P and S wave velocity of rocks in Jharia coalfield region for assessment of its geotechnical properties in dry, semi-saturated and saturated conditions

Shankar Kumar[1,*], A. K. Mishra[2], B. S. Choudhary[2]

1. JRF Dept of Mining Engg., India

2. Dept of Mining Engg IIT(ISM) Dhanbad, Dhanbad, India

Shankar729@rediffmail.com

ABSTRACT. *P-wave and S-wave velocity of the rock samples (Shale, Sandstone, Coal and Shaley sandstone) were determined in the laboratory in dry, saturated and partially saturated condition to determine the geotechnical rock properties of rock samples. The aim of this study was to predict the rock properties such as uniaxial compressive strength, tensile strength, and S wave from P-wave in dry, Semi saturated and Saturated condition. Highest values of P-wave velocities were obtained in a saturated condition and lowest values were obtained in dry condition. Different geotechnical properties of rock were determined in the laboratory. Utilizing the generated data, sets of empirical equations were developed between P-wave and relevant quantified rock parameters. The validity of the obtained empirical equations was confirmed using statistical analysis. Linear equations have been developed in this paper for estimation S-wave velocity, Uniaxial compressive strength (UCS) and tensile strength in both dry, partially saturated and semi-saturated rock conditions.*

RÉSUMÉ. *La vitesse des vagues P et S des échantillons de roche (schiste, grès, charbon et grès de Shaley) a été déterminée en laboratoire dans des conditions sèches, saturées et partiellement saturées afin de déterminer les propriétés géotechniques des échantillons de roche. Le but de cette étude était de prédire les propriétés de la roche telles que la résistance à la compression uniaxiale, la résistance à la traction et les vagues P et S dans des conditions sèches, semi-saturées et saturées. Les valeurs les plus élevées de la vitesse de la vague P ont été obtenues à l'état saturé et les valeurs les plus basses ont été à l'état sec. Différentes propriétés géotechniques de la roche ont été déterminées en laboratoire. À l'aide des données générées, des ensembles d'équations empiriques ont été développés entre les paramètres de la vague P et de la roche quantifiés pertinents. La validité des équations empiriques obtenues a été confirmée par analyse statistique. Des équations linéaires ont été développées dans cet article pour l'estimation de la vitesse de la vague S, de la résistance à la compression uniaxiale (UCS en anglais) et de la résistance à la traction des roches sous les conditions sèche, partiellement saturée et semi-saturée.*

KEYWORDS: *P-wave velocity, S-wave velocity, rock properties, coal mines, rock samples.*

MOTS-CLÉS: vitesse de la vague P, vitesse de la vague S, propriétés des roches, mines de charbon, échantillons de roche.

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1. Introduction

P-wave and S-wave velocities can be determined both in the laboratory as well as the field. It is the most common non-destructive test method used in civil, geotechnical and mining projects such as underground opening, quarrying, blasting and ripping. Seismic waves can also be used to predict the rock mass deformation, stresses developed around the opening in underground or opencast mines or tunnels and also in blasting. (Onodera, 1963; Hudson *et al.*, 1980; Gladwin, 1982). Thill and Bur (1969) found that the P-wave velocity changes with porosity and degree of saturation. A rise in the P-wave velocity. Several researchers (Hawkins and McConnell, 1992; Ulusay *et al.*, 1994; Tuğrul and Zarif, 1999; Kahraman, 2001; Yasar and Erdogan, 2004; Kahraman and Yeken, 2008; Sharma and Singh, 2008; Yagiz, 2009) reported that the P wave has a 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. The p-wave velocity of wet rock can be predicted from the P-wave velocity of dry rock (Kahraman, 2007). This paper attempts to investigate the empirical relationship between P-wave and S-wave and rock properties including the uniaxial compressive strength (UCS), Modulus of elasticity (E), Porosity, water absorption by weight (w), and both saturated (ρ_{sat}) and dry (ρ) density of rocks.

Table 1. Relationship between Vp, ρ and UCS

Researchers name	Equations	R – value	Rock type	UCS (MPa)	Vp(Km/s)
Tugrul and Zarif 1999 [7]	UCS=35.54Vp-55	0.8	Igneous rock	100-200	4.5-6.5
Kahraman 2001[8]	$UCS=9.95Vp^{1.21}$	0.83	Limestone, Marble	10-160	1.2-6.4
Yasar and Erdogan 2004 [9]	UCS=(Vp-2.0195)/0.032	0.81	Lime, marble, dolomite	38-120	2.9-5.6
	ρ=(Vp+7.707)/4.3183	0.80		2.43-2.97	2.9-5.6
Kahraman And Yeken 2008 [10]	ρ=0.213Vp+1.256	0.82	Carbonate rocks	2.0-2.6	3.6-6.1
Sharma And Singh 2008 [11]	UCS=0.0642Vp-117.99	0.90	7 types pf rocks	10-1970	2-3
Yagiz 2009 [12]	$UCS=0.258Vp^{3.543}$	0.92	9 types of rock	20-125	1.89-6.1
	UCS=49.4Vp-167	0.89			-
	ρ=0.19Vp+1.61	0.69		2.15-2.85	1.8-6.1

The classification of p wave velocity of rocks is shown in Table 2 was done by Anon in 1979.

Minear (1982) showed that clay suspended in the pores of sandstone has only a small effect on velocities, whereas both structure and laminated clay result in a dramatic velocity reduction. The presence of pore space reduces the bulk density of the rock. This would appear to increase P-wave and S-wave velocity due to the reduction in density. The effect of a general decrease in P-wave and S-wave velocity with increasing porosity is due to the increase in porosity reducing the rigidity of the rock that decreases both P-wave and S-wave. Pore structure has an effect on both bulk and shear modulus. The p-wave velocity of wet rock can be predicted from the P-wave velocity of dry rock.

Table 2. Classification of rocks on the basis of p wave velocities

Serial no.	Vp (in km/s)	Description
1	Less than 2.5	Very low
2	2.5 – 3.5	Low
3	3.5 – 4.0	Moderate
4	4.0 -5.0	High
5	Greater than 5	Very High

2. Field work and laboratory work

Rock samples were collected from different mines located in the Jharia coalfield region prior to blasting from the benches. The location of the mines is shown in figure 1. Generally, in coal mines, three types of materials encountered in the overburden are Sandstone, shale and shaly sandstone. So, different rock type was collected from each mine. Samples consisted of coal, sandstone, shale and shaley sandstone. Shaley sandstone is the most common occurring rock type in the Indian coal mines in the form of overburden. Each rock block was inspected to ensure that it would provide standard testing specimens without macroscopic defects, alteration zones and fractures. Samples were prepared following the ISRM standards 1981 (Brown, 1981). Relevant rock properties such as Vp, Vs, UCS, Tensile strength and bulk density. For each rock test, 5 different rock samples were taken. Entire rock mass was carried on intact rock mass.

Dry sample preparation: The samples were oven dried at 110 ◦C as shown in figure 2 and there P and S wave velocity was determined. The weight of the samples was taken on weighing machine having least count 0.1 kg as shown in figure 3. Semi saturated sample preparation: Than the samples were kept for one hour immersed in water for partial saturation and its P and S wave velocity was determined. Completely Saturated Sample: Sample was kept for 72 hours immersed in water to attain its full saturation as shown in figure 4. The weight of the samples was measured using a weighing machine of 0.1g least count as shown in figure 4. P wave and S wave velocity of the collected rock samples were determined using

Sonic viewer as shown in figure 5 and 6 respectively. The determination was done in dry, and completely saturated condition.

Figure 1. Sample collecting location of different coal mines in Jharia coalfield area

Figure 2. Samples in oven for drying

Figure 3. Samples being weighed

Figure 4. Samples immersed in water

Figure 5. P wave velocity of rock

Figure 6. S wave Velocity of rocks

2.1. Materials used in the study

2.1.1. Coal

Table 3. Results of different tests conducted on samples

Serial no.	Density(g/cc)	P wave (km/s)	S wave (km/s)	UCS (Mpa)	Tensile strength (Mpa)
1	1.45	2.92	0.68	12.01	1.65
2	1.34	1.72	0.52	8.57	1.26
3	1.45	3.86	0.81	19.25	1.81
4	1.43	3.37	0.69	14.44	1.63
5	1.44	3.48	0.74	18.13	1.79
6	1.49	3.75	0.84	18.25	1.73
7	1.49	3.59	0.94	16.65	1.61
8	1.36	2.5	0.61	14.52	1.62
9	1.34	1.92	0.56	9.56	1.47
10	1.4	2.01	0.57	10.71	1.51

Table 4. Obtained relationships between p wave and rock properties

Sl no.	Material	Rock property	Regression equation	R^2	Range
1	Coking coal	Density	$y=0.2672x^{6.7269}$	0.7859	1.34 -1.49 g/cc
2	Coking coal	UCS	y=4.4299x+1.309	0.8778	8.57 -19.25 Mpa
3	Coking coal	S wave	y=1.522x+0.529	0.8231	0.56 – 0.94 km/s
4.	Coking coal	Tensile strength	0.1745x+1.0999	0.7566	1.26 – 1.81 MPa

10 coal samples were tested for determination of P-wave, S-wave UCS and tensile strength. The bulk density of coal was determined by immersing the sample in the water. Tensile strength and shear strength of the coal sample was also determined in the laboratory. From figure 7 it is observed that S-wave velocity is directly proportional to P wave velocity. A plot of P wave velocity and density, S

wave, uniaxial compressive strength, and tensile strength is shown in figure 7 respectively.

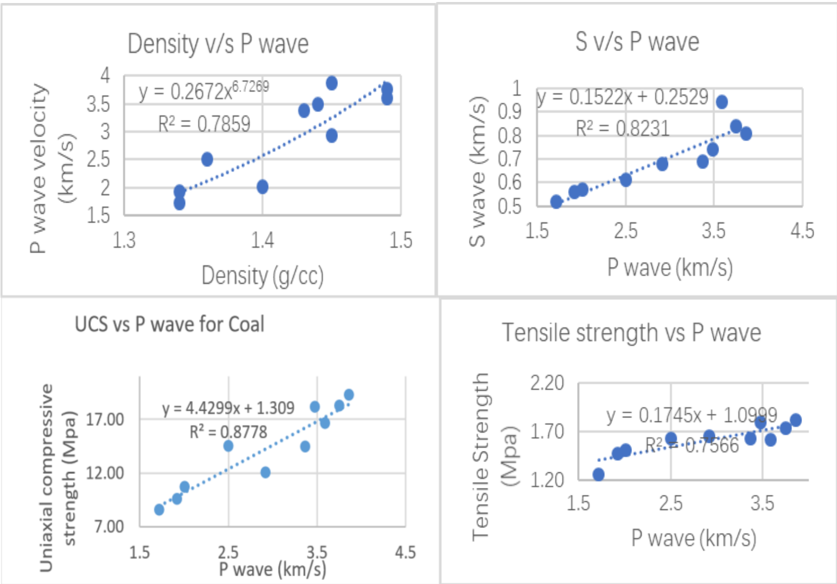


Figure 7. Plot between p wave velocity and tensile strength, density, UCS and S-wave of coal

From Figure 7, it is evident that that as the density of the material increases the P-wave velocity also increases. The relations found are as follows in Table 4:

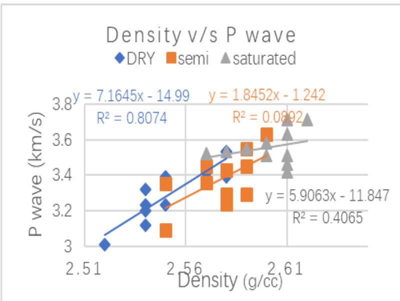
2.2.2. Sandstone

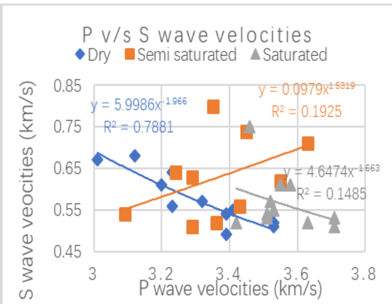
10 samples of sandstone were kept in the P and S-wave testing apparatus was determined and results are shown in table 5 for each of the three conditions. The coal samples were in dried condition saturated and semi-saturated. The semi-saturated samples were prepared by immersing the samples in water for 1 hour. The samples were cored from it blocks brought from different mines. The bulk density was determined by immersing the sample in the water and the tensile strength and shear strength was also determined. The S-wave was undetected for compressive samples due to its large length. Tensile strength and uniaxial compressive strength were determined in the laboratory.

From Figure 8, It is found that the relation between properties of sandstone such as S-wave, UCS and Tensile strength vs P-wave in all three conditions i.e. dry, semi-saturated and saturated is different. The relations obtained in dry samples were found to be more suitable for prediction of geotechnical properties of rock due to its high correlation coefficient values. Hence, it is recommended to use dry P-wave velocity for predictions. The relations found are as follows Table 6.

Table 5. Results of sample

Serial no	Dry density (g/cc)	P wave dry (km/s)	S wave dry (km/s)	Semi- Saturated density (g/cc)	P waves semi saturated (km/s)	S waves semi saturated (km/s)	Saturated density (g/cc)	P waves saturated (km/s)	S waves saturated (km/s)	Uniaxial compressive strength (Mpa)	Tensile strength (Mpa)
1	2.54	3.23	0.56	2.59	3.29	0.63	2.61	3.46	0.75	39.98	7.48
2	2.54	3.12	0.68	2.58	3.24	0.64	2.6	3.51	0.53	33.07	7.27
3	2.54	3.32	0.57	2.55	3.35	0.8	2.61	3.42	0.52	39.47	7.97
4	2.58	3.53	0.51	2.59	3.55	0.62	2.62	3.71	0.51	47.24	8.95
5	2.58	3.39	0.54	2.59	3.45	0.74	2.61	3.63	0.52	38.97	7.54
6	2.55	3.23	0.64	2.58	3.29	0.51	2.6	3.58	0.61	38.24	7.33
7	2.52	3.01	0.67	2.55	3.09	0.54	2.57	3.52	0.57	32.47	7.11
8	2.58	3.53	0.52	2.60	3.63	0.71	2.61	3.71	0.53	45.28	9.1
9	2.57	3.41	0.55	2.58	3.43	0.56	2.61	3.51	0.54	42.34	8.54
10	2.54	3.2	0.61	2.57	3.36	0.52	2.58	3.53	0.55	33.57	7.33
11	2.55	3.39	0.49	2.57	3.45	0.74	2.59	3.55	0.61	41.24	7.52





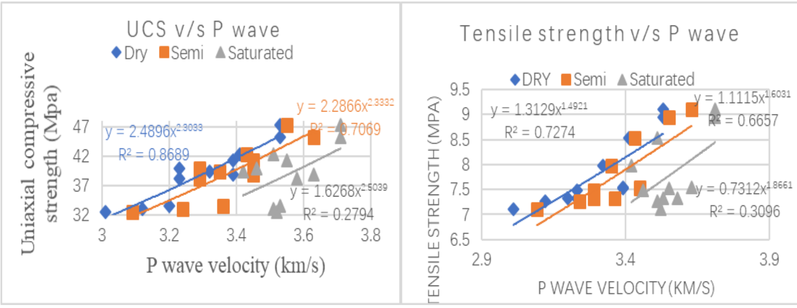


Figure 8. Plot between p wave velocity and tensile strength, desnity, UCS and S-wave of sandstone

Table 6. Regression equation obtained from the plot

Sl no.	Material	Property	Condition of material	Regression equation	R^2	Range
1	Sandstone	Density	Dry	y = 7.1645x - 14.99	0.8074	2.52 - 2.58 g/cc
			Semi	y = 1.8452x - 1.242	0.0892	2.55 – 2.6 g/cc
			Saturated	y = 5.9063x - 11.847	0.4065	2.57 – 2.62 g/cc
2	Sandstone	S-wave	Dry	y = 5.9986x-1.966	0.7881	0.49 – 0.68 km/s
			Semi	$y=0.0979x^{1.5319}$	0.1925	0.51 – 0.8 km/s
			Saturated	$y=4.6474x^{-1.663}$	0.1485	0.51 – 0.75 km/s
3	Sandstone	UCS	Dry	$y=2.4896x^{2.3033}$	0.8869	32.47 – 47.24 Mpa
			Semi	$y=2.8666x^{2.3332}$	0.7069	
			Saturated	$y=1.6268x^{2.5039}$	0.2794	
4	Sandstone	Tensile strength	Dry	$y=1.3129x^{1.4921}$	0.7274	7.11 – 9.1 Mpa
			Semi	$y=1.1115x^{1.6301}$	0.6657	
			Saturated	$y=0.7312x^{1.8661}$	0.3096	

2.2.3. Shaly sandstone

Shaly sandstone rock is the combination of sandstone and shale. The shale band appears in layer between the sandstone. The p wave velocity was dependent on the thickness of the shale. The UCS and tensile strength were also affected by the shale band.

Table 7. Shaly sandstone sample results

Sl no.	Dry density (g/cc)	P wave$_{dry}$ (km/s)	S wave$_{dry}$ (km/s)	Semi-Saturated density (g/cc)	P wave$_{semi saturated}$ (km/s)	S wave$_{semi saturated}$ (km/s)	Saturated density (g/cc)	P wave$_{saturated}$ (km/s)	S wave$_{saturated}$ (km/s)	Tensile strength (Mpa)	Uniaxial compressive strength (Mpa)
1	2.55	1.8	0.47	2.58	1.71	0.56	2.6	1.12	0.56	5.72	18.34
2	2.6	3.13	0.69	2.61	2	0.64	2.63	1.44	0.57	8.11	36.23
3	2.61	2.15	0.57	2.63	2.15	0.65	2.66	1.03	0.58	6.99	27.97
4	2.62	2.84	0.62	2.63	2.75	0.7	2.64	1.31	0.63	7.59	36.82
5	2.61	2.65	0.68	2.62	2.65	1.03	2.65	1.84	1.24	7.25	31.46
6	2.57	2.36	0.63	2.6	2.17	0.64	2.62	1.23	0.66	7.10	33.25
7	2.61	2.57	0.63	2.64	1.87	0.49	2.66	1.34	0.56	7.25	30.97
8	2.57	1.99	0.49	2.58	1.67	0.47	2.61	1.41	0.63	5.60	21.08
9	2.59	2.25	0.56	2.61	1.98	0.49	2.63	1.51	0.54	6.25	31.24
10	2.56	2.1	0.59	2.57	1.67	0.59	2.63	1.15	0.51	6.11	25.87

From Figure 9, It is found that the relation between properties of shale sandstone such as S-wave, UCS and Tensile strength vs P-wave in all three conditions i.e. dry, semi-saturated and saturated is different. The relations obtained in dry samples were found to be more suitable for prediction of geotechnical properties of rock due to its high correlation coefficient values. Hence, it is recommended to use dry P-wave velocity for predictions. The relations found are as follows

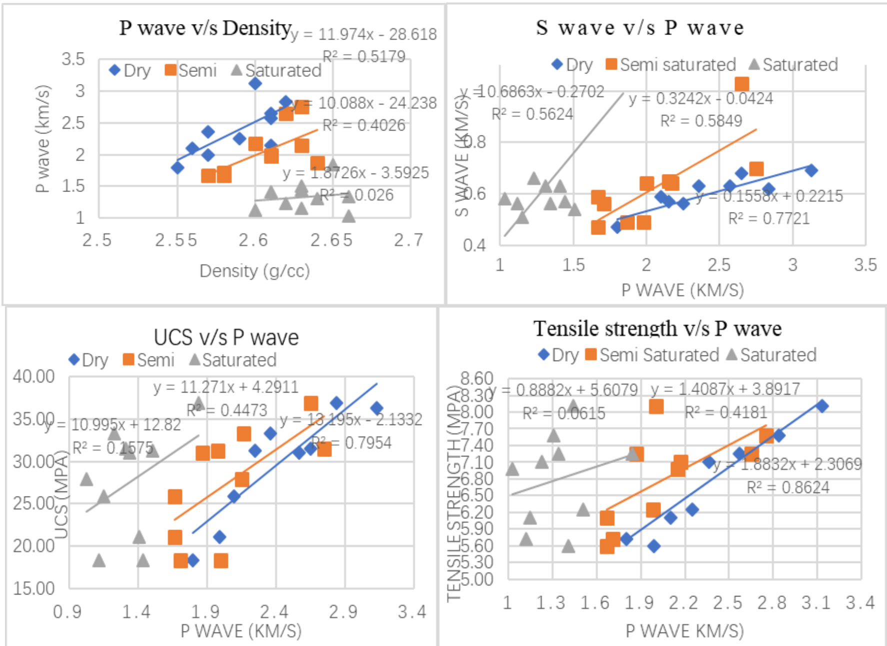


Figure 9. Plot between p wave velocity and tensile strength, density, UCS and S-wave of Shaly-sandstone

Table 8. Regression equations obtained from a plot of shaly sandstone

Sl no.	Material	Property	Condition of material	Regression equation	R^2	Range
1	Shaley-sandstone	Density	Dry	y= 11.794x – 28.618	0.5179	2.55 – 2.61 g/cc
			Semi	y=10.088x – 24.238	0.4026	2.57 – 2.64 g/cc
			Saturated	y=1.8726x + 3.5925	0.026	2.6 – 2.66 g/cc
2	Shaley-sandstone	S-wave	Dry	y=0.1558x + 0.2215	0.7721	0.47 – 0.69 (km/s)
			Semi	y=0.3242x – 0.0424	0.5849	0.47 – 1.03 (km/s)
			Saturated	y=0.6863x – 0.2702	0.5624	0.51 – 1.24 (km/s)
3	Shaley-sandstone	UCS	Dry	y = 13.195x + 2.1332	0.7954	18.34 - 36.82 Mpa
			Semi	y=11.271x +	0.4473	

				4.2911		
			Saturated	y=10.0995x + 12.82	0.1575	
4	Shaley-sandstone	Tensile strength	Dry	y=1.8832x + 2.3069	0.8624	5.72 – 8.11 Mpa
			Semi	y=1.4087x + 3.8917	0.4181	
			Saturated	0.8882x + 5.6079	0.0615	

2.2.4. Shale

Shale, any of a group of fine-grained, laminated sedimentary rocks consisting of silt- and clay-sized particles. Shale is the most abundant of the sedimentary rocks, accounting for roughly 70% of this rock type in the crust of the Earth. The p wave velocity, UCS, tensile strength and density was determined as shown in table 9. The relation between p wave and UCS, tensile strength, density, S-wave velocity is shown in figure 10.

Table 9. Test results of Shale

Sl no.	Dry density (g/cc)	P wave$_{dry}$ (km/s)	S wave$_{dry}$ (km/s)	Semi-saturated density (g/cc)	P wave$_{semi\ saturated}$ (km/s)	S wave$_{semi\ saturated}$ (km/s)	Saturated density (g/cc)	P waves$_{aturated}$ (km/s)	S waves$_{aturated}$ (km/s)	Tensile strength (Mpa)	UCS (Mpa)
1	2.34	4.17	0.5	2.36	3.66	0.56	2.4	1.66	0.5	7.31	16.6
2	2.45	4.49	0.55	2.48	3.06	0.55	2.51	1.72	0.59	8.56	30.91
3	2.46	4.54	0.59	2.49	3.02	0.57	2.53	1.56	0.53	9.27	27.93
4	2.29	4.19	0.51	2.32	3.46	0.87	2.37	1.58	0.67	6.46	17.25
5	2.19	3.79	0.49	2.24	3.74	0.79	2.31	1.85	0.63	5.79	16.57
6	2.34	4.12	0.52	2.39	3.89	0.9	2.45	1.69	0.68	6.22	20.37
7	2.5	4.23	0.53	2.54	3.23	0.67	2.59	1.74	0.69	6.45	24.8
8	2.43	4.44	0.61	2.45	3.56	0.8	2.49	1.68	0.63	8.23	27.9
9	2.48	4.65	0.69	2.51	3.19	0.55	2.55	1.9	0.89	9.74	30.2
10	2.5	4.43	0.59	2.52	3.09	0.52	2.58	1.77	0.63	7.56	28.4

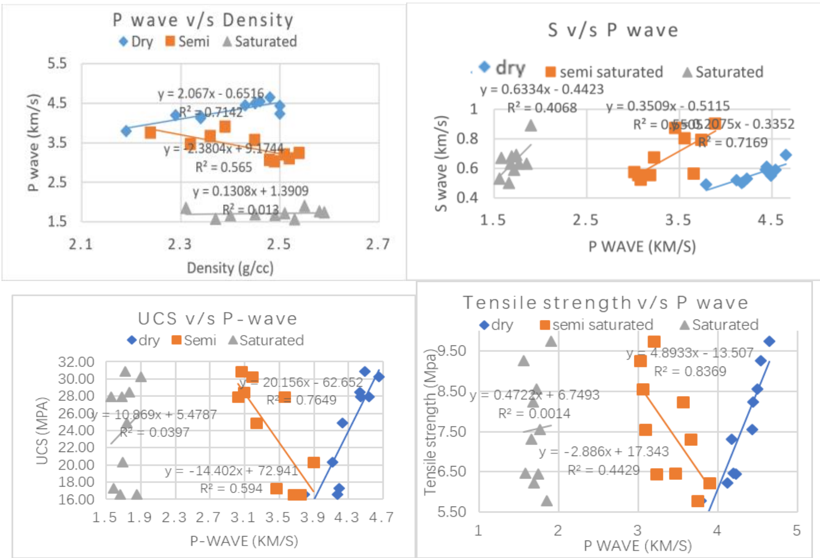


Figure 10. Plot between p wave velocity and tensile strength, density, UCS and S-wave of shale

Table 10. Regression equations obtained from plots of shale

Serial no.	Material	Property	Condition of material	Regression equation	Correlation coefficient	Range
1	Shale	Density	Dry	y=2.067x – 0.6516	0.7142	2.19–2.5 g/cc
			Semi	y= -2.3804x + 9.1744	0.565	2.24–2.54 g/cc
			Saturated	y=0.1308x + 1.3909	0.013	2.31–2.59 g/cc
2	Shale	S-wave	Dry	y=0.2075x + 0.3352	0.7169	0.5–0.69 km/s
			Semi	y=0.3509x – 0.5115	0.5505	0.52–0.87 km/s
			Saturated	y=0.6334x – 0.4423	0.4068	0.5–0.89 km/s
3	Shale	UCS	Dry	y = 20.156x + 62.652	0.7649	16.57–30.91 Mpa
			Semi	y= -14.402x + 72.941	0.594	
			Saturated	y=10.869x + 5.4787	0.0397	
4	Shale	Tensile strength	Dry	y=4.8933x – 13.507	0.8369	5.79–9.74 Mpa
			Semi	y= -2.886x + 17.343	0.4429	
			Saturated	y= 0.4722x + 6.7493	0.0014	

From Figure 10, it is found that the relation between properties of shale such as S-wave, UCS and Tensile strength vs P-wave in all three conditions i.e. dry, semi-saturated and saturated is different. The relations obtained in dry samples were found to be more suitable for prediction of geotechnical properties of rock due to its high correlation coefficient values. Hence, it is recommended to use dry P-wave velocity for predictions. The relations found are as follows Table 10.

3. Conclusions

From this study it is seen that in dry condition there is a strong correlation between the p wave value and other geotechnical parameters. This can be verified by the correlation coefficient values obtained for the dry sample condition was on the higher side. So the following conclusions can be drawn out from the study as shown in table 11.

Table 11. The following observation can be drawn out from the study

Sl no.	Material	Property	Condition of material	Regression equation	R^2	Range
1	Coal	S-wave	Dry	y=4.4299x+1.309	0.8778	8.57-19.25 Mpa
		UCS		y=1.522x+0.529	0.8231	0.56–0.94 km/s
		Tensile strength		0.1745x+1.0999	0.7566	1.26–1.81 Mpa
2	Sandstone	S-wave	Dry	y = 5.9986x-1.966	0.7881	0.49–0.68 km/s
		UCS		$y=2.4896x^{2.3033}$	0.8869	32.47–47.24 Mpa
		Tensile strength		$y=1.3129x^{1.4921}$	0.7274	7.11–9.1 Mpa
3	Shaly-sandstone	S-wave	Dry	y=0.1558x + 0.2215	0.7721	0.47–0.69 (km/s)
		UCS		y = 13.195x + 2.1332	0.7954	18.34-36.82 Mpa
		Tensile strength		y=1.8832x + 2.3069	0.8624	5.72–8.11 Mpa
4	Shale	S-wave	Dry	y=0.2075x + 0.3352	0.7169	0.5–0.69 km/s
		UCS		y = 20.156x + 62.652	0.7649	16.57–30.91 Mpa
		Tensile strength		y=4.8933x – 13.507	0.8369	5.79–9.74 Mpa

This shall help field engineers (mining and civil) to estimate the geotechnical properties of rock without undergoing destructive tests. The samples can be preserved for a future test. This p wave test can be carried out on rock mass in the field with the help of diode for better results. The laboratory results can also be normalized by the relation given by Barton for better estimation from laboratory P wave values. This shall be economical and time saving for industries in the assessment of rock properties for blasting and civil construction. As the testing process is tiresome and for every new test we require new samples as they are destructive tests. The samples also can be used in the future if preserved in a better way.

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