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Evaluation of Engineering Properties of Rock Using Ultrasonic Pulse Velocity and Uniaxial Compressive Strength

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A strong laboratory database of mechanical and engineering properties of rocks is very useful for site characterization and mining engineering applications. Owing to the discontinuous and variable nature of rock masses, it is difficult for rock engineers to directly obtain the specific design parameters of interest. As an alternative, they use empirical or analytical relationships among various physical and mechanical strength properties of materials to estimate the required engineering properties of rocks and other brittle materials of interest. We have found recently that the Ultrasonic Pulse Velocity (UPV) can also be used to estimate the engineering properties of rocks. We have carried out Ultrasonic Pulse Velocity (UPV) measurements and Uniaxial Compressive Strength (UCS) tests on a large number of sandstone samples of coal mining industry in our laboratory. The engineering properties such as brittleness, hardness, fracture toughness and drillability index of rocks have been obtained. It is found that there is a fairly good correlation between UPV & UCS and UPV & the above mentioned engineering properties of sandstones. A few case studies are presented and discussed in this paper.

Keywords: *UPV, UCS, Sandstone*

1. Introduction

A strong laboratory database of mechanical and engineering properties of rocks is very useful for site characterization and mining engineering applications. Owing to the discontinuous and variable nature of rock masses, it is difficult for rock engineers to directly obtain the specific design parameters of interest. As an alternative, they use empirical or theoretical correlations among various physical and mechanical properties of rocks to estimate the required engineering properties of rocks [1, 2]. We have found that the Ultrasonic Pulse Velocity (UPV) data can be used along with the strength data to estimate the engineering properties of rocks. The mechanical (Uniaxial Compressive Strength and Tensile Strength) and engineering properties can be measured through a destructive test whereas the Ultrasonic Pulse Velocity (UPV) is measured by a non-destructive test. The Uniaxial Compressive Strength (UCS) and tensile strength data can be used to calculate brittleness, which is one of the important engineering properties of rock [3]. Furthermore, the brittleness is empirically related to the other engineering properties such as hardness, fracture toughness and drillability index [4,5]. We have carried out UPV measurements and UCS tests on a large number of sandstone samples of coal mining industries namely, Neyveli Lignite Corporation Limited (NLC) and Singareni Collieries Company Limited (SCCL) of South India in our laboratory [6]. It is found that there is a fairly good correlation between UPV and UCS of coal and lignite bearing sandstons. The engineering properties such as brittleness, hardness, fracture toughness and drillability index of rocks can be calculated using the UCS data and the empirical relationships [4,5]. Therefore, the UCS data have been made use off for estimating the above mentioned engineering properties of sandstones of SCCL and NLC. Also, we have examined if there is any correlation between UPV and the engineering properties of the NLC and SCCL sandstones. The results are found to be very encouraging. These are presented and discussed in this paper.

2. Experimental Procedure

The samples for the present study were collected from the mines of Neyveli Lignite Corporation Limited (NLC) and Singareni Collieries Company Limited (SCCL) of South India. The rock samples collected from the lignite mine of NLC are clayey, mottled clayey sandstones, hard and very hard sandstones. Whereas samples of the SCCL coal mine are medium-strong sandstones associated with shaly coals. The samples used for the studies are AX-size (30 mm dia. and 60 mm long) cylindrical specimens. The two ends of each rock cylinder were ground and lapped parallel to attain an accuracy of ± 0.2 mm and both the ends were polished. Also, the cylindrical sides are made straight active an accuracy of ± 0.3 mm over the full length of each specimen.

2.1 Density

The density of each core sample was measured after the removal of moisture from it. The moisture was removed by placing the samples in an electric oven at ~ 80^0 C for one hour and they were dried at room conditions. The density data of dry samples was obtained from the measurements of bulk volume and mass of each core using the following formula.

$$\rho(g/cm^3) = \frac{Mass\ of\ sample}{Volume\ of\ sample} \quad (1)$$

2.2 Uniaxial Compressive Strength (UCS)

The Uniaxial compressive strength (UCS) has been determined by subjecting each rock sample to incremental loading at a nearly constant rate with the help of a Universal Testing Machine (UTM) of 100 ton capacity. The UCS of the test sample is calculated by the following formula.

$$UCS(MPa) = \frac{Failure\ load}{Cross\ sectional\ area\ of\ the\ sample} \quad (2)$$

2.3 Velocity

Ultrasonic Pulse Velocity (UPV) measurements of compressional waves have been carried out using a high-energy pulser-receiver on the driving side and a 2-channel digital storage oscilloscope on the receiving side for the measurement of travel time. We determined the P-wave velocity (V_P) using the time-of-flight measurement technique at 1 MHz frequency as described in detail elsewhere [7,8]. The velocity is computed using the following formula.

$$V_P(m/\sec) = \frac{Length\ of\ the\ sample}{Travel\ time} \quad (3)$$

3. Results and Discussion

The sandstone samples of the present study were obtained from two coal mines, namely Neyveli Lignite Corporation Limited (NLC) and Singareni Collieries Company Limited (SCCL) of South India. The laboratory rock mechanics tests have been carried out on 30 samples from NLC and 50 samples from SCCL. The summary of data of density, P-wave velocity, UCS and engineering properties of the rock samples of both the mines are presented in Table 1.

The density of NLC sandstones varies from 1.703 g/cc to 2.984 g/cc with an average value of 2.365 g/cc, whereas the density of SCCL samples ranges from 2.080 g/cc to 2.319 g/cc with an average value of 2.206 g/cc (Table 1). The P-wave velocity ranges from 2088 m/sec to 5407 m/sec with an average value of 4669 m/sec for NLC samples while it ranges from 2833 m /sec to 3831 m/sec with an average value of 3345 m/sec for SCCL samples (Table 1). The UCS of NLC sandstone ranges from 10.92 MPa to 164.10 MPa with an average value of 80.72 MPa whereas the UCS of SCCL sandstone varies from 15.00 MPa to 37.51 MPa with an average value of 24.60 MPa. The density, P-wave velocity and UCS data of sandstone samples of SCCL are less than those of sandstone samples of NLC. The relationship between UCS and velocity data of NLC and SCCL sandstones is plotted. The UCS increases with increase in the P-wave velocity in both the NLC (Fig. 1a) and SCCL (Fig. 1b) sandstone samples. The relationship between them has been analyzed using the method of least-square regression. We got useful empirical linear relationships between UCS and P-wave velocity with good correlation coefficient. The empirical relation between UCS and P-wave velocity is given below.

$UCS = 0.1564*V_P - 692.41;$

$R^2 = 0.8018$ (NLC) (4)

$UCS = 0.0144*V_P - 24.856;$

$R^2 = 0.5099$ (SCCL) (5)

3.1 Estimation of Engineering Properties

The engineering properties such as brittleness (B), hardness (Schmidt's Rebound Number, RN), fracture toughness (FT) and drillability index (DI) are useful for efficient planning of mining, quarrying operations and other applications of rock engineering. The brittleness is the property of materials that rupture or fracture with little or no plastic flow. There is a strong correlation between UCS and tensile strength [2] and among UCS, tensile strength and brittleness [3]. Hence, we made use off UCS data for calculating brittleness. Further, brittleness can be used for calculating the other engineering properties [4]. Hardness is the resistance to deformation of materials. Schmidt's Rebound Number (RN) is the one of the methods for determining the hardness of materials. It was originally developed for measuring the strength of hardness of concrete [9]. Fracture toughness is the ability of rock to resist fracturing and propagation of pre-existing cracks [10]. Drillability index is ratio of force to penetration rate. It is used for determine the bit type, average penetration rate and approximate bit life. The interrelationships among engineering properties, physical and mechanical properties have been reviewed by Zhang [2].

Some of the engineering properties (Index Properties) such as brittleness (B), Schmidt's Rebound Number (RN), fracture toughness (FT) and drillability index (DI) of sandstone samples of the NLC and SCCL have been estimated in the present study using UCS data and the empirical relationships published recently [4,5]. These empirical relationships are as follows.

$\sigma_T = \sigma_C/10$ (6)

$B = (\sigma_C*\sigma_T)/2$ (7)

$RN = 5.9528*\ln(B_2)+20.933$ (8)

$FT = 0.11*(B_2)^{0.43}$ (9)

$DI = 0.6344*(B_2)^{0.6186}$ for conical bit (10)

Where σ_T = Tensile strength (MPa)

σ_C = Uniaxial compressive strength (UCS, MPa)

B = Brittleness

RN = Schmidt's Rebound Number

FT = Fracture toughness (MPa $m^{1/2}$)

DI = Drillability Index (kN/mm)

The summary of engineering properties of NLC and SCCL sandstone samples calculated using above equations 7-10 are presented in Table 1. The engineering properties of NLC samples such as brittleness ranges from 5.96 to 1346.44 with an average value of 424.30, Schmidt's Rebound Number varies from 31.56 to 63.82 with an average value of 52.78, fracture toughness ranges from 0.24 MPa $m^{1/2}$ to 2.44 MPa $m^{1/2}$ with an average value of 1.30 MPa $m^{1/2}$ and drillability index varies from 1.91 kN/mm to 54.71 kN/mm with an average value of 23.76 kN/mm, while for SCCL samples the brittleness ranges from 11.25 to 70.35 with an average value of 31.69, hardness varies from 35.34 to 46.25 with an average value of 40.93, fracture toughness ranges from 0.31 MPa $m^{1/2}$ to 0.69 MPa $m^{1/2}$ with an average of 0.48 MPa $m^{1/2}$ and drillability index varies from 2.84 kN/mm to 8.81 kN/mm with an average value of 5.27 kN/mm (Table 1).

3.2 Empirical Relationships Between Engineering Properties and P-wave Velocity

Since the engineering properties have been calculated using UCS data, and since there is a good correlation between UCS and P-wave velocity data (Fig. 1), we examined the relationships between P-wave velocity data and the engineering properties of the NLC and SCCL sandstone samples. Hence, we have plotted data of engineering properties such as brittleness (Fig. 2), hardness (Fig. 3), fracture toughness (Fig. 4) and drillability index (Fig. 5) against P-wave velocity data of NLC and SCCL sandstone samples. The results have been analyzed using least square regression method. It is found that the above mentioned engineering properties increase with increase in the P-wave velocity of NLC (Figs. 2a-5a) and SCCL (Figs.2b-5b) samples tested in the present study. The empirical relationships between the engineering properties and P-wave velocity are given below:

Empirical relationship for NLC samples

$B = 1.0821 * V_P - 4898.2;\ R^2 = 0.7487$ (11)

$RN = 0.0207 * V_P - 50.793;\ R^2 = 0.6015$ (12)

$FT = 0.0014 * V_P - 5.8043;\ R^2 = 0.6345$ (13)

$DI = 0.0361 * V_P - 156.18;\ R^2 = 0.6226$ (14)

Empirical relationships for SCCL samples

$B = 0.0382 * V_P - 100.56;\ R^2 = 0.5413$ (15)

$RN = 0.0084 * V_P + 11.842;\ R^2 = 0.5044$ (16)

$FT = 0.0003 * V_P - 0.4112;\ R^2 = 0.5044$ (17)

$DI = 0.004 * V_P - 8.7153;\ R^2 = 0.5183$ (18)

The results (Table 1) show that NLC sandstones are much stronger (Mean UCS = 80.72 MPa; Schmidt's Rebound Number = 52.78) than the sandstones of SCCL (mean UCS: 24.60 MPa; Schmidt's Rebound Number = 40.93). The associated properties, namely brittleness, fracture toughness and drillabilty index of the sandstones of NLC are also found to be higher than those of the sandstones of SCCL (Table 1).

4. Conclusions

The Uniaxial Compressive Strength (UCS) is an important mechanical property from which some of the engineering properties can be calculated. The determination of UCS (destructive test) is relatively difficult than the room temperature UPV measurements (Non-destructive test) in rock samples. Hence, the relationship between UCS and laboratory P-wave velocity data of sandstones has been analyzed and we found a good correlation between UCS and P-wave velocity data.

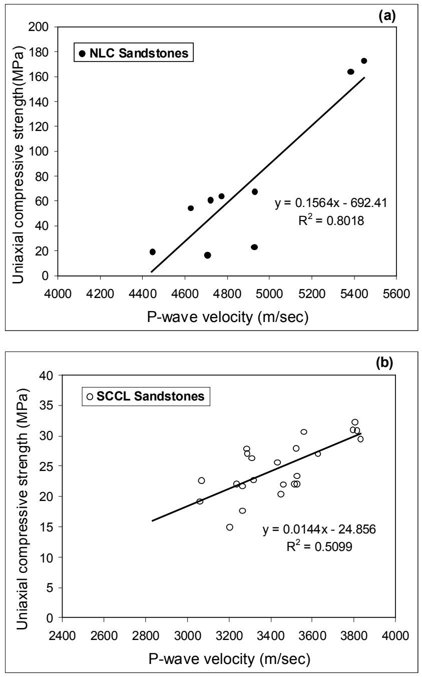

Fig.1: Plots showing the uniaxial compressive strength-P-wave velocity relationship of the samples of (a) NLC sandstones and (b) SCCL sandstones

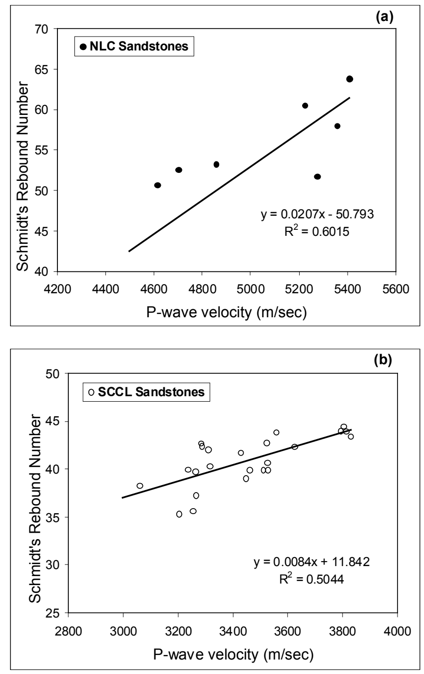

Fig.3: Plots showing the Schmidt's Rebound Number-P-wave velocity relationship of the samples of (a) NLC sandstones and (b) SCCL sandstones

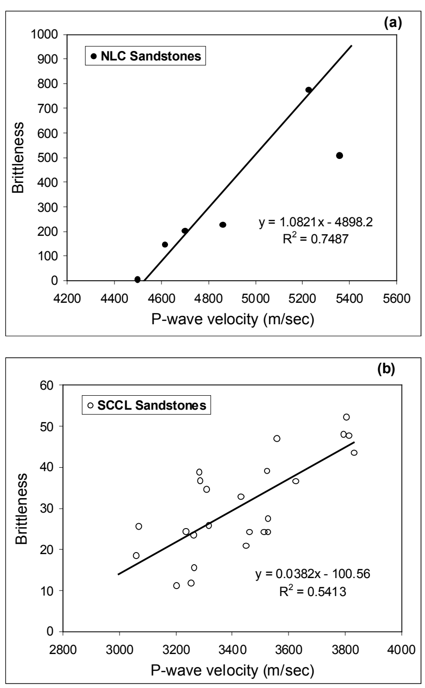

Fig.2: Plots showing the brittleness- P-wave velocity relationship of the samples of (a) NLC sandstones and (b) SCCL sandstones

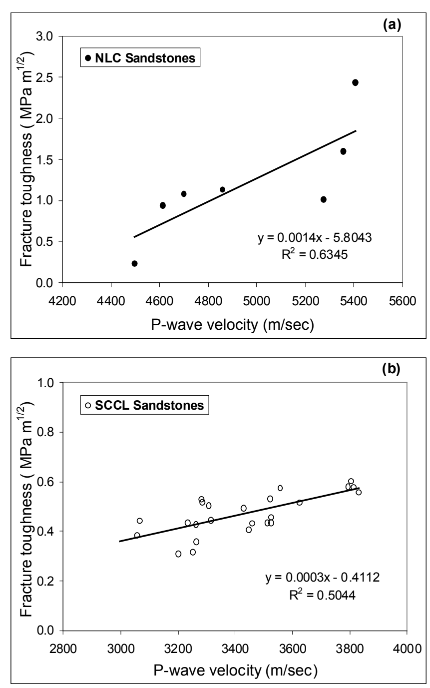

Fig.4: Plots showing the fracture toughness-P-wave velocity relationship of the samples of (a) NLC sandstones and (b) SCCL sandstones

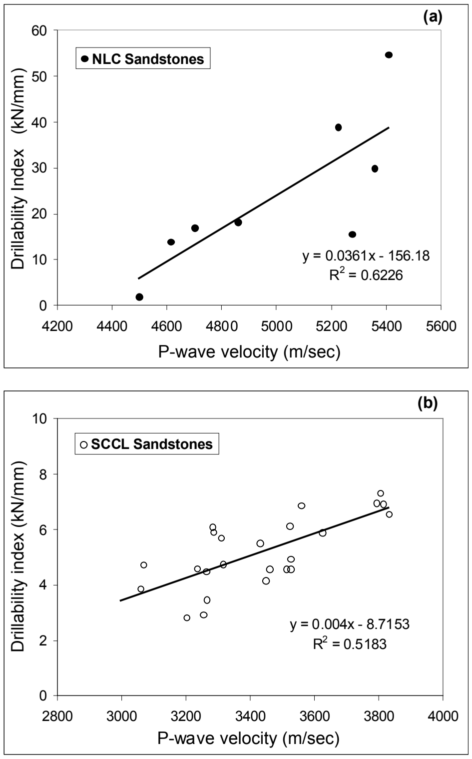

Fig.5: Plots showing the fracture toughness-P-wave velocity relationship of the samples of (a) NLC sandstones and (b) SCCL sandstones

The density, P-wave velocity and UCS data of the sandstone samples of lignite mines (NLC) are found to be higher than those of the sandstones of coal mines (SCCL).

The engineering properties of NLC sandstones are higher than those of SCCL sandstones.

The engineering properties of rock are difficult to obtain directly. Alternatively the empirical relationships can be used to estimate the engineering properties of rock. We got a good relationship between the engineering properties and P-wave velocity data of sandstones.

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Table 1**:** Summary of results of density, P-wave velocity, Uniaxial Compressive Strength (UCS) measurements and engineering properties of NLC and SCCL sandstones

	Density g/cc	V_P m/sec	UCS MPa	B	RN	FT MPa $m^{1/2}$	DI kN/mm
Sandstones from Lignite mines (NLC)							
Number of samples: 30							
Range	1.703-2.984	2088-5407	10.92-164.10	5.96-1346.44	31.56-63.82	0.24-2.44	1.91-54.71
Average	(2.365)	(4669)	(80.72)	(424.30)	(52.78)	(1.30)	(23.76)
Sandstones from Coal mines (SCCL)							
Number of samples: 50							
Range	2.080-2.319	2833-3831	15.00-37.51	11.25-70.35	35.34-46.25	0.31-0.69	2.84-8.81
Average	(2.206)	(3345)	(24.60)	(31.69)	(40.93)	(0.48)	(5.27)

V_P : P-wave velocity; UCS : Uniaxial compressive strength; B : Brittleness;
RN : Schmidt's Rebound Number; FT : Fracture Toughness; DI : Drillability Index;