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A New Approach to Estimate Joint Roughness Coefficient and its Influence on Bond Strength of Steel Fibre Reinforced Shotcrete

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ABSTRACT

Using linear variable displacement transducer (LVDT) and potentiometer along with data acquisition system, an instrumental setup has been fabricated and corresponding software is developed to plot profiles of rock surface and determine their roughness. Three parameters namely root mean square of first derivative of the profile (Z_2), structural function (SF) and length of rock profile (RL1) have been used to numerically characterize roughness of the rock surface. The joint roughness coefficients (JRC) is estimated by using the equation suggested by Yu and Vayssade (1991), considering the sampling interval of 1 mm. In order to determine the strength of bond between steel fibre-reinforced shotcrete (SFRS) and rock surface, an instrumental setup has been devised. The different coal measure rocks like shale and sandstone (coarse, medium, and fine grained) were acquired from various mines. A thorough laboratory study of adhesion of shotcrete to same rock with different surfaces roughness shows that roughness of the rock surface plays a more significant role in bond strength, for a particular range of JRC between 8 and 17. For a particular range of JRC, bond strength is strongly influenced by the values of JRC.

Keywords: Joint roughness coefficient; Bond strength; Rock profile; structural function

1. INTRODUCTION

The engineering properties of rock masses are mostly influenced by joints. Presence of joints divides the body of rock into small blocks and exhibits larger deformations when subjected to stresses. Moreover, the discontinuities in the rock mass increase permeability and decrease the bearing capacity and strength of a rock mass. The influence of joints on rock mass behaviour is mainly controlled by joint properties such as roughness, weathering grade, dip and dip directions, presence of infilling, openings etc. (Turk et al., 1987). Of these properties, joint roughness has attracted the attention of several researchers, because of its important influence on shear strength on jointed rock mass and also on the bond strength with SFRS shotcrete.

The roughness refers to the local departure from planarity at both small and large scale. It influences the friction angle, and peak shear strength of jointed rock mass. As per ISRM (1978), roughness may be of the small scale (several centimeters) or intermediate scale (several meters). In general, the profile characteristics are defined in terms of (i) rough (or irregular) and stepped, (ii) smooth and stepped, (iii) slickensided and stepped, (iv) rough (or irregular) and undulating, (v) smooth and undulating, (vi) slickensided and undulating (vii) rough (or irregular) and planar, (viii) smooth and planar, (ix) slickensided and planar.

Measurements of joint roughness using tape, geological compasses and profilographs are slow and often lead to an engineering design based on statistically inadequate sample of data. Applicability of these methods is limited to large-scale measurements particularly in the fields. On the other hand, optical methods measure precisely but are time-consuming and cover only a small-range of depth. Stylus instruments, suitable for profiles with high roughness amplitude, generally fail because deep and steep roughness troughs exhibit a continuous horizontal movement. Profilographs are also time taking and can measure upto a limited depth. Entire setup is mechanical and needs another setup for digitizing and analysis of the data (Heping, 1995).

Measure of joint roughness in the form of joint roughness coefficient (JRC) suggested by Barton (1973) has been more popular and adopted by the International Society for Rock Mechanics (ISRM, 1978).

Barton and Choubey (1977) proposed an approximation of the JRC by visually matching joint surface profiles (with their ten standard profiles) whose JRC value ranges from 0 to 20. This approach was highly subjective. To minimize this subjectivity, a quantitative measure of joint roughness was therefore necessary to adequately describe the joint behaviour and its influence on bond strength of shotcrete with rock surface. Several methods were proposed for analyzing roughness of rock joint profiles based on geo-statistical, fractal and numerical characterization approaches.

To overcome all these limitations a new setup has been designed and software has been developed. By this setup the joint roughness can be obtained on the computer. Analysis and digitization of data as well as Joint Roughness Coefficient (JRC) can also be estimated with the developed computer program.

Numerical characterization of joint surface profiles based on amplitude parameters, slope parameters, curvature parameters and surface texture parameters showed a better correlation between the JRC and the roughness parameters (Yu and Vayssade, 1991).

In this paper the roughness parameters Z_2, SF, and RL1 are used for quantitative assessment of joint roughness coefficient considering a better correlation between the JRC and the above-mentioned roughness parameters.

2. INSTRUMENTATION

2.1 Highlights of Setup

Schematic diagram of newly developed instrument set up is shown in Fig.1. It can record a large number of accurate two-dimensional profiles in a short time. A three dimensional picture is quickly built up by a combination of a set of linear measurement. The essential difference between this setup and other instruments known so far is that all the data are stored in memory of PC for future retrieval analysis. Further, the profile of required scale can be drawn from these data as well as mathematical processing of the data can be done to quantify the joint roughness profiles. The main inputs required for the estimation of JRC as well as plotting of profile are the horizontal traversing and vertical displacement.

2.2 Description of Instrumental Setup

2.2.1 Linear variable displacement transducer (LVDT)

Linear variable displacement transducer (LVDT) is used for vertical displacement measurement along the entire length of rock surface with 0.01 mm resolution. It is held in position by means of suitable clamping and stand arrangement in such a way that its position can be desirably changed. The vertical movement of the pointer-rod is converted into analog input, which is supplied to the channel-1 of the signal conditioner. Least count of the measurement was 0.01 mm.

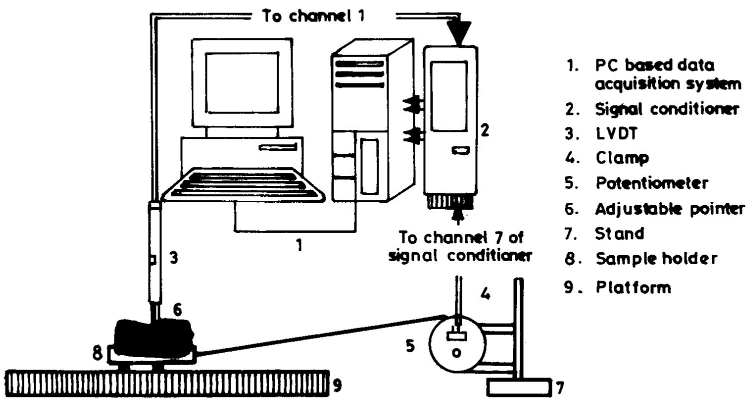

Fig.1 - Schematic diagram of experimental setup for determination of JRC

2.2.2 Potentiometer

Potentiometer is used to measure the horizontal traversing on the rock i.e. length of the roughness profile of the rock specimen. It works on the principle that when a voltage of 1.5 V is supplied to it; the output generated voltage is directly proportional to the movement of potentiometer pulley i.e. circular motion of pulley. An input of 1.5V DC is supplied to it through a battery. Output corresponding to the linear traverse of roughness profile (sampling interval = 1 mm) is supplied in the form of analog input to the channel-7 of the signal conditioner. Size, range and calibration factor of the instrument were 70 mm (Pulley diameter), (0-20 cm), and 1 mv (0.117 cm) respectively.

2.2.3 PC based data acquisition system (DAS)

The LVDT and potentiometer are connected to the channel-1 and channel-7 of DAS through a proper bridge connection. The signal provided an excitation voltage and received output signals from transducers. The analog signals received from the transducers are converted to digital signals depending on the channel coefficients (already supplied to DAS) and are stored continuously in a PC throughout the experiment. The 8-channeled DAS has following specifications:

Type of transducers	: Strain gauge, strain gauge based transducers and inductive displacement type transducers
Bridge	: 2v RMS, 10 KHz
ABC resolution	: 16 - Bit
Scan interval	: 1 ms to 10 sec
Data storage	: 15360 K byte
Power supply	: 12v DC or 230v ± 10% 50 Hz

2.3 Working of Instrument

When the plate on which the rock is kept, pulled at a constant speed by a mechanical means, the potentiometer pulley starts moving clockwise and at the same time it draws a voltage from supply battery (l.5V) proportional to the linear travel of plate and the same becomes an input to the one of the channel of signal conditioner. During the movement of the plate the LVDT pointer touching the rock surface, traverses on the rock surface and corresponding movement of pointer rod is converted into analog output, which is supplied as an input to the other channel of signal conditioner.

3. DETERMINATION OF JOINT ROUGHNESS COEFFICIENT

3.1 Setup of Rock Samples

Different coal measure rocks like coal, shale, fine grained sandstone, medium grained sandstone and coarse grained sandstone were acquired from different mines. These blocks were broken into pieces so as to make each sample size of 40 cm x 30 cm (approx.). Freshly exposed rock surface were used for the determination of roughness. All the rock specimens were almost rectangular in shape. The rock specimens were kept on the specimen holder (Fig. 2). With the help of bubble tube, proper leveling of rock specimen was made to eliminate the error due to unleveled base. The pointer rod of LVDT was positioned in such a way that the pointer of moving rod touches the rock surface and a reading of range 0 - 600 mv should be shown in the window of data acquisition system.

Fig.2 - Rock sample kept on specimen holder for determination of Joint Roughness Coefficient

3.2 Plotting Profile and Estimation of JRC

The batch program developed in Pascal language, was run to plot the profile and to estimate JRC value of the profile containing the following programs:

i. program to filter a row of five data for removing the noise and averaging the same with a maintained sampling interval (Δx) of 1 mm,
ii. program to multiply the data with the calibration factors to convert the data into linear scale in mm,
iii. program to plot the profile with a suitable specified scale with Y-axis as amplitude (distance normal to the sampling line Y) and X- axis showing distance along the sampling line,
iv. program to quantify roughness profile and to estimate numerical value of JRC based on the roughness parameters Z_2, SF, and RL1.

4. DETERMINATION OF BOND STRENGTH OF SHOTCRETE

Although a number of adhesion test methods have been developed, no universal procedure has been adopted or used extensively by the mining industry. Usually, the adhesion test equipment is either not easily available or too expensive (if available) and also complicated or fragile for extended use in underground. Some of the test methods are not practical for typical mining conditions, because they require special surface preparation, gluing or curing time to allow the shotcrete to gain sufficient strength before a test can be conducted. As a result, the adhesion strength of shotcrete is seldom measured in underground mines, even though this strength parameter plays a major role in the stability of the shotcrete, particularly during the initial phase of curing (Seymour et al., 2010).

Equipment named 'Bond strength tester' was designed and fabricated in the laboratory for the determination of bond strength of shotcrete to the rock surface. Figure 3 shows bond strength tester with rock sample. The rock surface on which shotcrete was to be sprayed, were cleaned properly. As far as possible, new fresh surface were used for casting of shotcrete mixture on the rock surface. Before spraying of shotcrete on rock surfaces, the surface profiles were plotted on the computer and rock joint roughness coefficient (JRC) were calculated using the method described earlier. Properly mixed shotcrete mixtures were sprayed (using the spraying gun) in the moulds that were specially fabricated to cast shotcrete on the rock surface. The thickness of shotcrete cast was kept constant to 7.5 cm. The inherent moisture content of the mixture was protected. To prevent dehydration at the contact surface between shotcrete and rock, the cotton (properly wet) was used all around the mould at the base. The normal time required for curing varied from 3 to 7 days.

4.1 Test Procedure

The Bond strength tester was attached to mould in such a way that a pull could be applied centrally to the casted sample mould (Figs. 3 & 4). The connection of strain-gauge wire to the strain meter in a full bridge circuit was made. The strain indicator was switched on and the reading was brought to zero through the balance knob. The X - Y recorder was connected to the strain meter and to the supply voltage, and was switched on. The pointer pen of X - Y recorder was brought to zero position. The pull load was then applied gradually by turning the screw nut handle clockwise. The load at which the bond failed was recorded on X - Y plotter. The bond surface area was also measured.

The tests for effect on roughness and tensile strength were carried on 14^{th} day of casting.

The test for effect of accelerator was carried with an interval of one day by adding 5% sodium silicate to the shotcrete mixture while casting.

At an interval of 7 days, the tests were carried out to find out the effect of time on bond strength of shotcrete.

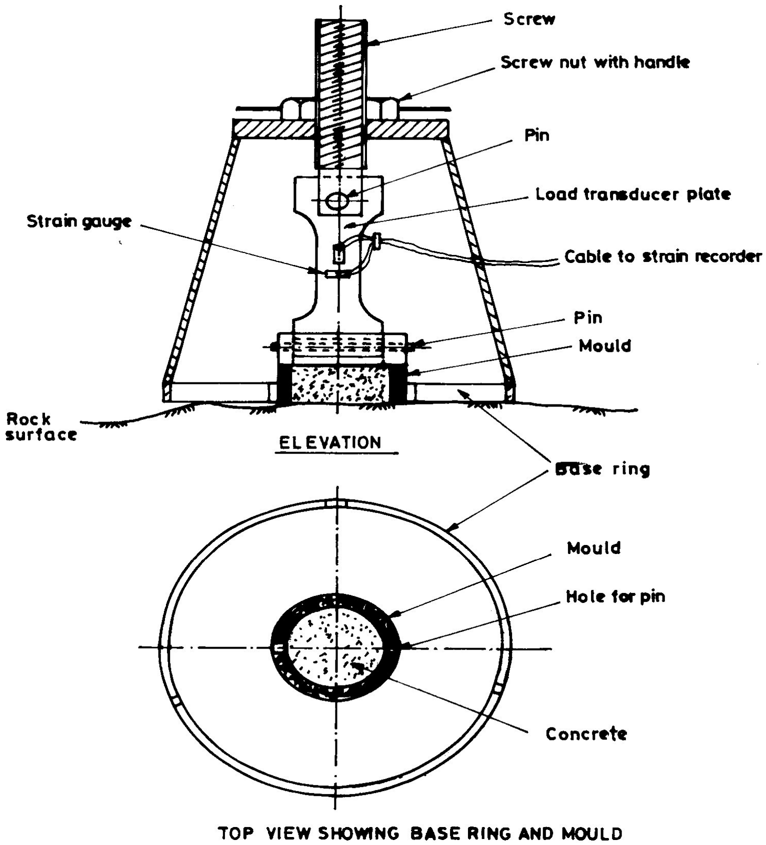

Fig. 3 - Bond strength testing equipment (Kumar et al., 2002)

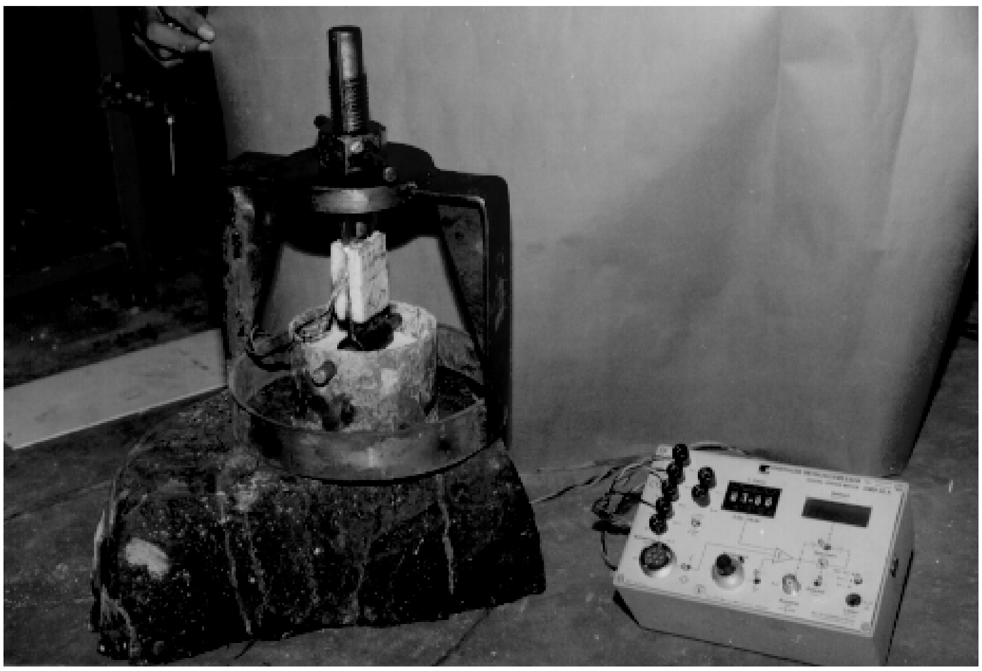

Fig.4 - Experimental setup for bond strength test

4.2 Materials for Sample Preparation

A typical design of wet mix used in sample preparation for bond strength test is shown in Table 1.

Table 1 - Mix design of steel fibre reinforced shotcrete used in sample preparation for bond strength test (Kumar et al., 2002)

Material	Unit	Wet mix amount
Natural sand	kg	4.3
Crushed aggregate (5 - 10 mm)	kg	5-7
Cement, Larsen & Tubro	kg	2.5
Silica fumes	kg	0.30
Steel fiber/Dramix. 30/0.50	kg	0.30
Accelerator – Sodium silicate	%	5 (by weight of cement)
Water /cement ratio	-	0.45
Density	kg/m^3	60

5. RESULTS AND ANAYSIS

5.1 Quantification of Rock Roughness Coefficient

In order to quantify the roughness of the rock surface, following parameters were used:

Slope parameter (Yu and Vayssade, 1991)

$$Z_2 = \left[\frac{1}{L} \sum \frac{(Y_{i+1} - Y_i)^2}{(X_{i+1} - X_i)^2} \right]^{1/2} \tag{1}$$

where Z_2 is the slope of the profile, L is the length of the profile, Y_i & Y_{i+1} are distances normal to the sampling line and X_i & X_{i+1} are the distances along the sampling line.

Structural function (Yu and Vayssade, 1991)

$$SF = \frac{1}{L} \sum (Y_{i+1} - Y_i)^2 (X_{i+1} - X_i) \tag{2}$$

Rock profile length (Yu and Vayssade, 1991)

$$RL = \frac{1}{L} \sum (\Delta X_i^2 + \Delta Y_i^2)^{1/2} \text{ and} \tag{3}$$

$$RL1 = RL - 1$$

where ΔX_i and ΔY_i are increment in distances along and normal to the sampling respectively.

The value of Z_2 is sensitive to sampling intervals (Yu and Vayssade, 1991). For estimating JRC, it cannot be employed without taking account of influence of sampling interval. Though the equations proposed by Yang et al. (2001) to estimate the value of JRC from slope parameter and structural function seem to be better correlated. But, as their sampling interval (Δx = 1.27 mm) is different from the authors' sampling interval, in order to estimate the joint roughness coefficient (JRC) from the above parameters, following equations are used (Yu and Vayssade, 1991):

$$JRC\ (Z_2) = 64.22\ Z_2 - 2.31 \qquad \text{Sampling interval} = 1\ \text{mm.} \qquad (4)$$

$$JRC\ (SF) = 63.69\ \sqrt{SF} - 2.31 \qquad \text{Sampling interval} = 1\ \text{mm.} \qquad (5)$$

$$JRC\ (RL1) = 95.23\ \sqrt{RL1} - 2.62 \qquad \text{Sampling interval} = 1\ \text{mm.} \qquad (6)$$

Table 2 shows estimated joint roughness coefficient by slope parameter (Z_2). Different types of rocks were chosen and the surface roughness was determined in horizontal plane (X and Y direction). Figures 5a & 5b show roughness profile of rock samples as plotted on computer. Table 3 shows the estimated values of JRC by different parameters for different rock samples.

A perfect correlation is achieved between JRC (Z_2) and JRC (RL1) as shown in Fig. 6a. A very good correlation is also achieved between JRC (Z_2) and JRC (SF) as shown in Fig. 6b.

Based on the analysis of the result, the following equations were obtained:

$$JRC\ (RL1) = 0.9587\ JRC\ (Z_2) + 1.2591 \qquad R^2 = 0.99 \qquad (7)$$

$$JRC\ (SF) = 1.102\ JRC\ (Z_2) + 2.2189 \qquad R^2 = 0.98 \qquad (8)$$

where *R* is the regression coefficient.

Table 2 - Estimated JRC by slope parameter (Z_2) for different rock sample

Rock Sample	Rock Type	Z_2 (X)*	Z_2 (Y)*	JRC (X)	JRC (Y)
R1	Fined Grained Sandstone	0.2781	0.3189	15.550	18.72
R2	Medium Grained Sandstone	0.2700	0.1045	15.032	4.399
R3	Medium Grained Sandstone	0.3063	0.2490	17.362	13.681
R4	Shale	0.0925	0.1201	3.629	5.402
R5	Shale	0.0801	0.0560	2.833	1.288
R6	Coarse Grained Sandstone	0.1285	0.2734	5.941	15.245
R7	Medium Grained Sandstone	0.1759	0.3139	8.985	17.969
R8	Fined Grained Sandstone	0.2690	0.4197	14.964	24.642
R9	Fined Grained Sandstone	0.0415	0.0971	0.323	3.923
R10	Coarse Grained Sandstone	0.1036	0.1257	4.336	5.76
R1 1	Medium Grained Sandstone	0.5803	0.3821	34.954	22.226
R12	Medium Grained Sandstone	0.3272	0.1822	18.704	9.394
R13	Carbonaceous Shale	0.0431	0.0459	0.457	0.637
R14	Carbonaceous Shale	0.0486	0.0495	0.813	0.875

<u>Note:</u> **X & Y are the two axes along which joint roughness coefficient are determined*

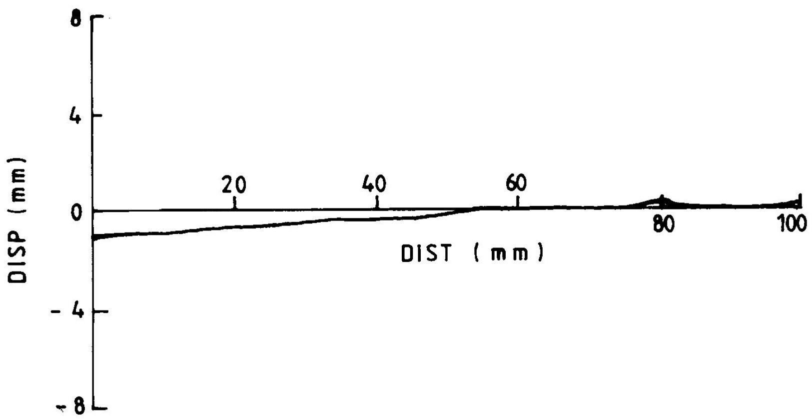

Fig. 5a - Roughness profile of rock sample R9 as obtained from the computer on different scale

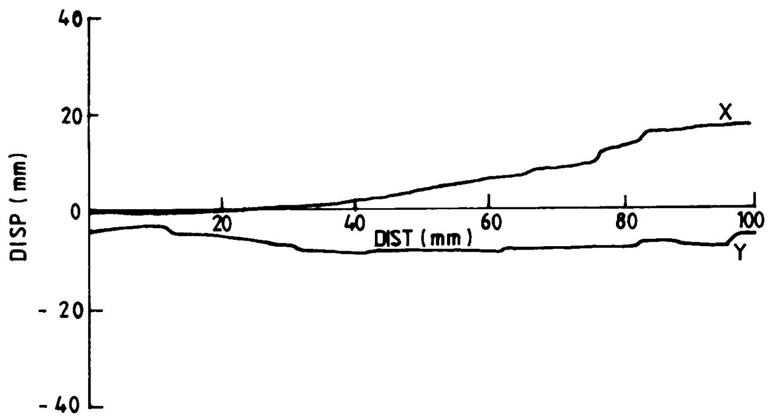

Fig. 5b - Roughness profile of rock sample R8 along X and Y direction

Table 3 - Estimation of Joint Roughness Coefficient (JRC) by different methods

Sample No.	Rock Type	Z_2	JRC (Z_2)	SF	JRC (SF)	RL1	JRC (RL1)
R20	Coarse Grained White Sandstone	0.3311	19.544	0.1489	22.262	0.0559	18.886
R21	Coarse Grained White Sandstone	0.2827	15.848	0.1201	19.765	0.0396	16.349
R22	Coarse Grained White Sandstone	0.3403	19.544	0.1851	25.094	0.0601	20.733
R23	Coarse Grained White Sandstone	0.1728	8.786	0.0477	11.594	0.0148	8.957
R24	Granite	0.2235	12.043	0.0856	16.320	0.0279	13.299
R25	Fine Grained Sandstone	0.2392	13.054	0 .074	15.103	0.0305	14.027
R26	Granite	0.1757	8.976	0.0491	11.804	0.0168	9.741
R27	Coal	0.2285	12.366	0.0938	17.205	0.0293	13.689

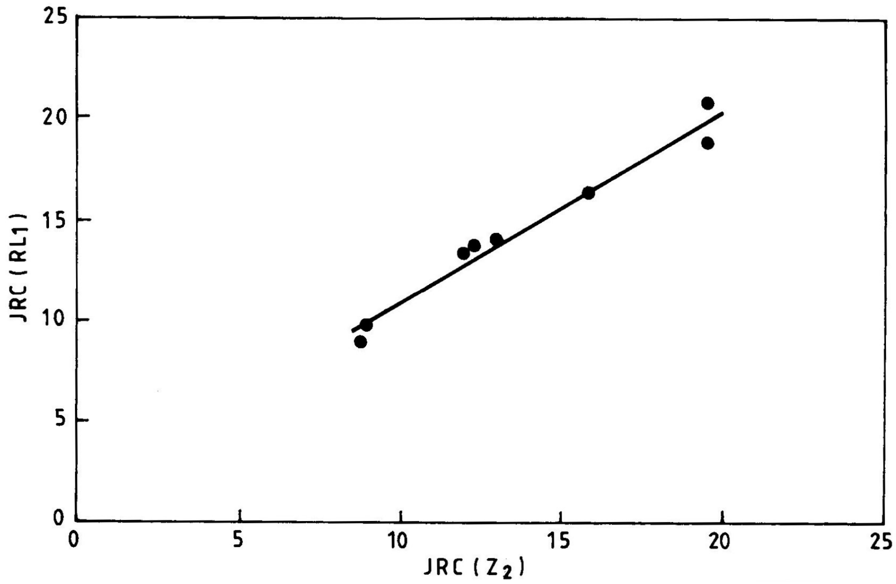

Fig. 6a - Relation between JRC (Z_2) and JRC (RL1)

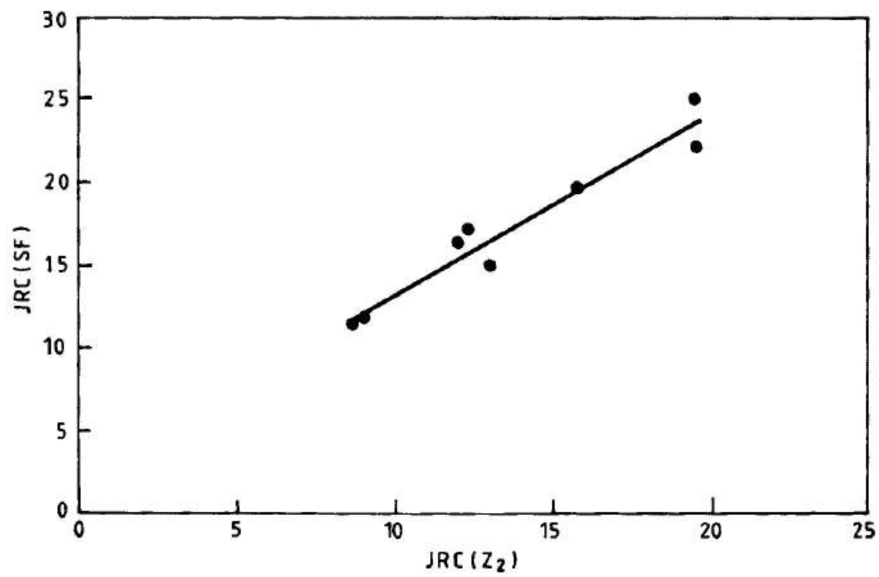

Fig. 6b - Relation between JRC (Z_2) and JRC (SF)

5.2 Effect of Rock Surface Roughness on Bonding Strength of Shotcrete

In order to determine effect of roughness on bonding strength of shotcrete, the same rock sample was broken into number of pieces to create different rough surfaces. Bond strength of shotcrete on these rock surfaces was determined. It was found that with the increase of JRC value, bond strength increased linearly. Table 4 shows the effect of roughness on bond strength of shotcrete.

Figure 7 shows a plot between the JRC and bond strength from the data given in Table 4. The best fit equation of the line for the JRC value between 9 and 16 is:

$$BS = 0.4599\ JRC - 3.5152 \quad MPa \qquad R^2 = 0.99 \tag{9}$$

where BS is the bond strength of shotcrete in MPa and JRC is the joint roughness coefficient.

Table 4 - Effect of roughness on bond strength of shotcrete
(rock type: medium grained sandstone)

Rock sample	JRC (X)	JRC (Y)	Average JRC	Bond Strength (MPa)
R2	15.032	4.399	9.7155	0.105
R3	17.362	13.681	15.52	0.387
R7	8.985	17.969	13.477	0.258
R12	18.704	9.394	14.049	0.270

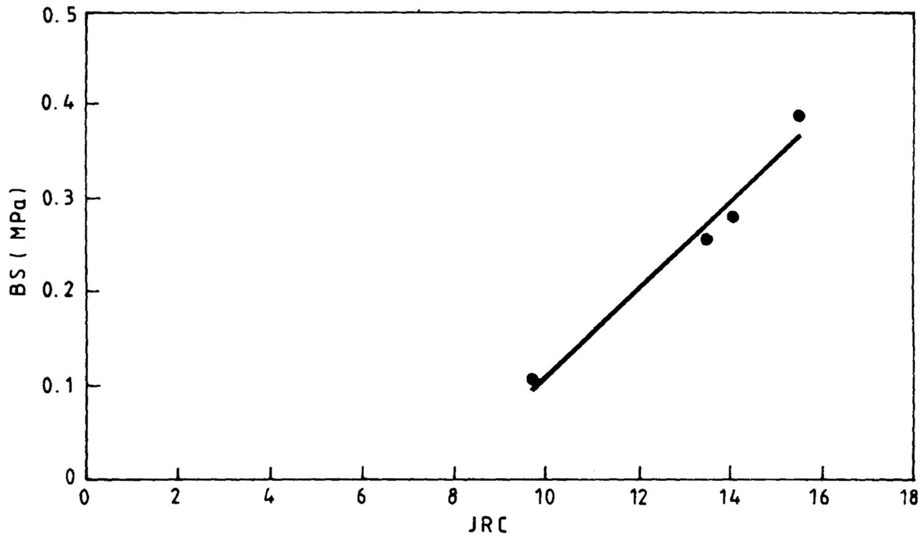

Fig. 7 - Relation between joint roughness coefficient (JRC) and bond strength (BS) of shotcrete (Kumar et al., 2002)

6. CONCLUSIONS

Using displacement transducer (LVDT) and Potentiometer along with data acquisition system; an instrumental setup was fabricated and corresponding software was developed to determine the rock surface roughness profiles and to quantify it. The joint roughness coefficients were estimated by using the equation given by Yu and Vayssade (1991), considering the sampling interval of 1 mm. In order to determine the bond strength of shotcrete to rock surface, an instrumental setup was fabricated. From the study, following conclusions may be drawn:

- A correlation between JRC (Z_2) and JRC (RL1) is obtained as shown by Eq. 6. Similarly, a correlation between JRC (Z_2) and JRC (SF) was also obtained and shown by Eq. 7.
- A good bond between shotcrete and rock mass is needed to reduce significantly the bending stresses in the shotcrete lining in underground openings. It can be emphasized that bond strength is sensitive to JRC in the range from 9 to 16. The bonding strength increases linearly with an increase in the JRC value. Equation 9 shows the relationship of bond strength with joint roughness coefficient (JRC). The Eq. 9 is valid for a JRC value ranging between 9 and 16 only. Influence of JRC value below 9 is not significant on shotcrete bond strength.

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