Experimental Evaluation of Geo-mechanical properties of Coal using Sonic Wave Velocity

Harinandan Kumar, S. Mishra, and M. K. Mishra

***Abstract*—** India is the third largest coals producing country in the world. Estimation indicates the coal reserve is about 522 BT and CBM magnitude is of 4.6 TCM. CBM is one of the proved clean energy resources with heating value of approximately 8500 KCal/kg. CBM is future hope for energy demand in India and worldwide. But successful exploitation of coal bed methane needs advance knowledge of the coal and its behavior at varying condition. Estimation and evaluation of geo-mechanical properties of the coal and coal matrix has a direct relationship with CBM production. It is related to the in situ stress, lateral strain, axial strain, Poisson's ratio, young's modulus, bulk modulus, shear modulus etc. The measurement of geo-mechanical parameters using laboratory experiments are expensive and quite time taking. The coal from deep mines contains higher percentage of carbon and hence fragile in nature. Many a times, it is very tough to get sample of desire size to test for specific properties. This is why the ultrasonic testing is frequently employed to resolve and characterize the dynamic properties of coal. The P-wave velocity is closely related to the intact coal. Present paper discussed about dynamic properties and petrographic analysis of some coal samples from Jharia coalfield India. Correlation of geo-mechanical parameters with P- wave velocity and petrographic analysis results was also discussed due to its greater applicability in CBM evaluation and production. Statistical technique was employed to analyze the results for the credibly of the findings.

***Keywords*—** Coal Bed Methane, Ultrasonic Testing, Petrographic Analysis, Statistical Analysis.

I. Introduction

COAL bed methane (CBM) is natural gas mostly methane (99%). Methane remains adsorbed in coal matrix that diffuses and desorb to pass in pores and cleats during its production. The desorbed gas passes through the cleat and pipeline and stored as fuel. The heating value of coal bed methane estimated as 8500Kcal/kg. CBM is future hope of energy for India as well as worldwide. Estimation indicates good potential of CBM in India (approx. 4.6 TCM). Production of CBM mainly depends on the petrographic parameters of coal as well as its geo-mechanical behavior. Petrographic analysis determines the gas content of coal while geo-mechanical study elucidates spatial behavior of coal matrix during CBM production. Desorption of methane cause shrinkage of coal matrix that results in reduction of permeability. The disturbance in permeability ultimately causes hindrance in gas flow in coal matrix. The effect of effective stress and matrix sorption also considered by most of the coal permeability models (Gray, 1987; Sawyer et al., 1990; Palmer and Mansoori, 1998; Liu et al., 2011) Hence the study of geo-mechanical behavior of coal matrix is most important for economical production of CBM. It is tedious and time consuming to determine these properties in laboratory as well as in in-situ condition. Greater accuracy and standard samples are also required for determination of these properties. Sometime it is not possible to get required size of samples for laboratory testing. Therefore, a simple and reliable technique has been required to determine geo-mechanical properties of coal. Sonic wave velocity (P-wave velocity) determination is an easy, simple and reliable technique that can be used in field as well as in laboratory. Study found the P-wave velocity of a rock is closely related to the intact rock properties and measuring the velocity in rock masses describes the rock structure and texture (Khandelwal and Singh, 2009). Correlation between physico-mechanical properties of rock and P-wave velocity of rock was found elsewhere (Smorodinov et al., 1970; Gaviglio, 1989; Boadu, 2000; Khandelwal, 2012; Altindag, 2012; Rahmouni et al., 2013, Karaman and Kesimal, 2014; Hosseini and Shirin, 2015; Azimian and Ajalloeian, 2015). The Sonic wave velocity depends on density and elastic properties of the material (Franklin and Dusseault, 1989; Parthasarathi et. al., 1993; Hamidnia and Honarvar, 2012). The sonic wave velocity describes about elstic properties of material (Vasconcelos et al., 2007; Khandelwal and Ranjith, 2010; Altindag, 2012).

In this paper petrographic analysis as well as geo-mechanical study of coal was studied to determine the gas content and spatial behavior of coal matrix. The coal samples were tested experimentally as well as using sonic wave velocity. Experimental data and data obtained from sonic wave velocity were statistically correlated.

II. Geological Location

The samples for the study were collected from Jharia coal field. It falls between latitude 23042'47" and 23045'42" North and longitude 86019'21" and 86022'26" East (Figure 1). The coal block covers 15 km2 areas. The samples were collected from underground mines.

Harinandan Kumar is with the Department of Mining Engineering, NIT, Rourkela (e-mail: harinandankumar88@gmail.com).

S. Mishra is with the Department of Chemical Engineering, NIT, Rourkela (e-mail: smishra@nitrkl.ac.in).

M. K. Mishra is with the Department of Mining Engineering, NIT, Rourkela (corresponding author's phone: +919437408039; e-mail: mkmishra@nitrkl.ac.in).

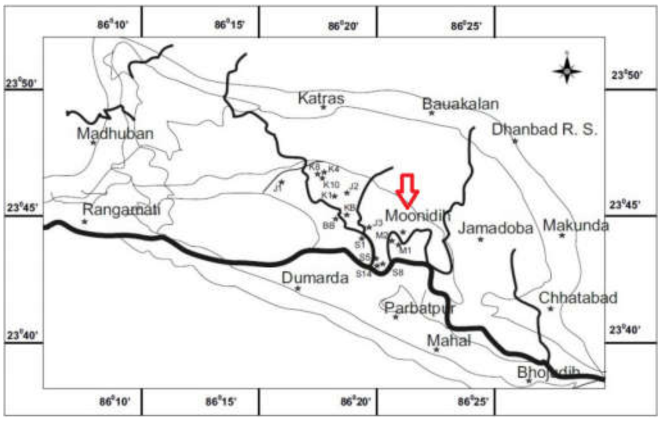


Fig. 1 Geological map of the Jharia Coalfield showing Moonidih coal block.

III. Material And Methods

A. Sample Collection

Coal samples were collected from the seams at varying depth from 450 m – 500 m (1312-1640ft) (Table 1). Samples were collected from freshly exposed coal surface and kept in air tight multi cover bags to prevent moisture loss.

TABLE 1
SAMPLES COLLECTED FROM DIFFERENT DEPTH

Sample	A_1	A_2	A_3	A_4	A_5
Depth (m)	500	500	475	450	450

B. Petrographic Analysis

Coal sample was prepared as per prescribed guideline [IS: 436 (Part l/Section 1) - 1964] (Figure 2). MC (%), VM (%), A (%) and FC (%) of coal was determined using standard test method [IS: 1350 (Part I) - 1984]. 1 gram of finely crushed and powdered (-212μ) air dried coal sample (Figure 2) was taken in a silica crucible for testing of petrographic parameter. approximately 8 to 12 point type.

Fig. 2 Powdered coal sample for analysis

C. Geo-mechanical properties

The unconfined compressive strength of coal samples was determined as per [ASTM D7012-14]. Coal core specimen was cut to the length and end was polished to make it flat. The specimen was placed in the loading frame for application of required load (Figure 3). Axial as well as lateral deformation was obtained by using extensometer.

Fig. 3 (a) Coal core sample for testing (b) Sample placed between platen (c) Fracture profiles of sample after application of load

The dynamic properties of coal sample were obtained by using ultrasonic interface device (ULT-100 Ultrasonic Device). Polished and flattened coal core specimen was placed in between two platen (Sender and Receiver) to pass sonic wave for detection of dynamic properties of coal (Figure 4).

Fig. 4 Coal sample placed in between platens to pass sonic wave through it.

IV. Result and discussion

The coal core samples was analysed for petrographic test. It was observed that the ash content varies from 9.0112 % to 20.64 % while Moisture content vary from 0.9393 % to 1.4027 % and volatile matter varies from 18.9222 % to 26.8860 % whereas fixed carbon content varies from 55.55 % to 62.70 % (Table 2). From this observation it was found that the increasing in depth of coal seam increases the fixed carbon percentage that contains to the determination elsewhere (Laxminarayana and Crosdale, 1999). Irregular and unusual values of proximate analysis parameters of some coal seam are due to weathering or localized stresses. The shearing stress is uncertain for metamorphic grade of coal and variation of macerals in coal is another reason for anomalous behaviour of parameters with depth of occurrence (Trent et al., 1982).

TABLE II
RESULTS OF PROXIMATE ANALYSIS

Sample	A_1	A_2	A_3	A_4	A_5
Depth (m)	500	500	475	450	450
M (%)	0.93	1.27	1.26	1.4	1.19
A (%)	18.49	20.64	15.38	9.01	13.46
VM (%)	18.92	22.53	25.28	26.88	24.81
FC (%)	61.64	55.55	58.06	62.7	60.53
VM (d) (%)	19.1	22.82	25.61	27.26	25.11
FC (d) (%)	62.4	56.53	59	63.72	61.42
VM (daf) (%)	23.48	28.85	30.33	30.01	29.07
FC (daf) (%)	76.51	71.14	69.66	69.98	70.92

The coal mass samples were cored to determine geo-mechanical properties. The coal block was cored by coring machine and ends were trimmed and flattened as required. The core specimens were made to standard size as per [ISRM, 1981] standards for different geo-mechanical properties. The specimens were dried at 105°C for 24 h to remove the moisture. Unconfined test was conducted to determine the elastic properties of specimen (Figure 3). UCS values of different coal samples are shown in (Table 3). Further sonic wave velocity was passed to the samples to determine dynamic properties (Figure 4). The P-wave velocity of coal was determined by using Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) as per [ISRM, 1978]. In this testing piezo-electric transducers were used to generate mechanical pulse in coal samples. In this system, the pulses are transmitted from one end of specimen (sender) and received at another end of the specimen (receiver).

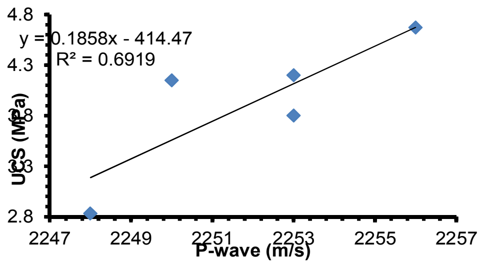
TABLE III
EXPERIMENTALLY EVALUATED STATIC AND DYNAMIC PARAMETERS OF SAMPLE

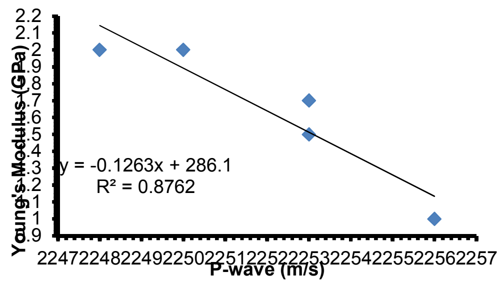
Sample	A_1	A_2	A_3	A_4	A_5
P - wave (m/s)	2256	2248	2250	2253	2253
UCS (MPa)	4.67	2.83	4.15	4.2	3.8
E (GPa)	1	2	2	1.7	1.5
G (GPa)	0.36	0.74	0.76	0.63	0.55
K (GPa)	4.55	6.67	5.56	6.07	5.77
µ	0.39	0.35	0.32	0.36	0.37
Density (kg/m^3)	1440	1368	1341	1393	1360

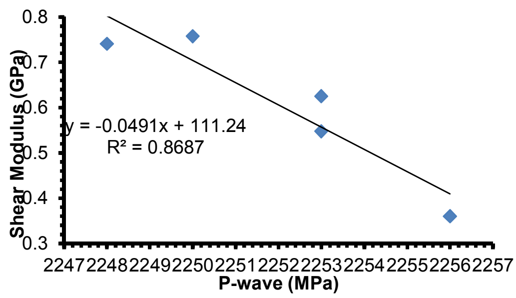
V. STATISTICAL ANALYSIS OF TEST RESULTS

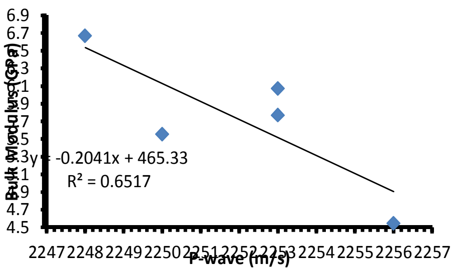
The least square regression method was employed for analysis of results of P-wave velocity with all other static geo-mechanical properties of coal samples. The best fit line equation as well as coefficient of determination (R^2) was also determined for each regression.

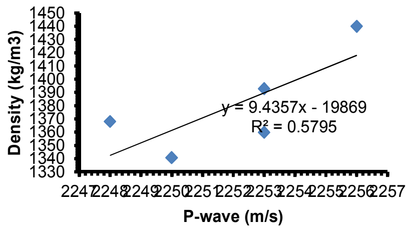
The graphs between P-wave velocity and static geo-mechanical properties of coal samples are shown (Figure 5). A good correlation between P-wave velocity and geo-mechanical properties was found. From the graph it can be observed that there is linear relation between the geo-mechanical properties with P-wave velocity of samples. The result of regression equations and the coefficient of determination are presented in (Table 4). Experimental data was utilized for the development of empirical equations to estimate the geo-mechanical properties of coal.











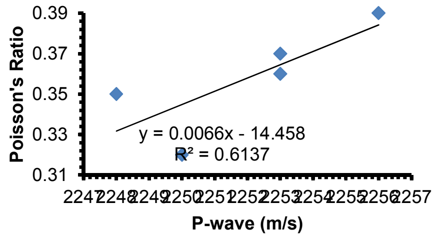


Fig. 5 Correlation between P-wave and Geo-mechanical properties of coal samples.

TABLE IV
REGRESSION ANALYSIS RESULTS.

SI. No.	Parameter to be related	Regression Equation	R^2 Value
1	UCS Vs P-wave	Y = 0.1858x-414.47	0.69
2	Young's Modulus Vs P-wave	Y = -0.1263x+286.1	0.88
3	Shear Modulus Vs P-wave	Y = -0.0491x+111.24	0.87
4	Bulk Modulus Vs P-wave	Y = -0.2041x+465.33	0.65
5	Poisson's Ratio Vs P-wave	Y = 0.0066x-14.458	0.61
6	Density Vs P-wave	Y = 9.4357x-19869	0.58

VI. CONCLUSIONS

The study indicates

- The uniaxial compressive strength, Young's modulus, Shear modulus, Bulk modulus, Poisson's ratio and density of various coal samples of Jharia coal field can be estimated from sonic-wave values by using simple and easy mathematical relations.
- The Geo-mechanical properties of coal samples showed linear relationship with P-wave velocity.
- Good correlation was found between P-wave velocity and geo-mechanical properties of the tested coal samples.
- These equations are practical and simple enough to apply for the determination of elastic properties of coal and coal bed.

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