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P-wave velocity test for assessment of geotechnical properties of some rock materials

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Abstract. ***P*-wave velocity test, a non-destructive and easy method to apply in both field and laboratory conditions, has increasingly been conducted to determine the geotechnical properties of rock materials. The aim of this study is to predict the rock properties including the uniaxial compressive strength, Schmidt hardness, modulus of elasticity, water absorption and effective porosity, slake durability index, saturated and dry density of rock using *P*-wave velocity (V_p). For this purpose geotechnical properties of nine different rock types were determined in the laboratory and their mineralogical composition examined using thin section analysis. Utilizing the generated data, sets of empirical equations were developed between V_p and relevant quantified rock parameters. The validity of the obtained empirical equations was confirmed using statistical analysis. It is evident that rock texture and mineralogical compositions affect the geotechnical properties of rock materials. Therefore, the best relationship obtained between both E and UCS with V_p in the correlation coefficient of 0·92 and 0·95 in that order. It is concluded that V_p could be practically used for estimating the measured rock properties except dry and saturated density of rocks ($r = 0{\cdot}58$ and 0·46 respectively).**

Keywords. **Empirical equations; *P*-wave velocity; regression analysis; rock properties.**

1. Introduction

P-wave velocity test that can be carried out both in the laboratory and on-site is a common non-destructive testing method used in civil, geotechnical and mining projects such as underground opening, quarrying, blasting and ripping. Seismic techniques can be used for predicting the rock mass deformation and stress as well as extend of damage zone developed around the underground opening and tunnels (Onodera 1963; Hudson *et al* 1980; Gladwin 1982). The method is also commonly used for determination of rock weathering degree and rock mass characterization (Turk and Dearman 1986; Karpuz and Pasamehmetoglu 1997; Boadu 1997). Thill and Bur (1969) stated that the *P*-wave velocity changes with porosity and degree of saturation. Lama and Vutukuri (1978) indicated that the wetting of rock usually leads to a rise in the *P*-wave velocity. Several researchers (Hawkins and McConnell 1992; Ulusay *et al* 1994; Tugrul and Zarif 1999; Kahraman 2001; Yasar and Erdogan 2004; Kahraman and Yeken 2008; Sharma and Singh 2007; Yagiz 2009) reported that the V_p has relationship with some rock properties such as uniaxial compressive strength, hardness, density and slake durability index of rock as shown in table 1. However, obtained correlations are not constant and can be varied with rock types. This paper attempts to investigate the empirical relationship between V_p and rock properties including the uniaxial compressive strength (UCS), modulus of elasticity (E), Schmidt hardness (Hr), slake durability index (Id_2), effective porosity (n'), water absorption by weight (w), and both saturated (ρ_{sat}) and dry (ρ_{dry}) density of rocks. Further, obtained results are also compared with previous studies in the literature.

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2. Rock sampling and laboratory tests

Rock blocks were collected from various stone quarries located around the cities of Denizli and Antalya in southwestern Turkey (figure 1). Nine different rocks consisting of four types of travertine, three types of limestone and two types of schist were collected from the study area. Each rock block was inspected to ensure that it would provide standard testing specimens without macroscopic defects, alteration zones and fractures. Following the European Norms (EN 2000a, b) and ISRM (1981) suggested methods, relevant rock properties i.e. V_p, UCS, E, Hr, Id_2, n', w, ρ_{sat} and ρ_{dry} were determined. For each test, 10 rock samples were prepared. The average values obtained along with the standard deviation are given in table 2. Entire tests were performed on intact rock samples. If a rock failed along the anisotropy zone or weak-

Table 1. Relationship between V_p with both ρ and UCS.

Researchers	Equations	*r* value	Rock type/ lithology	UCS (MPa) ρ (g/cm^3)	V_p (km/s)
Tugrul and Zarif (1999)	$UCS = 35{\cdot}54{\cdot}V_p - 55$	0·80	Igneous rocks	100–200	4·5–6·5
Kahraman (2001)	$UCS = 9{\cdot}95{\cdot}V_p^{1{\cdot}21}$	0·83	Limestone, marble	10–160	1·2–6·4
Yasar and Erdogan (2004)	$UCS = (V_p - 2{\cdot}0195)/0{\cdot}032$	0·81	Lime, marble, dolomite	38–120	2·9–5·6
	$\rho = (V_p + 7{\cdot}707)/4{\cdot}3183$	0·80		2·43–2·97	2·9–5·6
Sharma and Singh (2007)	$UCS = 0{\cdot}0642{\cdot}V_p - 117{\cdot}99$	0·90	7 types of rocks	10–1970	2–3.2.0
	$Id_2 = 0{\cdot}069{\cdot}V_p + 78{\cdot}577$	0·88		–	–
Kahraman and Yeken (2008)	$\rho = 0{\cdot}213{\cdot}V_p + 1{\cdot}256$	0·82	Carbonate rocks	2·0–2·6	3·6–6·1
This study	$UCS = 0{\cdot}258{\cdot}V_p^{3{\cdot}543}$	0·92	9 types of rock	20–125	1·89–6·1
	$UCS = 49{\cdot}4{\cdot}V_p - 167$	0·89		–	–
	$\rho = 0{\cdot}19{\cdot}V_p + 1{\cdot}61$	0·58		2·15–2·85	1·8–6·1
	$Id_2 = 0{\cdot}71{\cdot}V_p + 95{\cdot}7$	0·69		–	–

*UCS = uniaxial compressive strength (MPa), V_p = *P*-wave velocity (km/s), ρ = density (g/cm^3)

Table 2. Geotechnical properties of studied rock units based on averaged properties and standard deviation.

Sampling locations	Rock type	V_p ± SD (km/s)	Hr $\bar{x}$ ± SD –	UCS $\bar{x}$ ± SD (MPa)	*E* $\bar{x}$ ± SD (GPa)	*n′* $\bar{x}$ ± SD (%)	*w* $\bar{x}$ ± SD (%)	ρ_{dry} $\bar{x}$ ± SD (g/cm^3)	ρ_{sat} $\bar{x}$ ± SD (g/cm^3)	Id_2 $\bar{x}$ ± SD (%)
Denizli/Kocabas	Shrub travertine	4·8 ± 0·12	45 ± 4·5	61 ± 20·6	43 ± 6·9	1·35 ± 0·46	0·55 ± 0·19	2·474 ± 0·25	2·488 ± 0·22	98·91 ± 0·10
Denizli/Kocabas	Noche travertine	5·0 ± 0·08	47 ± 3·1	64 ± 10·9	44 ± 3·3	1·59 ± 0·89	0·66 ± 0·38	2·419 ± 0·48	2·435 ± 0·42	98·55 ± 0·14
Denizli/Kaklık	Reed travertine	4·5 ± 0·11	39 ± 4·7	41 ± 16·6	35 ± 5·8	1·89 ± 0·50	0·80 ± 0·22	2·362 ± 0·56	2·381 ± 0·54	98·87 ± 0·12
Denizli/Honaz	Onyx travertine	4·7 ± 0·19	51 ± 3·3	58 ± 15	44 ± 5·2	2·05 ± 0·88	0·76 ± 0·34	2·715 ± 0·46	2·735 ± 0·38	99·24 ± 0·07
Antalya/Korkuteli	Beige lime	5·0 ± 0·17	54 ± 1·9	82 ± 28·3	46 ± 4·0	0·16 ± 0·10	0·06 ± 0·04	2·682 ± 0·08	2·683 ± 0·08	99·43 ± 0·04
Denizli/Bozkurt	Dolomitic lime	4·9 ± 0·29	53 ± 2·4	92 ± 33·3	52 ± 11·8	0·60 ± 0·27	0·22 ± 0·10	2·778 ± 0·34	2·784 ± 0·32	99·65 ± 0·06
Antalya/Elmali	Soft lime	3·8 ± 0·41	41 ± 3·6	32 ± 3·7	22 ± 4·7	9·70 ± 2·20	4·24 ± 1·14	2·311 ± 0·98	2·408 ± 0·78	98·49 ± 0·25
Denizli/Bekilli	Biotite schist	5·1 ± 0·44	58 ± 4·4	98 ± 7·1	51 ± 7·9	0·74 ± 0·11	0·29 ± 0·04	2·547 ± 0·42	2·554 ± 0·43	n/a
Denizli/Baklan	Mica schist	5·6 ± 0·32	59 ± 1·1	114 ± 13·4	57 ± 6·8	0·43 ± 0·53	0·17 ± 0·21	2·638 ± 0·72	2·642 ± 0·67	n/a

$\bar{x}$ = Average values and SD = Standard deviation.

ness plane, the results were excluded. V_p is measured on samples by direct transmission using a Portable Ultrasonic Nondestructive Digital Indicating Tester (PUNDIT) that measures the time of propagation of ultrasound pulses with a precision of 0·1 μs and its transducers were 42 mm in diameter with 54 kHz (figure 2). V_p test was performed perpendicular to observed layers. The *P*-wave velocity of studied rocks ranges from 3·8–5·1 km/s and can be classified as shown in table 3.

3. Mineralogical composition of rock materials

Block rocks including travertine, limestone and schist were collected from various rock quarries in southwestern Turkey (figure 3). Mineralogical and textural studies were conducted on prepared thin section samples using optical microscope in accordance with EN 12407 (2002) Standard (table 4). Travertine, from Quaternary to Neogene ages, is one of the most common carbonate rocks in the area. Travertine precipitated at different depositional conditions shows variations of colour, appearance, bedding, porosity, texture and composition (Chafetz and Folk 1984; Yagiz 2010). Travertine litho types in the basin mainly include shrub, onyx, reed and noche. Shrub type travertine represented by small bush like growths in the field is a common deposit on horizontal and sub horizontal surface in the basin (figure 3a). Noche, a commercial name for compact and dense reed type travertine is dark brownish in colour, dense and low porous (figure 3b). Reed travertine is one of the prominent elements in the study area and rich in molds of reed and coarse grass as in figure 3c (Guo and Riding 1998). Onyx travertine is commonly formed as a result of rapid precipitation due to fast flowing water on gentle slope. Dense, crudely fibrous and light coloured one is composed of elongated calcite feathers and developed perpendicular to the depositional surface (figure 3d). Jurassic aged beige coloured crystalline limestone and Eocene aged white coloured, fine grained spray-calcite cemented limestone outcrops around the City of Antalya (figures 3e and f). Dolomitic limestone is dark coloured, medium to coarse grained and massive in Eocene age (figure 3g). Two types of schist outcropped around the Denizli basin is categorized according to their mineralogical properties (figures 3h and i).

Figure 1. Sampling locations in the study area.

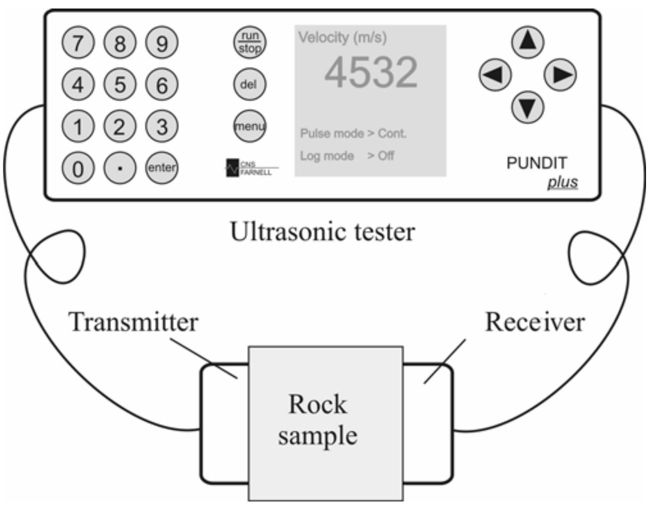

Figure 2. *P*-wave velocity apparatus utilized in this study.

4. Statistical analysis and discussions

Using the linear and nonlinear regression techniques including simple or multiple analysis for predicting the unknown from known variables are commonly encountered in the literature (O'Rourke 1989; Cargill and Shakoor 1990; Kahraman 2001; Sharma and Singh 2007; Yagiz 2008, 2009a). In this study, to develop the sets of empirical equations between V_p and other rock properties including uniaxial compressive strength, modulus of elasticity, Schmidt hardness, slake durability index, effective porosity, water absorption by weight, and both saturated and dry density of rocks, linear and nonlinear simple regression analysis were performed with 95% confidence limits. To investigate the reliability of the obtained relationships, *t*-test and factor of significance (*P*-value) test were conducted among the achieved equations using the SPSS version 15 (2007) statistical package. Set of equations developed between the V_p and measured rock properties using regression analysis are given in table 5. The significance of *r*-value can be determined by various statistical tests such as *t*-test and *P*-value test that is also known as observed level of significance test (α). The *t*-test compares the computed values with tabulated values using null hypothesis (Levine *et al* 2001). According to the *t*-test, when computed *t*-value is greater than tabulated *t*-value, the null hypothesis is rejected and obtained correlation coefficient (*r*-value) is acceptable. Also, observed level of significance is often used in hypothesis test. In this case, as *p*-value is smaller than level of significance ($\alpha = 0{\cdot}05$), the null hypothesis is rejected. Therefore, it means that there is a relation between the correlated parameters and this shows that *r*-value is significant.

In this study, the result of the regression analysis indicates that V_p have reliable relationship with the E, UCS, Hr, n', and water absorption by weight (figures 4–8) in accordance with the result of statistical analysis. On the other hand, the relation between V_p and Id_2 is not strong

Table 3. *P*-wave velocity classification (Anon 1979).

V_p (km/s)	Description
< 2·5	Very low
2·5–3·5	Low
3·5–4·0	Moderate
4·0–5·0	High
> 5·0	Very high

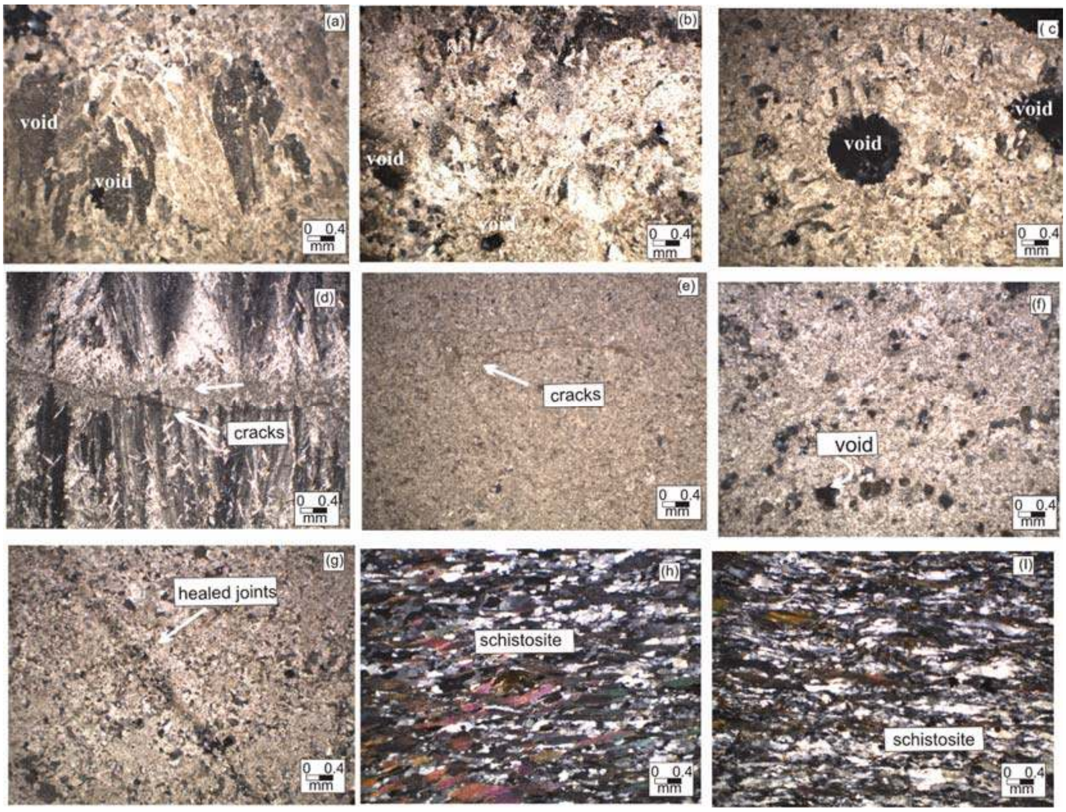

Figure 3. Mineralogical and textural studies of rock using thin section analysis (× 10); (**a**) Shrub travertine (**b**) Noche travertine (**c**) Reed travertine (**d**) Onyx travertine (**e**) Beige limestone (**f**) Soft limestone (**g**) Dolomitic limestone (**h**) Biotite schist (**i**) Muscovite schist.

Table 4. Mineralogical and petrographical composition of studied rocks together with location.

Rock type/ lithology	Locations	Microscopic description	Grain size
Sedimentary/ shrub travertine	Denizli/ Kocabas	Sparite micrite cemented, densely packed texture, crystals 5–10 μm in size with no internal architecture	Fine to fine medium
Sedimentary/ Noche travertine	Denizli/ Kocabas	Sparite calcite cemented. Crystal size 20 μm or more in dia; compact texture with low pores and organic matter.	Fine to medium
Sedimentary/ reed travertine	Denizli/ Kaklik	Sparite calcite cemented, crystal size from 20–150 μm in diameter. Relatively more organic content and porous.	Fine to medium
Sedimentary/ onyx travertine	Denizli/ Honaz	Micrite and sparite cemented matrix, dark coloured. Sparry crystals 10 μm wide and 100–200 μm in length with iron content, layered texture.	Fine with organic matter
Sedimentary/ beige limestone	Antalya/ Korkuteli	Sparite calcite cemented, micro crack observed with coarse spar-calcite and calcite fillings, no fossils.	Medium to coarse
Sedimentary/ dolomitic lime	Denizli/ Bozkurt	Sparite and micrite cemented texture with healed joints filled with secondary calcite fillings.	Medium to coarse
Sedimentary/ white limestone	Antalya/ Elmali	Sparite calcite cemented, light cream coloured, some micro fossils with no cracks.	Fine grain
Meta-sedimentary/ quartz-biotite-schist	Denizli/ Bekilli	Crystal size 0·1–0·2 mm, elongated calcite and quartz crystals along the schistose, quartz biotite, mica schist with opaque and schistose texture.	Fine to medium fine
Meta-sedimentary/ quartz-mica-schist	Denizli/ Baklan	Crystal size 0·1–0·2 mm, elongated calcite and quartz crystals along the schistose, quartz muscovite, schist with opaque and schistose texture.	Fine to medium fine

Table 5. Empirical equations between V_p and the measured rock properties.

Rock properties	Equations	r-value	t-value	t-table	P-value < α = 0·05
E (GPa)	$E = 20{\cdot}1{\cdot}V_p - 53$	0·95	8·22	± 2·31	0·000
UCS (MPa)	$\text{UCS} = 49{\cdot}4{\cdot}V_p - 167$	0·89	5·22	± 2·31	0·001
n' (%)	$n' = -5{\cdot}19{\cdot}V_p + 27{\cdot}1$	0·86	−4·53	± 2·31	0·003
w (%)	$w = -2{\cdot}23{\cdot}V_p + 11{\cdot}6$	0·85	−4·30	± 2·31	0·004
Hr	$\text{Hr} = 11{\cdot}68{\cdot}V_p - 6{\cdot}64$	0·80	3·55	± 2·31	0·009
Id_2	$Id_2 = 0{\cdot}71{\cdot}V_p + 95{\cdot}7$	0·69	2·12	± 2·31	0·088
ρ_{dry} (g/cm^3)	$\rho_{dry} = 0{\cdot}19{\cdot}V_p + 1{\cdot}61$	0·58	1·85	± 2·31	0·107
ρ_{sat} (g/cm^3)	$\rho_{sat} = 0{\cdot}14{\cdot}V_p + 1{\cdot}88$	0·46	1·40	± 2·31	0·206

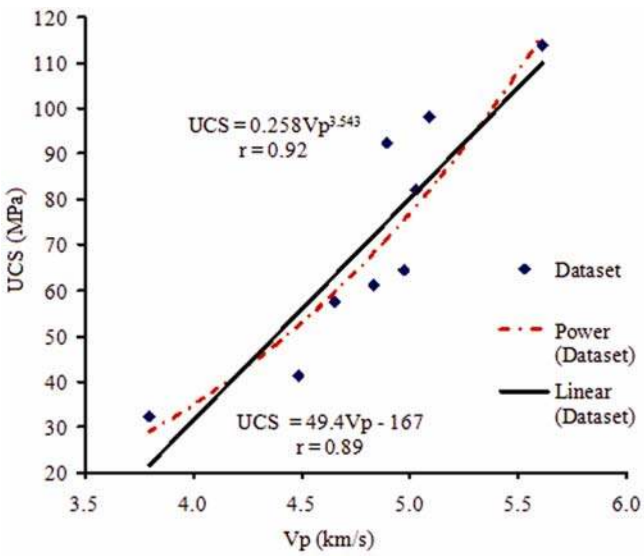

Figure 4. Relationship between the UCS and V_p.

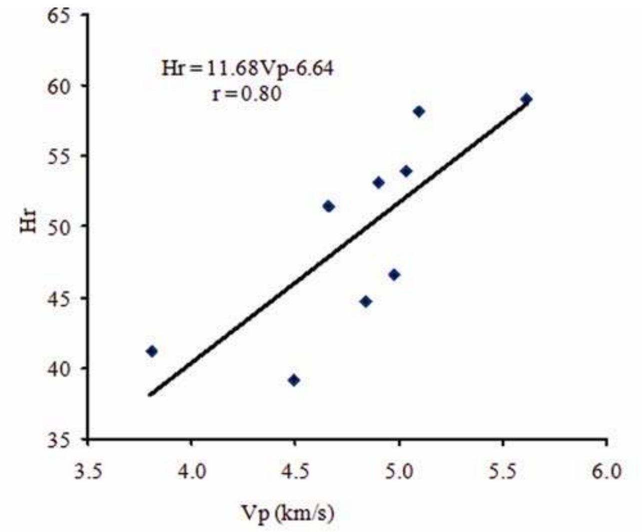

Figure 6. Relationship between the Hr and V_p.

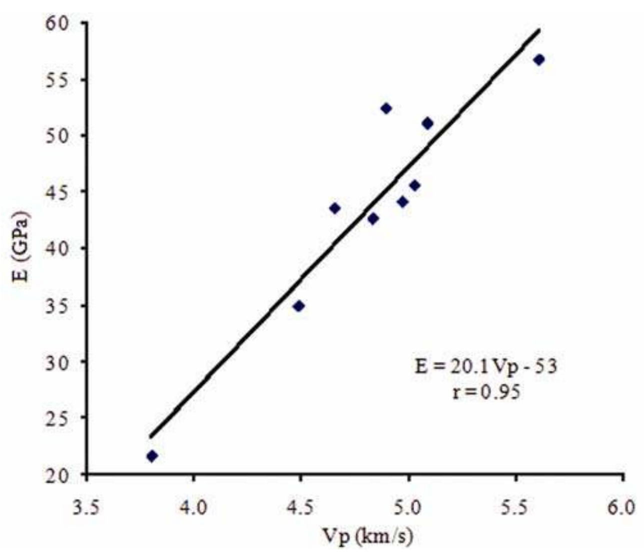

Figure 5. Relationship between the E and V_p.

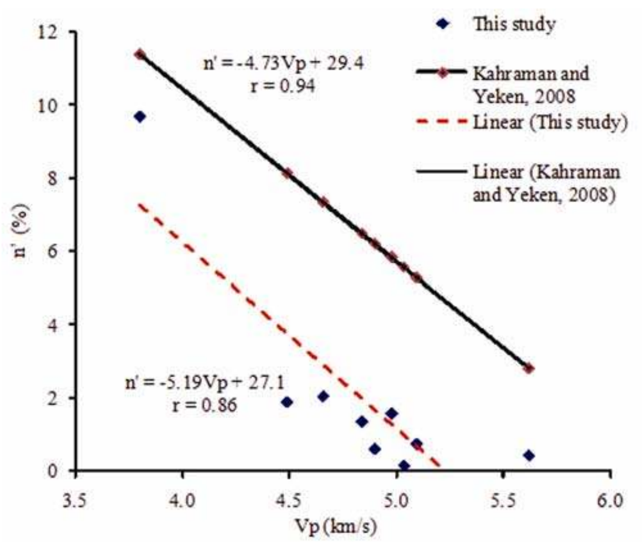

Figure 7. Relationship between the n' and V_p.

enough to rely on ($r = 0{\cdot}69$) as given in figure 9. Further, the V_p provides lower relationship with dry and saturated density of rock with $r = 0{\cdot}58$ and 0·46 respectively (figure 10). To evaluate the validity of the generated equations between the rock properties and P-wave velocity, obtained empirical equations are compared with those equations available in the literature. The relationship between V_p and rock properties including effective porosity, water absorption by weight and slake durability index are compared with the previous studies in figures 7–9. Further, produced empirical relationship between V_p and both UCS and dry density of rocks are also associated with previous researches in figures 11 and 12. As seen from the figures 7–12, the obtained equations and coefficient of correlations are various ranging from 0·46 to 0·95.

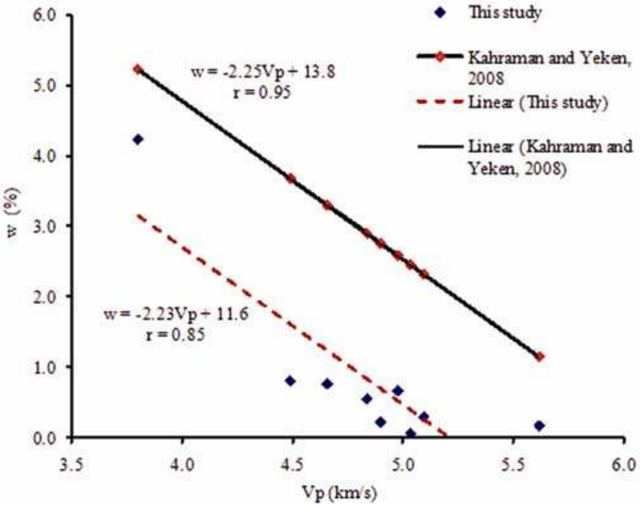

Figure 8. Relationship between the w and V_p.

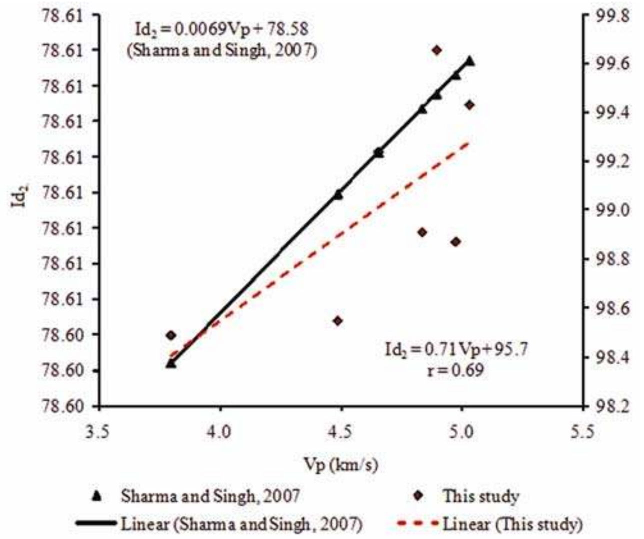

Figure 9. Relationship between Id_2 and V_p together with previous study from literature.

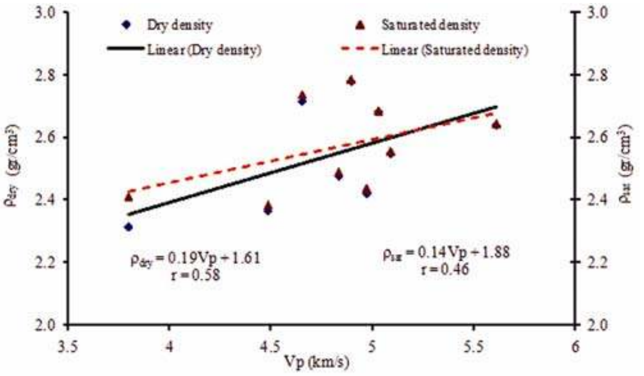

Figure 10. Relationship between both the ρ_{dry} and ρ_{sat} with V_p.

5. Conclusions

Using the standard testing methods, nine different rock types were tested and the results examined to generate

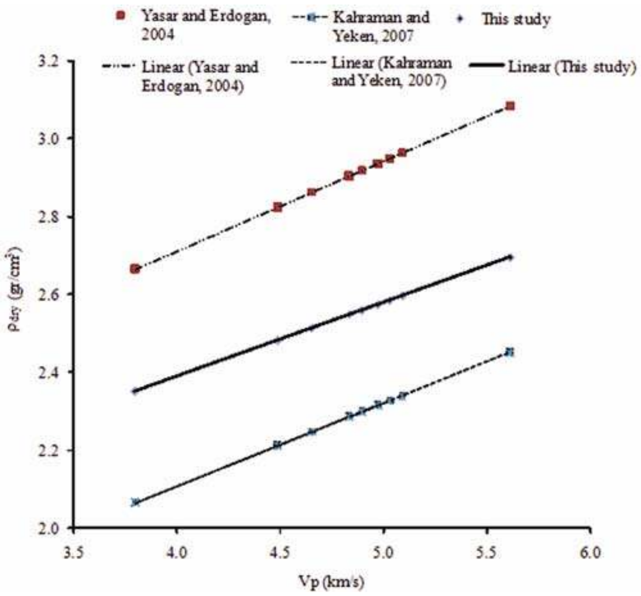

Figure 11. Comparison of the obtained results with previous researches; ρ_{dry} vs V_p.

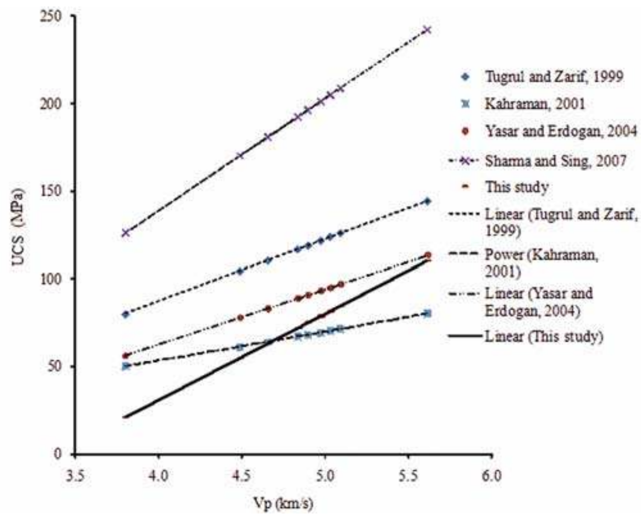

Figure 12. Comparison of the obtained results with previous researches; UCS vs V_p.

empirical relationship between V_p and rock properties including uniaxial compressive strength, modulus of elasticity, Schmidt hardness, slake durability index, effective porosity, water absorption by weight and both dry and saturated density of rocks. Further, petrographical and mineralogical studies were conducted using thin section analysis. It is evident that rock texture and type have great affect on their geotechnical properties. The result shows that the UCS, E, Hr, n', w and Id_2 of rocks can be estimated by conducting V_p test that is non-destructive, simple, faster and a relatively economic method for rock characterization. The best relationships obtained between the V_p and both UCS and E were with correlation coefficient of 0·92 and 0·95, respectively. The relationship between the V_p and measured rock properties are acceptable according to the statistical analysis including *t*-test, *p*-value test and coefficient of correlations except that obtained between the V_p and both dry and saturated unit weight of rock ($r = 0{\cdot}58$ and 0·46, respectively). The investigated rock properties excluding dry and saturated density of rock can be estimated as function of V_p using derived equations; however, those equations should be used with care for only similar rocks.

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