81	0,87	11.73	
Limestone	103.3	6.08		6.22	13.31	16.99	0,89	17.72	
Limestone	126.67	7.94		6.27	13.70	15.95	0,88	22.42	
Limestone	118.24	7.35		6.18	13.95	16.09	0,88	20.85	
Limestone	106.86	5.49		6.18	13.18	19.46	0,90	17.13	
Limestone	78.73	6.37		5.84	11.51	12.36	0,85	15.84	
Limestone	84.41	6.86		6.2	11.47	12.30	0,85	17.02	
Limestone	46.32		4.91	5.78	24.11				[79]
Limestone	58.02		4.36	5.75	23.21				
Limestone	51.2		4.95	5.13	23.98				
Limestone	50.33		3.72	3.52	8.00				
Limestone	11.5		3.75	3.74	7.60				
Limestone	62.97		3.594	4.753					[67]
Limestone	63.7		3.86	4.799					
Limestone	74.07		3.94	4.866					
Limestone	74.11		4.05	4.869					
Limestone	74.93		4.408	5.109					
Sandstone	82.66		7.425	4.911					
Sandstone	85.25		8.5	4.926					
Sandstone	97.94		9.5	4.973					
Sandstone	105.42		11.29	4.979					
Sandstone	105.47		11.356	5.007					
Marl	24.9	3.56	0.76			6.99	0,75	6.66	[80]
Marl	34	7.9	1.5			4.30	0,62	11.59	
Marl	16.9	2.13	0.46			7.93	0,78	4.24	
Marl	24.8	2.29	0.72			10.83	0,83	5.33	
Clayey marl	2.7	0.06	0.07			45.00	0,96	0.28	
Marl	23.8	6.03	1.05			3.95	0,60	8.47	
Sandstone	43.2	3			15.4	14.40	0,87	8.05	[81]
Sandstone	64.53	4.34			22.5	14.87	0,87	11.83	
Limestone	68.92	3.93		4.45	30.29	17.54	0,89	11.64	[82]
Limestone	115.79	8.41		6.13	61.95	13.77	0,86	22.07	
Limestone	121.8		5.17	5.73	40.42				[83]
Limestone	99		4.61	4.99	30.97				
Limestone	90.6		4.29	3.98	19.74				
Limestone	74.2		2.24	3.21	16.68				
Limestone	138.1		5.77	6.75	46.23				
Limestone	134.2		5.46	6.08	45.48				
Limestone	109.1		5.07	5.86	38.06				
Limestone	92.4		4.3	4.84	34.16				
Limestone	118.2		4.85	5.94	46.81				
Limestone	100.5		3.89	5.59	36.51				
Limestone	131.6		6.32	6.2	41.56				
Limestone	114		4.86	5.55	42.64				
Limestone	76		1.74	3.6	18.58				
Limestone	111		4.42	4.99	44.3				
Limestone	93.7		3.4	4.67	31.6				
Limestone	86.4		3.55	3.88	24.75				
Limestone	124.8		6.3	6.02	41.46				
Limestone	81.6		2.61	3.47	18.95				
Limestone	90		3.31	3.62	17.62				
Limestone	85.8		3.54	3.52	16.77				
Mudrock-Shale	54.37	4.67	2.457	2.548	5.158	11.64	0,84	11.27	[84]
Marl	24.93	3.56	0.47	2.33	5.19	7.00	0,75	6.66	[85]
Marl	23.4	2.85	0.44	2.44	3.3	8.21	0,78	5.77	
Marl	24.8	2.29	0.72	2.43	8.37	10.83	0,83	5.33	
Limestone	163	10.1	4.1	5.69	19.3	16.14	0,88	28.69	[77]
Sandstone	160	12	4	5.18	20.7	13.33	0,86	30.98	
Limestone	127	10.3	3	6	19.7	12.33	0,85	25.57	
Sandstone	122	10.3	3.3	4.75	18.1	11.84	0,84	25.07	
Limestone	112	9.8	2.2	5.84	15.9	11.43	0,84	23.43	
Sandstone	111	9.2	2.6	4.58	13.2	12.07	0,85	22.60	
Travertine	62	1.7	1.7	4.5	13	36.47	0,95	7.26	
Marl	64.9	4.4	3	3.4	4.758	14.75	0,87	11.95	[86]
Marl	11.4	1	0.8	1	0.241	11.40	0,84	2.39	
Marl	21.4	2.2	1.7	1	1.595	9.73	0,81	4.85	
Marl	13.5	1.5	1.4	1.5	0.98	9.00	0,80	3.18	
Limestone	123.8	6.6	5.3	5.3	10.682	18.76	0,90	20.21	
Limestone	45.1	6	4.6	3.3	22.419	7.52	0,77	11.63	
Sandstone	70.5	5.5	6.3	3.7	13.855	12.82	0,86	13.92	
Limestone	42.1	6	4.4	4.7	16.757	7.02	0,75	11.24	
Sandstone	45.2	5.8	3.6	4.5	11.092	7.79	0,77	11.45	
Dolomite	68	6	3.5	6.3	6.83	11.33	0,84	14.28	
Limestone	51.3	7	4.6	5.4	7.193	7.33	0,76	13.40	
Marl	39.5	5.2	2.7	3.1	4.06	7.60	0,77	10.13	
Limestone	15.7	0.9	1.1	2.2	0.79	17.44	0,89	2.66	
Limestone	85.2	9.1	8	5.5	20.253	9.36	0,81	19.69	
Limestone	70.56	5.5	3.9	4	12.517	12.83	0,86	13.93	
Limestone	49.7	7.75	-	-	23.1	6.41	0,73	13.88	[87]
Limestone	53.5	5.5	-	-	19.6	9.73	0,81	12.13	
Limestone	85.6	8.45	-	-	24.2	10.13	0,82	19.02	
Limestone	87.2	7.4	-	-	23.9	11.78	0,84	17.96	
Sandstone	102.94	11.74	9.41	-	48.7	8.77	0,80	24.58	[88]
Limestone	83.63	4.77	6.28	-	15.25	17.53	0,89	14.12	
Claystone	57.9	5.6	-	-	-	10.34	0,82	12.73	[89]
Sandstone	113.6	6.6	-	3.74	17	17.21	0,89	19.36	
Sandstone	87.4	8.3	-	5.2	33.3	10.53	0,83	19.04	
Siltstone	58	5.3	-	4.95	30	10.94	0,83	12.40	
Sandstone	173.7	11.6	-	5.33	28	14.97	0,87	31.74	
Slate	150	-	-	5.046	-	-		-	[90]
Slate	181	-	-	4.743	-	-		-	
Limestone	68	-	-	5.036	-	-		-	
Sandstone	64.7	6.3	-	3.148	-	10.27	0,82	14.28	
Sandstone	44.1	2	-	2.582	12.5	22.05	0,91	6.64	[91]
Sandstone	36.6	0.9	-	2.385	14	40.67	0,95	4.06	
Sandstone	35.1	1.8	-	3.26	7.5	19.50	0,90	5.62	

* Calculated values by the author

used in many studies[45–50], although it remains only an indication and there is no physical basis for using the ratio as a brittleness indicator.

Evans and Pomeroy[51] showed theoretically that the impact energy of a cutter pick is inversely proportional to brittleness. Singh[52] indicated that cuttability, penetrability, and the Protodyakonov strength index of coal strongly depend on the brittleness of coal. Singh[53] also showed that a linearly proportional relationship existed between *in situ* specific energy and the brittleness (B_2) of three Utah coals. Goktan[54] stated that the brittleness concept (B_2) adopted in his study might not be a representative measure of specific energy consumption during rock cutting. Kahraman[55] statistically investigated the relationships between three different brittleness indices and both drillability and borability using the raw data obtained from the experimental work of different researchers. Altindag[56–58] found significant correlations between his proposed new brittleness concept (B_3) and the penetration rate of percussion drills, the drillability index in rotary drilling, and the specific energy in rock cutting. Kahraman and Altindag[59] correlated fracture toughness values with different brittleness values using the raw data obtained from the experimental works of two researchers. They indicated that the Altindag's brittleness concept (B_3) can be used as a predictive rock property for the estimation of the fracture toughness value. Kahraman *et al.*[60] found a strong correlation between Los Angeles abrasion loss and the brittleness (B_3) for 26 different rocks. Gunaydin *et al.*[61] reported a very strong correlation between hourly production and the brittleness B_3, and they emphasised that the brittleness B_3 is the most reliable index among the brittleness indices used in their study. Yilmaz *et al.*[62] stated that the grain size seems to predominantly influence their relative brittleness index values in granitic rocks. Goktan and Yılmaz[63] investigated the relationships between brittleness (B_1) and specific energy (SE) and no meaningful correlations could be found between B_1 and SE. However, after normalization of SE by uniaxial compressive strength and classification of test data for a particular rock group, the correlation is significantly improved.

The brittleness concepts based on the compressive strength and tensile strength in this study are given as follows:

$$B_1 = \frac{\sigma_c}{\sigma_t} \qquad [1]$$

$$B_2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \qquad [2]$$

$$B_3 = \sqrt{\frac{\sigma_c x \sigma_t}{2}}, (MPa) \qquad [3]$$

where B_1, B_2, and B_3 brittleness indices, σ_c is the uniaxial compressive strength (MPa) and σ_t is the tensile strength (MPa). The calculated values of brittleness for the dataset prepared in this study are displayed in Table II.

Regression analysis applied to rock properties

Many equations, some of which are presented in Table I, are reported in literature to estimate the UCS of rock from the *P*-wave velocity. The majority of the equations yield linear and power relationships between the UCS and *P*-wave velocity. In each study, the amount of data was limited and the same statistical analysis was applied to various rock types, regardless of the differences in their geological origins. Thus, a concern arises as to the reliability of the empirical equations developed. In this study, only sedimentary rocks were taken into account to improve the reliability of the equations.

Statistical analyses used in this study relying on the relationship between V_p and other intact rock properties were based on the data obtained from different studies. Results of the basic descriptive statistical analysis performed on data set are given in Table III. The boxplot of the dataset is shown in Figure 1.

Simple regression analysis

The raw dataset (Table II) was subjected to least squares regression analysis. Linear ($y = ax+b$), logarithmic ($y = a + \ln x$), exponential ($y = ae^x$), and power ($y = ax^b$) curve fitting approximations were executed and the approximation equations that have the highest correlation coefficient were determined for each regression. A power correlation was found between the UCS and *P*-wave velocity for the entire dataset (Figure 2). The equation of the curve is:

$$UCS = 12.743 Vp^{1.194} \qquad [4]$$

where UCS is the uniaxial compressive strength (MPa) and *Vp* is the *P*-wave velocity (km/s). The correlation coefficient of the relationship is 0.76.

A plot of tensile strength vs. *Vp* is shown in Figure 3. The empirical equation of this relation is:

$$TS = 1.0562 Vp^{1.1222} \qquad [5]$$

where *TS* is the tensile strength (MPa) and *Vp* is the *P*-wave velocity (km/s). The correlation coefficient of the relationship is 0.77.

In Figure 4, a power relationship between point load index and *P*-wave velocity is shown. The equation of the curve is:

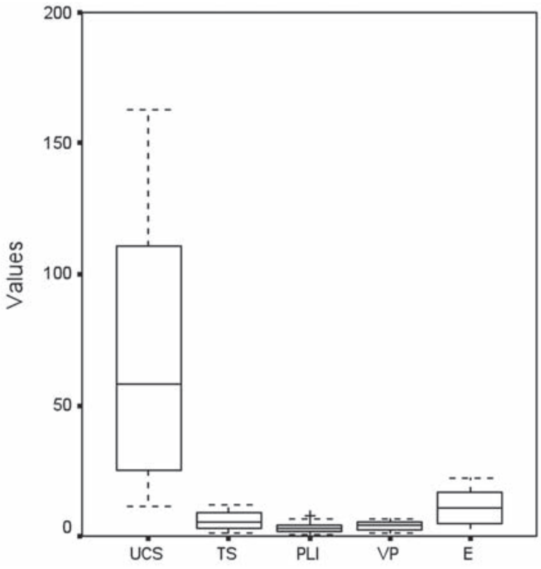

Figure1—Boxplot of the data set

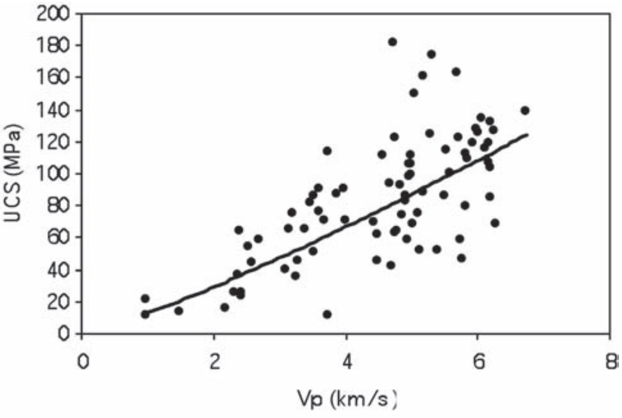

Figure 2—The relationship between the *P*-wave velocity and UCS of rocks

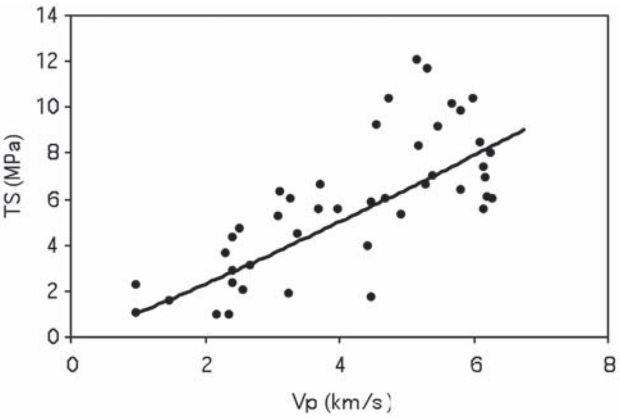

Figure 3—The relationship between the *P*-wave velocity and *TS* of rocks

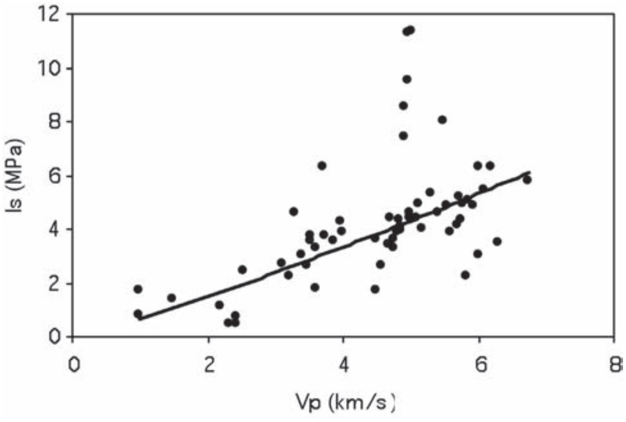

Figure 4—The relationship between the *P*-wave velocity and *Is* of rocks

$$I_s = 0.6709Vp^{1.1556} \qquad [6]$$

where *Is* is the point load index (MPa) and *Vp* is the *P*-wave velocity (km/s). The correlation coefficient of the relation is 0.70.

There is a power relationship between Modulus of elasticity (E_t) and *P*-wave velocity (Figure 5). The equation of the curve is:

$$E_t = 0.919Vp^{1.9122} \qquad [7]$$

where E_t is the modulus of elasticity (GPa) and *Vp* is the *P*-wave velocity (km/s). The correlation coefficient of the relationship is 0.79.

However, the relationships between brittleness B_1 and B_2 and *P*-wave velocity resulted in quite weak correlation coefficients, as seen in Figures 6 and 7. A power correlation between brittleness B_3 and *P*-wave velocity was obtained, as shown in Figure 8. The equation of the curve is:

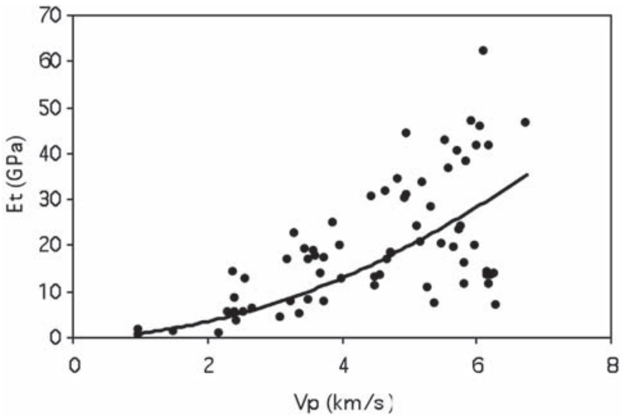

Figure 5—The relationship between the *P*-wave velocity and modulus of elasticity of rocks

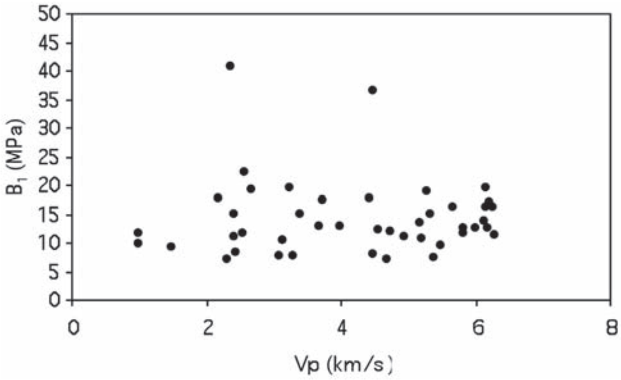

Figure 6—The relationship between the *P*-wave velocity and B_1 of rocks

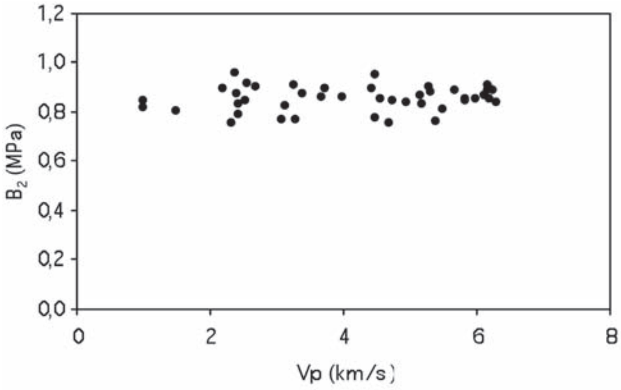

Figure 7—The relationship between the *P*-wave velocity and B_2 of rocks

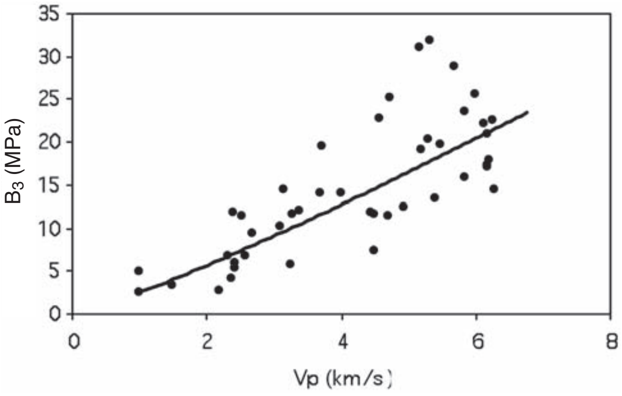

Figure 8—The relationship between the *P*-wave velocity and B_3 of rocks

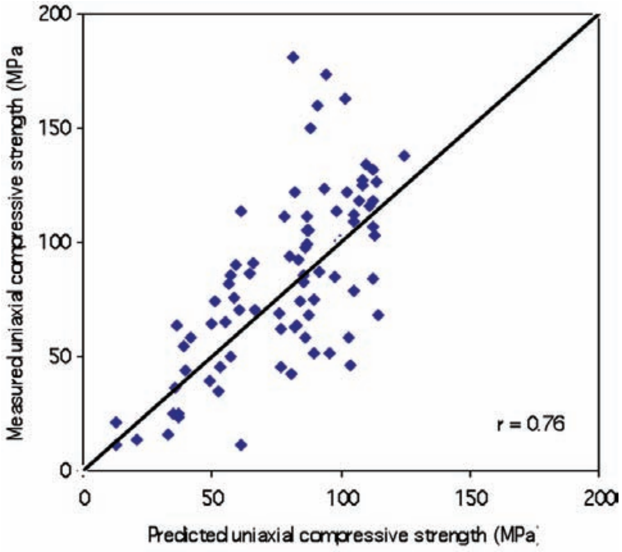

Figure 9—The relationship between the measured and predicted uniaxial compressive strength values from the simple regressions (Equation [4])

$$B_3 = 2.5554Vp^{1.1614} \qquad [8]$$

where B_3 is brittleness and Vp is the *P*-wave velocity (km/s). The correlation coefficient of the relation is 0.84.

Figures 2–8 show the plots of *P*-wave velocity versus uniaxial compressive strength, tensile strength, point load index, modulus of elasticity and brittleness concepts. The results of such regressions also represented good correlations between the properties tested. Relationships are statistically significant according to the student's t-test with 95% confidence.

The scatter diagram of observed and estimated values of UCS of rocks is shown in Figure 9. In the plot of Equation [1], the points are scattered uniformly about the diagonal line, suggesting that the model is reasonable.

Multiple regression analysis

In the second stage of the regression analyses, a series of multiple regression analyses were performed. It may not be always possible to predict the rock strength from a particular rock index test only, owing to the reason that rock strength parameters are a function of physical, textural, and mineralogical properties of rock.

Multiple linear regression analysis was also undertaken, including tensile strength, point load index, and *P*-wave velocity values in the model. The equations derived to estimate the uniaxial compressive strength of sedimentary rocks can be listed as follows:

$$UCS = -7.155 + 6.194\ Vp + 9.774\ TS \qquad [9]$$

$$UCS = -10.029 + 5.734\ Vp + 10.876\ TS - 2.408\ Is \qquad [10]$$

where *UCS* is the uniaxial compressive strength (MPa), *Vp* is *P*-wave velocity (km/s), *TS* is tensile strength (MPa) and *Is* is point load index (MPa). The correlation coefficients are 0.88 and 0.90, respectively.

The multiple regression models to predict the uniaxial compressive strength are summarized in Tables III and IV, and the regression equations obtained are given in Equations [9–10].

The relationships between the measured and the predicted values are illustrated in Figures 10–11. As can be seen, the prediction models appear to be more reliable than that of obtained by simple regression analysis. In addition, determination of *P*-wave velocity, tensile strength, and point load index requires relatively shorter core samples than those needed for uniaxial compressive test. Hence, the predictive models obtained in this study for sedimentary rocks can be suggested as useful tools for researchers and engineers.

Conclusion

The results of simple regression analyses may suggest that the relationships between *P*-wave velocity and uniaxial compressive strength, point load index, modulus of elasticity,

Table III

Multiple regression model for the prediction of uniaxial compressive strength (coefficient of correlation is 0.88)

Independent variables	Coefficient	St. error	t-values	Sig. level
Constant	-7.155	8.761	-0.817	0.419
P-wave velocity	6.194	2.928	2.116	0.040
Tensile strength	9.774	1.553	6.293	0.000

Table IV

Multiple regression model for the prediction of uniaxial compressive strength (coefficient of correlation is 0.90)

Independent variables	Coefficient	St. error	t-values	Sig. level
Constant	-10.029	11.375	-0.882	0.388
P-wave velocity	5.734	4.731	1.212	0.238
Tensile strength	10.876	2.250	4.833	0.000
Point load index	-2.408	2.957	-0.815	0.424

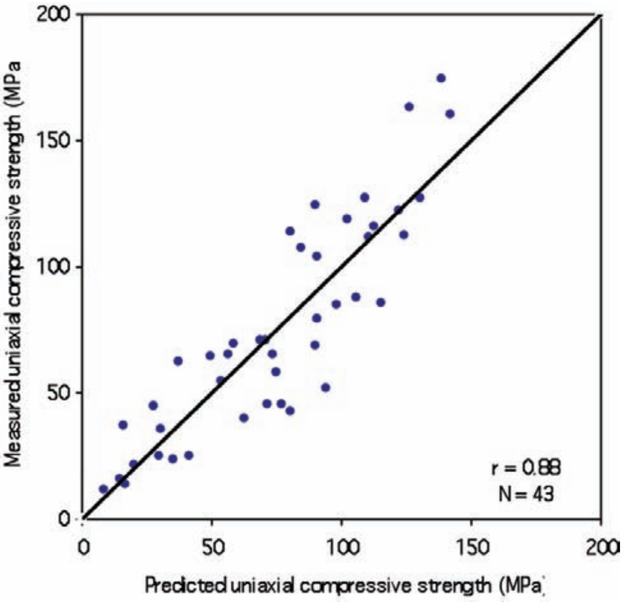

Figure 10—The relationship between the measured and predicted uniaxial compressive strength values from the multiple regression (Equation [9])

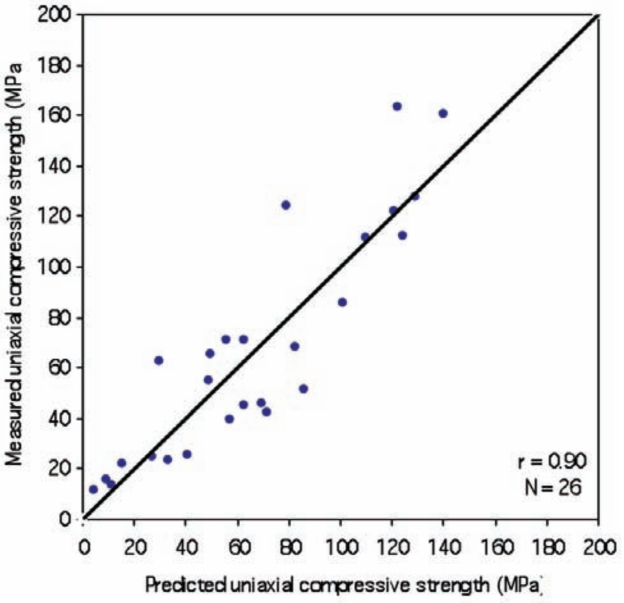

Figure 11—The relationship between the measured and predicted uniaxial compressive strength values from the multiple regression (Equation [10])

and brittleness values are meaningful. Two equations with high prediction performance were developed by multiple regression analysis for the prediction of uniaxial compressive strength.

The relationship equation between the *UCS*, *Vp,* and *TS* is:

$$UCS = -7.155 + 6.194\ Vp + 9.774\ TS \qquad [11]$$

Equation [9] is simple and easier to use to predict the uniaxial compressive strength than other multiple regression equations.

Under certain conditions, it may be difficult and complicated to measure the uniaxial compressive strength of rocks. The use of empirical relationships to estimate the uniaxial compressive strength of rock can be more practical and economical.

The equations found in the literature are derived using the rocks from different geological origins to estimate the UCS from *P*-wave velocity. The author of this work believes that the geological origins of rocks should be taken into account separately in statistical analysis when seeking for the relationships between *P*-wave velocity and UCS of rocks.

In this way, more reliable predictions will be possible for project engineers and researchers.

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