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Full Length Research Paper

Assessment of Geo-mechanical properties of some Gondwana Coal using P-Wave Velocity

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India is a country rich in coal reserves. Estimation of geo-mechanical properties of the coal has a direct bearing on the production of the mine. It is directly related to the design and stability of slope benches, dumps, in surface mine and pillar design in underground workings. The measurement of strength parameters by the conventional laboratory experiments are quite time taking, cumbersome and expensive. Many a times, rock sample of desire size is not available to test the rock for specific properties. The seismic techniques are frequently employed to resolve and characterize the dynamic properties of coal and other rock types. The P-wave velocity of a geo-material is closely related to the intact as well as composite geo-mass. An attempt has been made in the present study is to correlate uniaxial compressive strength, tensile strength, shear strength, density, young's modulus, and point load index of Gondwana coal, India, with the P-wave velocity due to its greater applicability in planning and design for better productivity and stability. The results have been analyzed with statistical technique for the credibly of the findings. The correlating equations, equating the various physico-mechanical properties, with the p-wave velocity have been proposed.

Keywords: Geo-mechanical properties, Coal, P-wave Velocity.

INTRODUCTION

India is a country rich in coal reserves. Estimation of geo-mechanical properties of the coal has a direct bearing on the production of the mine. It is directly related to the design and stability of slope benches, dumps, in surface mine and pillar design in underground workings. These properties are equally vital for the understanding bursts and bumps in underground mines, pillar designs, prediction of failures in coal mines (Dubey et al.2000, Monjezi et al. 2000). The measurement of strength parameters by the conventional laboratory experiments are quite time taking, cumbersome and expensive. Many a times, rock sample of desire size is not available to test the rock for specific properties. The unconfined compressive strength test is the most conservative laboratory tests which is used for the determination of the static and dynamic strength parameters of intact rock material and coal. These methods require precision in preparation and testing of relevant samples. There has been no such attempt by which all the geo-mechanical properties can estimated with relative ease and considerable accuracy. An attempt has been made to establish a relationship between p-wave velocity and other geomechanical properties like UCS, Young's modulus, density, tensile strength and point load index. The geo-mechanical parameters have been correlated for quick and reliable estimation of these properties with simplicity and less time.

The seismic techniques are frequently employed to resolve and characterize the dynamic properties of coal and other rock types. It is well known that these techniques are non-destructive and relatively easy to perform in laboratory as well as in situ condition. Now a day, these techniques are increasingly being used in field of geological, geotechnical petroleum sciences. The determination of P-wave velocity is an easy and simple task as compare to other geo-mechanical properties and it can be determined in field as well as in laboratory. The P-wave velocity of a geo-material is closely related to the intact as well as composite geo-mass. There are number of important parameters that influence the geo-

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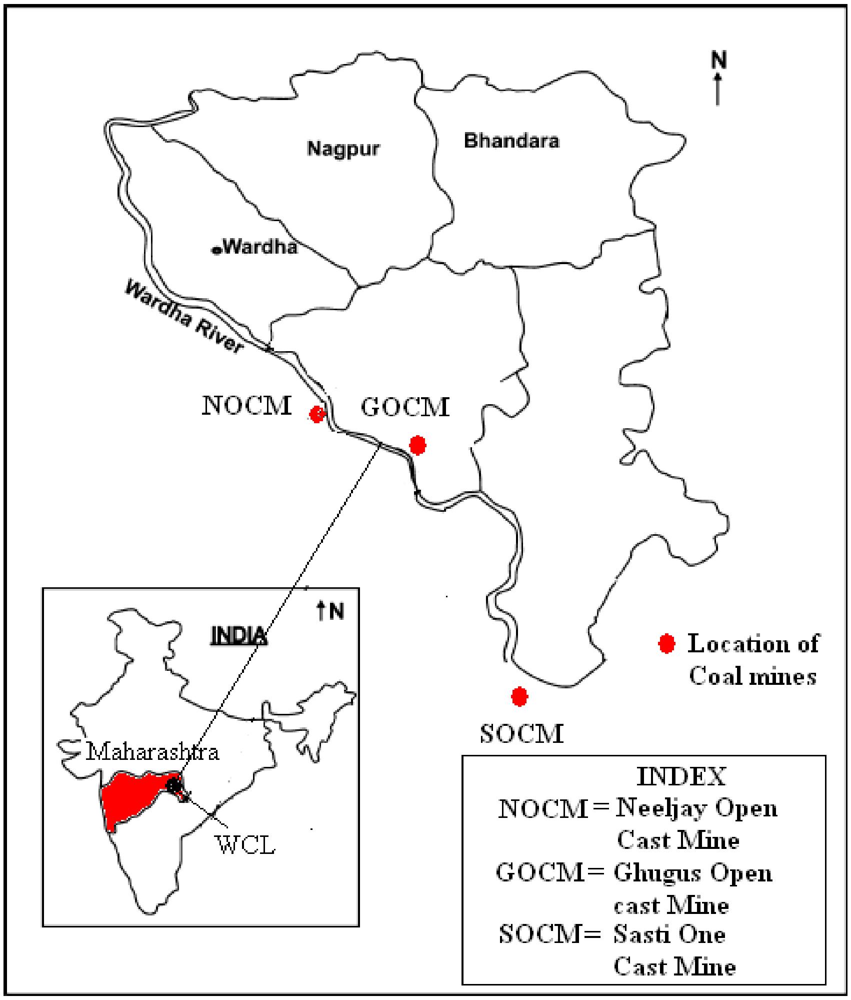

Figure 1. Study area and sample collecting location of different coalmines (Jhanwar and Thote, 2011)

mechanical properties of the rock mass like grain size and shape, density, porosity, anisotropy, pore water, confining pressure, temperature, weathering and alteration zones, bedding planes, and joint properties (roughness, filling material, water, dip and strike, etc.)(Khandelwal and Singh, 2009, Kaharaman, 2001 a). An attempt has been made in the present study is to correlate uniaxial compressive strength, tensile strength, shear strength, density, Young's modulus, and Point load index of some Gondwana coal with the P-wave velocity due to its greater applicability in planning and design for better productivity and stability.

Field Study

For the present study coal samples were collected from three different mines, Neeljay, Ghugus and Sasti open cast mines a subsidiary of Western Coal field Limited (WCL). The coal deposits comes under the Wardha Valley Coal Field (WCV) of Lower Gondwana. The Wardha Valley coalfields comes under the Toposheet no. 56M and covers an area of approximately about 1440 km^2 between latitudes ~$19^{\circ}28$ ' and $20^{\circ}27$ and longitudes ~$78^{o}50$ ' and $79^{0}45$ ', located in the Chandrapur and Yeotmal district of Maharashtra state. They extend over a length of 150 km from NW to SE in an almost straight line. The Ghugus mine, which comes under the Wani area lies 28 Km in SE direction from Wani and east of the Wardha River. The Neeljay mine, which is also a part of the Wani area lies 25 Km in SE direction from Wani and west of Wardha River. The Sasti mine is located 5 km south from Ballarpur area, which is controlling office and SW from the Wardha River (Figure 1). In general, all the mines are located along Wardha River.

Previous Research

A number of researchers have studied the relation betw-

Table 1. Relation between P-wave velocity and Geo- mechanical properties reported by various researchers

Sr. No	Empirical relation	Coefficient of determination (r)	Researchers
1	UCS = $k_p V^2_p + A$	0.86	Inoue and Ohomi (1981)
2	UCS = 0.036 Vp – 31.18	0.85	Goktan (1988)
3	UCS = aV_p^b	0.88	Mccann et al. (1990)
4	qu = $9.95VP^{1.21}$	0.83	Kahraman (2001)
5	$V_p = 0.0317\sigma c + 2.0195$	0.80	Yasat &Erdogan (2004)
	$Vp = 0.0937Es + 1.7528$	0.86	
	$V_p = 4.3183\rho - 7.5071$	0.81	
6	Thermal Conductivity=$0.097e^{0.001Vp}$	0.83	Zkahraman et al. (2004)
7	UCS = ae^{bVp}(a = 0.78, b = 0.88)	0.53	Entwisle et al. (2005)
8	UCS = aV_p^b (a = 0.78, b = 0.88)	0.53	Entwisle et al. (2005)
9	UCS = 0.1564*VP - 692.41	0.80	Chary et al. (2006)
	UCS = 0.0144*VP - 24.856	0.50	
10	UCS = 0.0642VP – 117.99	0.90	Sharma & Singh (2008)
	Id = 0:0069 VP + 78:577	0.78	
	ISI = 0:0118 VP + 58:105	0.81	
11	UCS=a exp(b/ Vp),a= 165.05, b= –4,451.07	0.70	Moradian and. Behnia(2009)
	UCS=a exp(b/ ρVp), a= 142.47 b=–9,560.57 0.75	0.75	
	$Es = aV^b{}_p$, a=2.06, b= 2.78	0.92	
12	UCS = 0.1333 V_p – 227.19	0.96	Khandelwal and Singh (2009)
	TS = 0.0145 V_p – 24.55	0.94	
	SS = 0.0291V_p – 49.494	0.95	
	Den = 0.0011V_p – 0.0847	0.97	
	YM = 4.9718V_p – 7151	0.97	
	PR = $8 \times 10^{15} V_p^{-5.0509}$	0.94	

een different geo-mechanical properties of rock material and have been reported that the P-wave velocity is closely related to geo-mechanical properties (Smorodinov et al. 1970, Inoue and Ohomi, 1981, Gaviglio, 1989, Boadu, 2000, Kahraman, 2001a, Kahraman, 2001b, Ozkahraman et al. 2004,Yasar and Erdogan, 2004 Khandelwal and Singh, 2009). Some researchers have suggested that the P-wave velocity in a solid rock depends on the density and elastic properties of that material (Rzhevsky and Novik, 1971, Franklin and Dusseault, 1989). The strength of geo-material is sometimes related to their elastic stiffness so that measurement of P-wave velocity in such materials can often be used to indicate their quality as well as to determine elastic properties (Singh et al. 2006, Sharma and Singh, 2008). Inoue and Ohomi (1981) investigated the relation between uniaxial compressive strength and P-wave velocity of soft rocks and reported very poor correlation between them. Relation between density and P-wave velocity was given by Gaviglio (1989). Boadu (2000) predicted the transport properties of fractured rocks from seismic waves. Kahraman (2001a) correlated P-wave velocity with the number of joints and Schmidt rebound number and found a strong influence of the joint density on P-wave velocity, he also reported that the evaluated uniaxial compressive strength using Schmidt rebound number, point load index, impact strength index and P-wave velocity. He had used 48 different rock types to establish the correlation among them and found a non-linear relation between the P-wave velocity and uniaxial compressive strength. Ozkahraman et al. (2004) determined the thermal conductivity of rocks from the P-wave velocity. Yasar and Erdogan (2004) studied carbonate rocks of different origins and established a linear relation between density, Young's modulus, and uniaxial compressive strength with P-wave velocity. They found appreciable error between measured and estimated values of uniaxial compressive strength and Young's modulus than in density.

Ultrasonic techniques have been used for many years in geotechnical practice and mining science. They are employed in the field for geophysical investigations and in the laboratory for the determination of dynamic properties of rocks. A number of researchers, including Birch (1960,1961), Deere and Miller (1966), Babuska and Pras (1984), Kern (1993), Moradian and Behnia (2009), Barruol and Kern (1996), Karpuz and Pa- Samehmetoglu (1997), have attempted to established the relations between rock properties and sound velocity. They have found that the sound velocity is closely related to rock properties. The various correlating equations by previous researchers are given in Table 1.

Laboratory Investigation

Representative coal sample were collected from the three different coal mines of Western Coal Field Limited in

Table 2. Geo-mechanical characterization of coal Samples

Coal	P-Wave (m/s)	UCS (MPa)	Tensile (MPa)	Shear Strength (MPa)	Density (gm/cc)	Young Modulus (MPa)	Point load Index (MPa)
Ghugus Open Cast Coal Mine							
C1	1915.12	28.8	2.75	5.3	1.55	2255.12	1.35
C2	1908.1	28.8	2.65	5.24	1.5	2250.15	1.33
C3	1945.2	29.75	2.69	5.53	1.57	2271.13	1.41
C4	1950.13	29.85	2.74	5.67	1.59	2277.14	1.43
C5	2000	31.35	2.98	5.98	1.71	2299.12	1.6
C6	1900.14	28.2	2.58	5.2	1.48	2246.16	1.32
C7	1980.04	30.91	2.95	5.8	1.67	2285.12	1.55
C8	1990.01	30.95	3.05	5.88	1.7	2299.13	1.58
C9	1902.06	28.45	2.6	5.25	1.5	2245.2	1.31
C10	1918.09	28.99	2.66	5.43	1.54	2258	1.36
C11	2003.12	31.89	3.09	6.12	1.71	2298.13	1.65
C12	2010.05	32.05	3.15	6.21	1.72	2310.14	1.7
C13	1995.2	30.99	3.01	6.09	1.68	2295.17	1.59
C14	2015.15	32.39	3.2	6.3	1.75	2320.21	1.75
C15	1895.14	27.96	2.55	5.12	1.47	2240.16	1.25
Neeljay Open Cast Mine							
Coal	P-Wave (m/s)	UCS (MPa)	Tensile (MPa)	Shear Strength (MPa)	Density (gm/cc)	Young Modulus (MPa)	Point load Index (MPa)
C1	1890.05	18.5	2.4	4.5	1.8	2411.07	1.02
C2	1885.02	18.45	2.35	4.47	1.79	2405.12	1.01
C3	1880.23	18.4	2.3	4.45	1.78	2410.23	1
C4	1878.8	18.42	2.33	4.43	1.78	2409.31	1
C5	1905.12	18.6	2.45	4.55	1.92	2420.09	1.03
C6	1910.14	18.65	2.5	4.6	1.95	2425.06	1.04
C7	1900.06	18.58	2.43	4.53	1.9	2418.07	1.03
C8	1853.03	18.01	2.26	4.35	1.7	2395.05	1
C9	1920.09	18.68	2.53	4.61	1.98	2435.26	1.05
C10	1893.08	18.5	2.37	4.47	1.78	2410.03	1.06
C11	1769.17	17.49	1.87	3.89	1.4	2340.95	0.87
C12	1754.34	17.41	1.84	3.85	1.38	2337.9	0.84
C13	1746.41	17.38	1.81	3.81	1.37	2334.99	0.81
C14	1778.21	17.58	1.92	3.92	1.42	2344	0.91
C15	1784.32	17.69	1.99	3.98	1.45	2350.25	0.93
Sasti Open Cast Mine							
Coal	P-Wave (m/s)	UCS (MPa)	Tensile (MPa)	Shear Strength (MPa)	Density (gm/cc)	Young Modulus (MPa)	Point load Index (MPa)
C1	1895.01	18.9	1.97	3.66	1.43	2250.02	1.06
C2	1950.09	19.2	2	3.75	1.45	2264.03	1.1
C3	1960.02	19.25	2.05	3.79	1.46	2270.09	1.12
C4	1870.12	18.78	1.85	3.55	1.41	2230.05	1.04
C5	1880.06	18.8	1.9	3.6	1.42	2238.01	1.04
C6	1890.08	18.88	1.96	3.67	1.41	2243.12	1.05
C7	1860.14	18.7	1.8	3.5	1.41	2225.21	1.03
C8	1865.13	18.75	1.83	3.43	1.42	2230.14	1.03
C9	1878.05	18.73	1.88	3.57	1.42	2233.06	1.05
C10	1945.17	19.15	1.99	3.73	1.45	2260.08	1.09

Table 2. Continue

C11	2010.08	19.93	2.22	4.18	1.48	2325.16	1.2
C12	1829.13	18.12	1.78	3.35	1.39	2205.22	1.01
C13	1790.15	17.85	1.73	3.12	1.37	2190.32	0.95
C14	2005.03	19.84	2.2	4.12	1.47	2315.41	1.19
C15	1970.18	19.35	2.05	3.85	1.45	2280.19	1.14

Figure 2. Measurement Instruments of geo-mechanical properties, A) P-wave velocity, B) Brazilian Test, C) Point Load Test, D) Triaxial Test.

India, which is one of the subsidiary of Coal Indian Limited. Coal sample were collected from fifteen different locations at each mine. Coal sample blocks were cored with care and precaution to NX size in laboratory to determine geo-mechanical properties. To obtain core sample is very difficult and tedious job. Special care was taken to avoid water absorption by the coal samples. The core specimens were prepared as per ISRM (1981).

Since some of coal samples are very weak to be cored to the desired NX-size therefore, 16cm^3 cubical samples were prepared by cutting the coal by simple cutting machine. These samples were used to determine the geo-mechanical properties of the coal. (Table 2)

The P-wave velocity of coal sample was determined using a Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) as per ISRM (1978) standards (Figure 2a). In this test, a mechanical pulse is generated on the prepared rock core specimens by piezo-electric transducers using high density grace at both end to avoid any air gap between transducer and specimen. The seismic pulses are transmitted from emitter and received at other end of the specimen. The

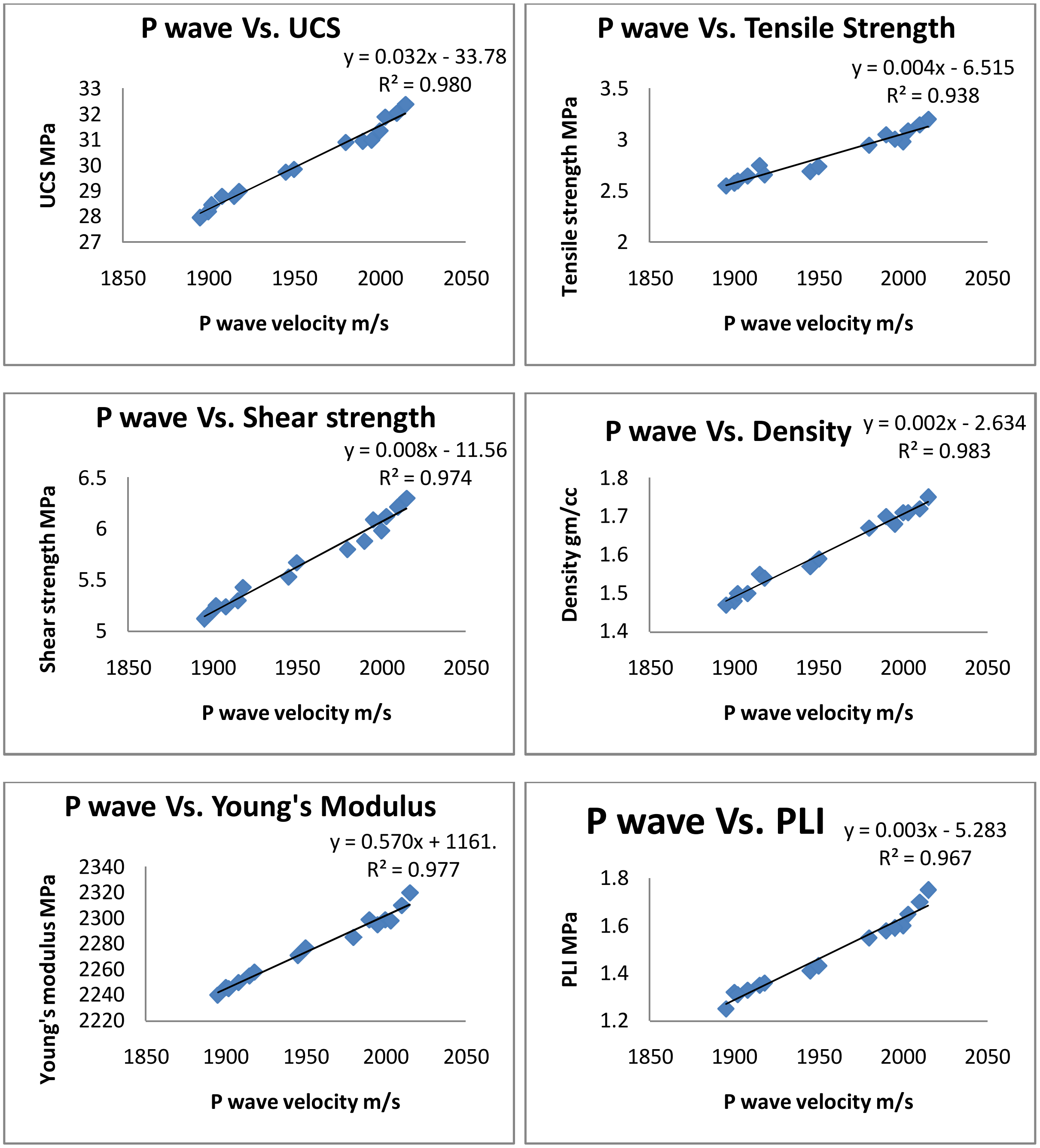

Figure 3. Correlation of geo-mechanical propeties with P wave velocity at Ghugus open cast coal mine

time elapsed in the transmission of pulses between the two ends of the specimen is used for the determination of sonic wave velocity through the material.

Statistical evaluation of geo-mechanical properties of Coal for different mines:

The experimental data was analyzed statistically with ordinary least squares analysis. The objective was to adjust a model function to best fit a data sets.

The physico-mechanical assets of coal from Ghugus mine was segregated into three very close but distinct zones with an average compressive strength of 30 MPa which is normally high as compared to other coal in Gondwana basin. The various strength parameters varied quite linearly with the p-wave velocity of the coal with very little variation (Figure 3). Tensile has the lowest correlating coefficient of 0.93, while other properties have higher correlation coefficient.

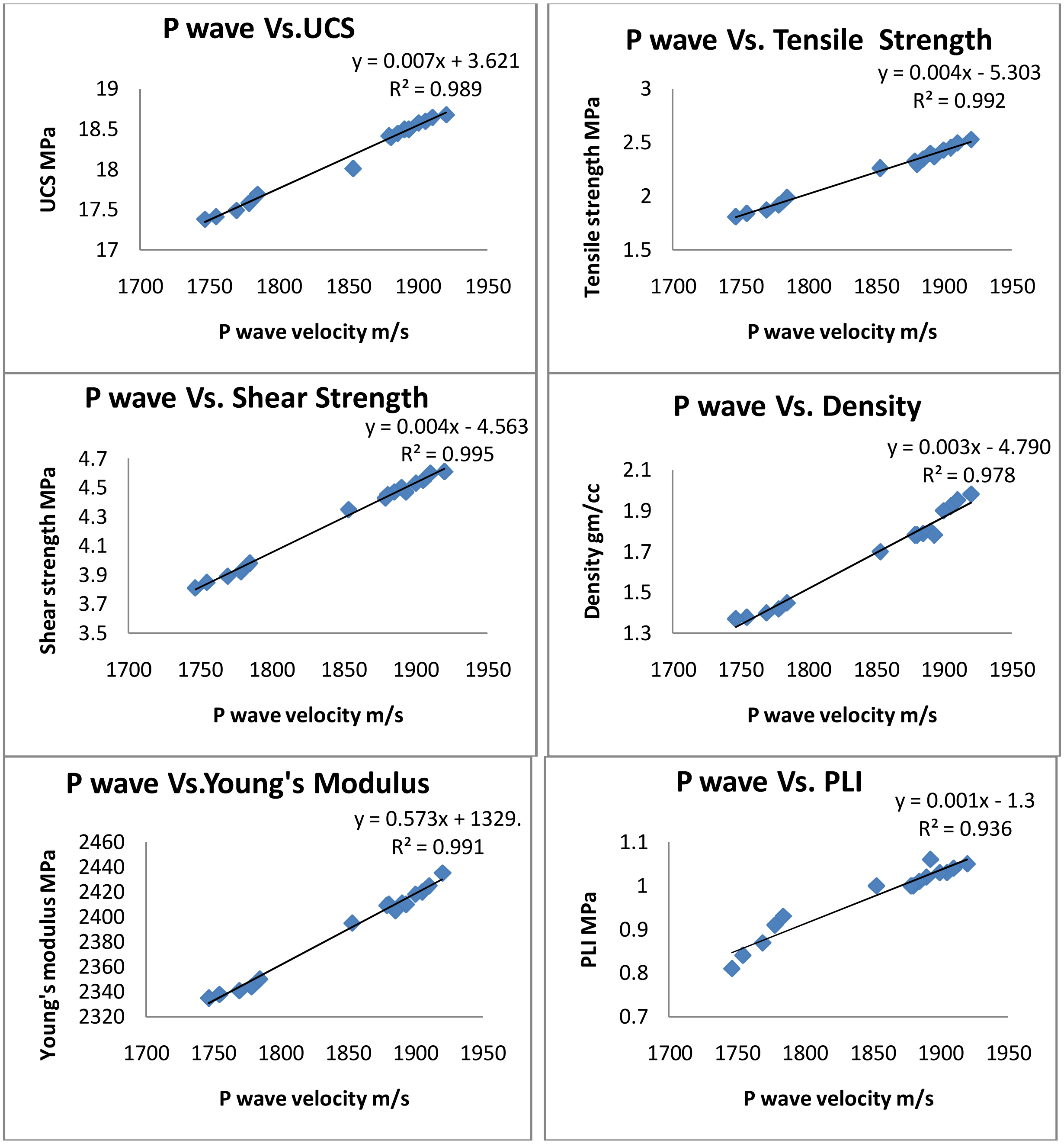

Figure 4. Correlation of geo-mechanical propeties with P wave velocity at Ghugus open cast coal mine

Ghugus open cast coal mine

Neeljay Open Cast Coal Mine

Compared to Coal samples of Ghugus coal mine, there is a better correlation between p-wave velocity and physic-mechanical properties for Neeljay coal mine. Here the coal can be distinctly divided into two types with very close but distinct sonic wave velocity values. This is because of two distinct sources and distinct maturity of coal resulting in varied mineralogical and physic-mechanical evolution. (Figure 4)

Sasti Open Cast Coal Mine

There is slightly more scatter for the data of coal from Sasti coal mine, with a lower correlating coefficient as compared to Ghugus and Neeljay mine (Figure 5). This scatter may be due to the anisotropy of the coal samples

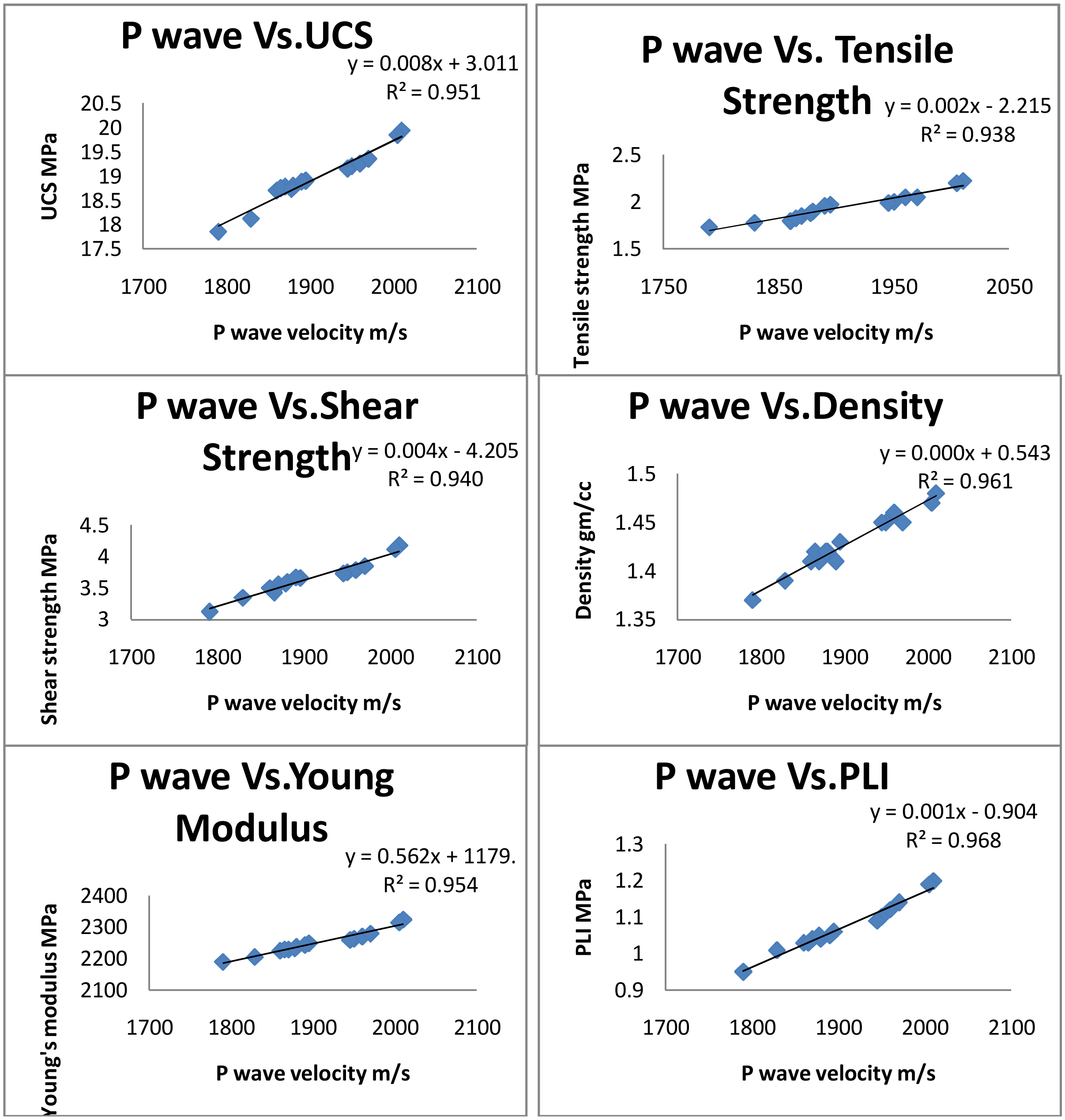

Figure 5. Correlation of geo-mechanical propeties with P wave velocity at Ghugus open cast coal mine

that were tested. The predicted and observed value has a good correlation as compared to the above two mine. There was no significant correlation found between density and sonic wave velocity for Sasti coal. Density was found independent of the sonic wave velocity in this case.

RESULTS AND DISCUSSION

The results for geo-mechanical properties of coal sample were analyzed using the methods of least square regression technique. The equation of regression, best fit line and coefficient of determination were calculated for each mine and for each geo-mechanical properties and was correlated with the P-wave velocity.

At Ghugus coal mine a strong correlation coefficient was found between P-wave velocity and geo-mechanical properties of coal (Figure. 3). The geo-mechanical properties of the coal at this site varied linearly with the p-wave velocity. The correlation coefficient values for UCS, Shear Strength, Density, Young Modulus and Point Load Index (PLI) are 0.98, 0.97, 0.98, 0.97, 0.96 resp-ectively (Figure.6) Comparatively a little weak correlation

Table 3. The Statistical analysis of experimental data

Sr. No.	Parameter	P-Wave (m/s)	UCS (MPa)	Tensile (MPa)	Shear Strength (MPa)	Density (gm/cc)	Young Modulus (MPa)	Point load Index (MPa)
				Ghugus Open Cast Mine				
1	No. of samples	15	15	15	15	15	15	15
2	Maximum Value	2015.15	32.39	3.2	6.3	1.75	2320.21	1.75
3	Minimum Value	1895.14	27.96	2.55	5.12	1.47	2240.16	1.25
4	Average	1955.17	30.08	2.84	5.67	1.60	2276.67	1.47
5	Standard Deviation	45.61	1.50	0.22	0.40	0.09	26.32	0.16
				Neeljay Open Cast Mine				
1	No. of samples	15	15	15	15	15	15	15
2	Maximum Value	1920.09	18.68	2.53	4.61	1.98	2435.26	1.05
3	Minimum Value	1746.41	17.38	1.81	3.81	1.37	2334.99	0.81
4	Average	1849.87	18.15	2.22	4.29	1.69	2389.82	0.97
5	Standard Deviation	63.46	0.50	0.25	0.30	0.22	36.54	0.08
				Sasti Open Cast Mine				
1	No. of samples	15	15	15	15	15	15	15
2	Maximum Value	2010.08	19.93	2.22	4.18	1.48	2325.16	1.2
3	Minimum Value	1790.15	17.85	1.73	3.12	1.37	2190.32	0.95
4	Average	1906.56	18.94	1.94	3.65	1.42	2250.67	1.07
5	Standard Deviation	64.01	0.54	0.14	0.27	0.03	36.82	0.06

Table 4. Regression analysis result for Ghugus Open Cast Coal Mine

Sr. No.	Related Parameter	Regression equation	R^2 Value
1	UCS- P wave	UCS= 0.032(Vp)-33.78	0.98
2	Tensile Strength- P wave	Ts= 0.004(Vp)-6.014	0.90
3	Shear Strength- P wave	SS=0.008(Vp)-11.56	0.97
4	Density- P wave	Ds= 0.002(Vp)-2.634	0.98
5	Young's Modulus- P wave	YM= 0.552(Vp)+1195	0.96
6	Point Load Index- P wave	PI= 0.003(Vp)-5.283	0.96

Table 5. Regression analysis result for Neeljay open cast coal mine

Sr. No.	Related Parameter	Regression equation	R^2 Value
1	UCS- P wave	UCS= 0.007Vp-3.621	0.98
2	Tensile Strength- P wave	Ts= 0.004Vp-4.303	0.99
3	Shear Strength- P wave	SS=0.004Vp-4.563	0.99
4	Density- P wave	Ds= 0.003Vp-4.790	0.97
5	Young's Modulus- P wave	YM= 0.565Vp+1343	0.98
6	Point Load Index- P wave	PI= 0.001Vp-1.3	0.93

Table 6. Regression analysis result for Sasti open cast coal mine.

Sr. No.	Related Parameter	Regression equation	R^2 Value
1	UCS- P wave	UCS= 0.008Vp-3.011	0.95
2	Tensile Strength- P wave	Ts= 0.002Vp-2.215	0.93
3	Shear Strength- P wave	SS=0.004Vp-4.205	0.94
4	Density- P wave	No Significant change with due to large scale	
5	Young's Modulus- P wave	YM= 0.555Vp+1190	0.94
6	Point Load Index- P wave	PI= 0.001Vp-0.835	0.90

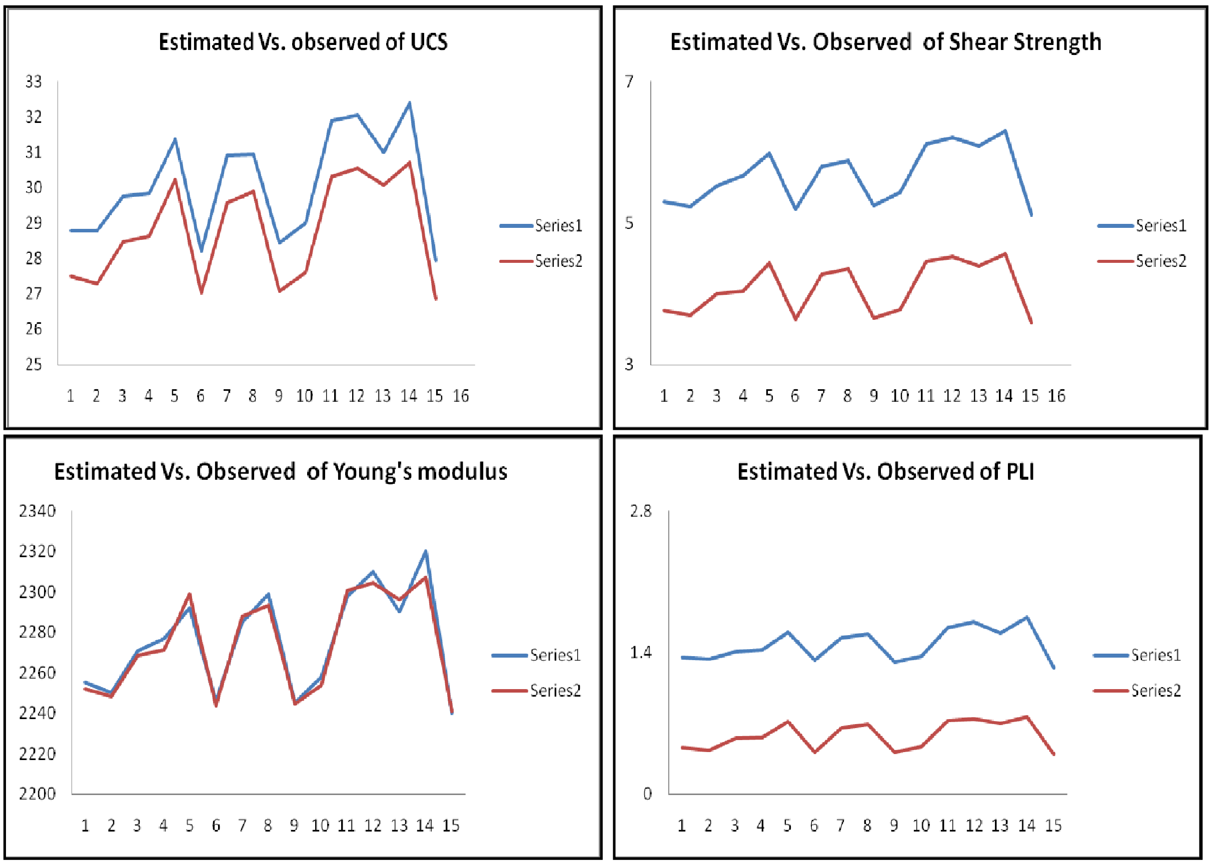

Figure 6. Graphical representation of comparasion between estimated and observed values at Ghugus Open Cast Coal Mine (Red line = Estimated value, Green line= Observed value).

coefficient (0.93) was found for Tensile Strength as compared with the other geo-mechanical properties. Kandelwal and Singh (2009) have investigated the geo-mechanical properties of northern coal field, India, and established an empirical equation correlating different physico-mechanical attributes for coal measure rock. The correlation coefficient in this present case is better as compared to Khandelwal and singh (2009). Other researchers have also proposed similar equations relating p-wave velocity with other strength parameters, but mostly are for hard rock (Table 1).

The estimated and predicted values are very close in our case depicted by the graphical representation of the comparative study between the estimated and observed values for the coal (Figure 6, 7 and 8). Based on the tests results following correlating equations have been proposed for the Ghugus coal mine given in Table 4

For Neeljay coal mine, a stronger correlation was found between the Sonics wave and coal strength properties as compared to the Ghugus coal mine. All the correlation coefficient value varies between 0.97-0.99 except for point load index, where correlation coefficient is 0.93 (Figure 4). The Sonics wave values for the Neeljay mine can be divided into two distinct groups, first with sonic velocity ranging between 1700–1800 m/s and the second set with values between 1880-1950 m/s. The predicted and observed values for the strength values have the same correlation coefficient (Figure 7). Out of all

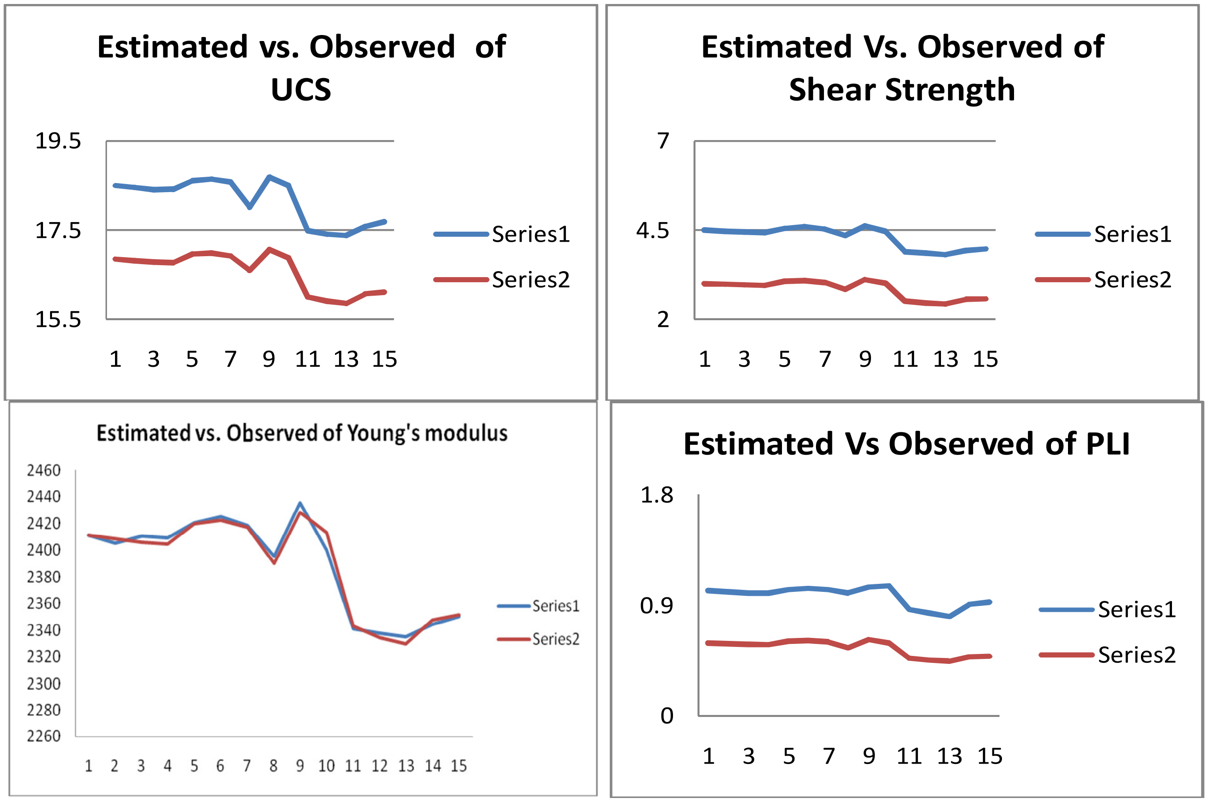

Figure 7. Graphical representation of comparasion between estimated and observed values at Neeljay Open Cast Coal Mine (Red line = Estimated value, Green line= Observed value).

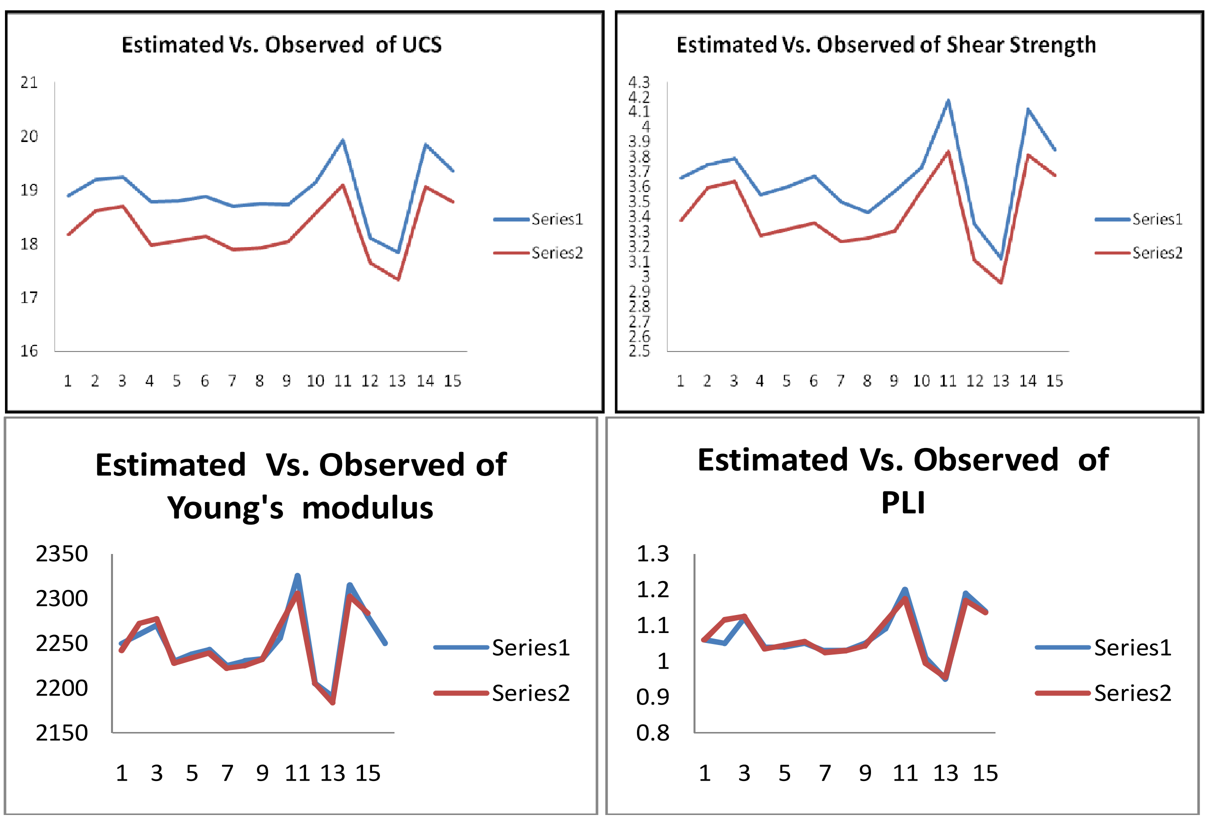

Figure 8. Graphical representation of comparision between estimated and observed values at Sasti Open Cast Coal Mine (Red line = Estimated value, Green line= Observed value).

Table 7. Tabulated t-test result for Ghugus open cast mine

Sr. No.	Test Parameter	t- test	
		Calculated Value	Tabulated value
1	UCS- P wave	163.37	2.04
2	Tensile Strength- P wave	165.77	2.04
3	Shear Strength- P wave	165.33	2.04
4	Density- P wave	165.88	2.04
5	Young's Modulus- P wave	-23.64	2.04
6	Point Load Index- P wave	165.84	2.04

Table 8. Tabulated t-test result for Neeljay open cast mine

Sr. No.	Test Parameter	t- test	
		Calculated Value	Tabulated value
1	UCS- P wave	111.77	2.04
2	Tensile Strength- P wave	112.74	2.04
3	Shear Strength- P wave	112.62	2.04
4	Density- P wave	112.77	2.04
5	Young's Modulus- P wave	-28.55	2.04
6	Point Load Index- P wave	112.82	2.04

Table 9. Tabulated t-test result for Sasti open cast mine

Sr. No.	Test Parameter	t- test	
		Calculated Value	Tabulated value
1	UCS- P wave	114.19	2.04
2	Tensile Strength- P wave	115.23	2.04
3	Shear Strength- P wave	115.12	2.04
4	Density- P wave	115.26	2.04
5	Young's Modulus- P wave	-18.04	2.04
6	Point Load Index- P wave	115.28	2.04

the material strength parameters, Young's modulus and tensile strength have the best correlation between predicted and observed value (Table 5).

For Sasti coal mine, a correlation coefficient ranging between 0.93-0.96, was found for all the investigated rock material properties (Figure 5). Tensile strength had a slightly lower correlation coefficient of 0.93. The overall correlation coefficient values for coal of Sasti mines are a little less as compared to the Ghugus and Neeljay mine. The reason for this better correlation of strength parameters of Ghugus and Neeljay mines is due to the comparatively uniform isotropy in their coals. The predicted and observed value has a good correlation as compared to the above two mine. There was no significant correlation found between density and sonic wave velocity for Sasti coal because of the very little variation from the mean value with respect to the large scale. Following equation found through the linear regression analysis for the coal in Sasti opencast mine (Table 6).

Correlation between estimated and observed value

The estimated and observed physico-mechanical parameters were graphically co-plotted to assess the the estimated and observed values. Youngs modulus values estimated from p-wave velocity for the Ghuhus coal varied most closely with the observed results.

Ghugus Open Cast Coal Mine

Neeljay Open Cast Coal Mine

Here too the best predicition was for elastic modulus values. (Figure 7)

Sasti Open Cast Coal Mine

For Sasti coal, the Young modulus and point load indices strayed very closely to the predicted values (Figure 8)

Student *t* test

The significance of *r*-values can be determined by the *t*-test, assuming that both variables are normally distributed and the observations are chosen randomly.

The test compares the computed *t*-value with a tabulated *t*-value using the null hypothesis. It is done for comparing the means of two variables, even if they have different numbers of replicates. In simple terms, the *t*-test compares the actual difference between two means in relation to the variation in the data.

The value for the *t*-test is positive, when the first mean is larger than the second and t value is negative if it is lower. Once the *t* value is computed, it is then compared with the tabulated value. If the computed value is larger than the tabulated one, then it indicates strong and significant correlation. To test the significance, one needs to set a risk level or called the alpha level. In most cases, the "rule of thumb" is to set at 95% confidence interval. Since, a 95% confidence level was chosen in this test, a corresponding critical *t*-value 2.07 is obtained. As it is seen in Table 7, 8 and 9 for all three mines, the two computed *t*-values remain in the upper critical region. For the t test results it can be concluded that there is a real correlation between the P-wave velocity and uniaxial compressive strength, tensile strength, shear strength, density, Young's modulus and Point Load Index.

The t value for young's modulus is negative as the first mean is smaller compared to the second mean. In all the above six cases for different mines, calculated value of *t*-test is much higher than the tabulated value and hence they all have significantly strong correlation among themselves and this may be used for prediction of these parameters using P-wave velocity. The Ghugus coal mine samples have the strongest correlation among all the samples tested for different mines.

CONCLUSION

The study was primarily done to deduce a steadfast correlation between p-wave velocity and strength properties for coal of Wardha valley coal basin in India. A total no. of 135 samples with 45 sets of data from three different coal mines was experimented upon for different physico-mechanical properties. The material physico-material properties varied linearly against the p-wave velocity. The correlation coefficient of above 90% resulted for all the tests conducted against p wave velocity. For all the coal samples tested from the three mines, young's modulus had the best correlation. The results were also verified using student t test which showed a strong correlation. The following equations are proposed for the different strength parameters of coal.

1. UCS= 0.032(Vp)-33.78 (r^2= 0.98)
2. Ts= 0.004Vp-4.303 (r^2= 0.99)
3. SS=0.004Vp-4.563 (r^2= 0.99)
4. Ds= 0.002(Vp)-2.634 (r^2= 0.98)
5. YM= 0.565Vp+1343 (r^2= 0.98)
6. PI= 0.003(Vp)-5.283 (r^2= 0.96)

As a non-destructive and swift testing approach, the sonic wave tests can be used for deducing the physic-mechanical properties of the coal with considerable reliability which has wider use in slope stability, underground planning and design for safety and productivity. This approach is cost effective and time saving.

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REFERENCE

Babuska V, Pros Z (1984). Velocity anisotropy in granodiorite and quartzite due to the distribution of microcracks. *Geophys. J. R. Astron. Soc.*, 76(1), 121–127.

Barruol G, Kern H (1996). Seismic anisotropy and shear-wave splitting in lower-crustal and upper mantle rocks from the Ivrea zone experimental and calculated data. *Phys. Earth Planet. Inter.*, 95(3-4) 175–194.

Birch F (1960). The velocity of compressional waves in rocks 10 kbars: Part 1. *J. Geophys. Res.*, 65, 1083–1102.

Birch F (1961). The velocity of compressional waves in rocks 10 kbars: Part 2. *J. Geophys. Res.*, 66, 2199–2224.

Boadu FK (2000). Predicting the transport properties of fractured rocks from seismic information: numerical experiments, J. Appl. Geophys. 44, 103–113.

Chary KB, Sarma LP, Prasanna KJ, Lakshmi VNA, Lakshmi VN, Rao MVMS (2006). Evaluation of Engineering Properties of Rock Using Ultrasonic Velocity and Uniaxial Compressive Strength, National Seminar on Non-Destructive Evaluation Dec. 7 - 9, Hyderabad.

Deere DU, Miller RP (1966). Engineering classification and index properties for intact rock. *Technical Rep. No. AFWL-TR 65- 116*, Air Force Weapons Laboratory, Kirtland Base, N.M.

Dubey RK, Singh TN (2000). Effect of Size on Stress - Strain Behaviour of Coal, Mining Engineer's Jl., 1(5), 39 - 47.

Entwisle DC, Hobbs PRN, Jones LD, Gunn D, Raines MG (2005). The relationship between effective porosity, uniaxial compressive strength and sonic velocity of intact Borrowdale volcanic group core samples from Sellafield. Geotech Geol Eng 23: 793–809.

Franklin , Dusseault (1989). Rock Engineering, McGraw Hill Publ. Co, New York.

Gaviglio P (1989). Longitudinal waves propagation in a limestone: the relationship between velocity and density, Rock Mech. Rock Eng. 22, 299–306.

Goktan RM (1988). Theoretical and practical analysis of rock rippability.PhD. Thesis. Istanbul Technical University.

Inoue M, Ohomi M (1981). Relation between uniaxial compressive strength and elastic wave velocity of soft rock, Proceedings of the Int. Sym. Weak Rock, Tokyo, 9–13.

ISRM (1978). Suggested method for determining sound velocity, Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 15, A100.

ISRM (1979). Suggested methods for determining the uniaxial compressive strength and deformability of rock materials, Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 16, 135–140.

ISRM (1981). Suggested Method for Rock Characterization, Testing and Monitoring, ISRM Commission on Testing Methods, Pergamon Press, Oxford, 211.

Jhanwar JC, Thote NR (2011). Slope Failures in the Opencast Coal Mines of Wardha Valley Coalfield in Central India: A Study, Rock Mech Rock Eng, DOI 10.1007/s00603-011-0139-4

Kahraman S (2001). A correlation between P-wave velocity, number of joints and Schmidt hammer rebound number, Int. J. Rock Mech. Min. Sci. 38, 729–733.

Karpuz C, Pa-Samehmetoglu AG (1997). Field characterization of weathered Ankara andesites. *Eng. Geol. (Amsterdam)*, 46(1), 1–17.

Kern H (1993). *P* and S wave anisotropy and shear-wave splitting at pressure and temperature in possible mantle rocks and their relation to the rock fabric. *Phys. Earth Planet. Inter.*, 78(34),.245–256.

Khandelwal, M. and Singh, T.N., 2009. Correlating static properties of coal measures rocks with P-wave velocity , International Journal of Coal Geology Volume 79, Issues 1-2, 55-60.

Mccann DM, Culshaw MG, Northmore KJ (1990). Rock mass assessment from seismic measurements. In: Bell, Culshaw, Cripps, Coffey (eds) Fields testing in Engineering Geology, Geol. Soc. Eng. Ape. Pub. No. 6, 257–266.

Monjezi M, Singh TN (2000). Slope Instability in an Opencast Mine, Coal International, 145-147.

Moradian ZA, Behnia M (2009). Predicting the Uniaxial Compressive Strength and Static Young's Modulus of Intact Sedimentary Rocks Using the Ultrasonic Test. International Journal of Geomechanics, Vol. 9, No. 1, @ASCE, ISSN 1532-3641/1-14–19.

Rzhevsky V, Novik G (1971). The Physics of Rocks, MIR Publ.

Sharma PK, Singh TN (2008). A correlation between P-wave velocity, impact strength index, slakes durability index and uniaxial compressive strength, Bull. Eng. Geol. Environ. 67, 17–22.

Singh TN, Pandey AC, Verma AK (2006). Prediction of Elastic Constants of Rock by Dynamic Waves, Mining Engg. Jl., 8 (2), 19-27.

Smorodinov EA, Motovilov, Volkov VA (1970). Determinations of correlation relationships between strength and some physical characteristics of rocks, Proc. of the Second Congress of the Int. Society of Rock Mechanics vol. 2, A.A. Balkema, Rotterdam, Belgrade,35–37.

Yasar E, Erdogan Y (2004). Correlating sound velocity with the density, compressive strength and Young's modulus of carbonate rocks, Int. J. Rock Mech. Min. Sci. 41, 871–875

Zkahraman O, Selver R, Isık EC (2004). Determination of the thermal conductivity of rock from P-wave velocity, Int. J. Rock Mech. Min. Sci. 41, 703–708.