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Strength and Modulus of Jointed Rock Mass in Uniaxial and Triaxial Compression

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Introduction

In Nature rocks generally exist as jointed masses. The presence of joints makes the rock mass weaker. Geotechnical engineers often face problems of instability in the foundations of structures, in open excavations and in underground works.

Piteau (1970) suggested the following factors pertaining to joint controlling the engineering behaviour of rock mass, namely, nature of their occurrence, their orientation in space, continuity, intensity, surface geometry and nature and thickness of gouge material. Amongst these factors which influence most in the generation of strength and modulus are the number of joints, the inclination of the planes of weakness and strength along the weak plane. Several researchers to quote a few Brown (1970) Brown and Trollope (1970), Einstein and Hirschfeld (1973), Yaji (1984), Ramamurthy and Gokhale (1986), Arora (1987), Ramamurthy and Arora (1994), Ramamurthy (1993), Roy (1993), Roy, Ramamurthy and Kate (1995) have reported on the strength and deformation characteristics of jointed mass. Ramamurthy and Arora (1991) introduced a factor called joint factor (J_f) which takes care of the combined influence of joint frequency, joint inclination and the strength along the sliding joint to account for the weakness in the rock mass.

In this paper, an attempt has been made to predict compressive strength

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and modulus values in uniaxial compression for jointed mass and its material parameters for the strength criterion from the joint factor obtained from the field data. The Joint factor forms a link between intact rock and jointed rock mass.

Experimental Study

Specimen Preparation

Using plaster of Paris as a model material, the intact specimens (76 mm height and 38 mm diameter) were prepared. The quantity of water required for mixing and curing was determined by trail tests. A standard methodology and curing procedure were adopted for the specimen preparation.

Two types of gouge material namely gouge 1 (plaster of Paris with 20% mica) and gouge 2 (plaster of Paris with 45% mica) were selected to study the gouge filled joints. Similar procedure was adopted for the preparation of all gouge filled jointed Specimens. The reason for choosing these grades of gouge material was to achieve lower friction values of the order of 20° along the joints so as to make this study as a part of a comprehensive study covering the behaviour of joints having friction angle varying from 20° to 45° under taken at IIT Delhi.

Curing of Specimens

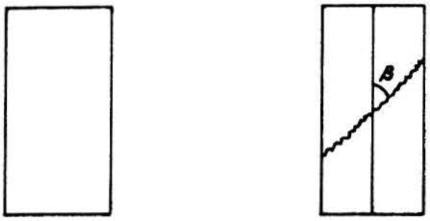
Specimens dried in infra-red oven for 12 hours were cured in a desiccators containing sulfuric acid (47.7 ml of 1 normal with distilled water to make up to 100 ml solution) maintaining a relative humidity in the range of 60% for further drying. The intact and jointed specimens of plaster of Paris with gouge filling were cured adequately following a set procedure to give consistent results.

Development of Joints

Rough broken joints were developed in intact specimens in the desired orientation to achieve the intended joint inclination, β, with the axis of the specimen with the help of a special set up developed for this purpose. The joint inclination was checked using a device (Set-up of pins) designed and fabricated .

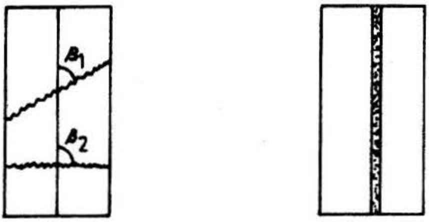
Types of Joints Studied

The types of joints studied are presented in Fig.l. In addition to the intact specimens, jointed specimens with single and double joints with varying



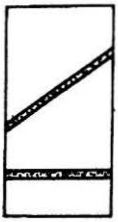
(a) Intact

(b) One tight joint with varying β from 2° to 86°



(c) Two tight joints β_1 varying from 2° to 63° β_2 varying from 44° to 90°

(d) One joint with gauge β varying from 0° to 90°



(e) Two joints with gauge β_1 varying from 30° to 90° β_2 varying from 45° to 90°

FIGURE 1 : Types of Joints Studied

inclination β, to the axis of the specimen and with and without gouge material were subjected to uniaxial and triaxial compression tests after curing. The variation in the inclination of the joints adopted for each category of joint is indicated in Fig.1.

Gouge Filling in Joints

The gouge paste was prepared by adding required percentage of mica in the plaster of Paris powder and mixing it thoroughly with water equal to

Table 1 : Physical and Engineering Properties of Materials Tested

Properties	Materials		
	Plaster of Paris	Gouge 1	Gouge 2
Dry density, γ_d, kN/m^3	10.99	9.70	8.90
Specific Gravity, G	2.59	–	–
σ_{ci}, MPa	9.46	4.72	2.28
E_{ti}, GPa	1.11	0.47	0.20
Friction angle, ϕ_j, degree	31.00	25.00	20.00
Deere and Miller (1966) Classification	EL	EL	EL
ISRM (1970) classification	Low Strength	Very Low Strength	Very Low Strength

Note: Subscripts i for intact specimen and j for jointed specimen.

75% of the combined weight. This percentage of water was used for making gouge paste so as to keep a provision of about 10% of water absorbed by joint faces from the gouge paste. The lower part of the broken specimen with joint face up was placed inside a semi-circle trough held vertically. The gouge paste was then placed on the joint face to give a thickness of more than 3 mm. The upper part of the broken specimen with joint face down was pressed on the gouge part so as to allow its squeezing to give a gouge thickness of 3 mm. The excess of gouge paste was trimmed off with the help of steel knife carefully to get a cylindrical specimen with gouge filled joint.

In the present investigation, the gouge thickness adopted was 3 mm since no significant change in shear strength of specimen filled with gouge materials having thickness more than 2 mm as reported by Lama (1974), due to non interference of the roughness on the joint faces.

Test Programme

The physical and engineering properties of the intact specimens (plaster of Paris, gouges 1 and 2 are presented in Table 1.

Uniaxial and Triaxial Compression Tests

The uniaxial compression tests on intact and jointed specimens with or without gouge were conducted in a 5 t loading frame as per ISRM (1977) and IS: 9143 test procedures at a deformation rate of 0.5 mm/min. The axial deformation and the axial load were recorded at regular intervals. The triaxial

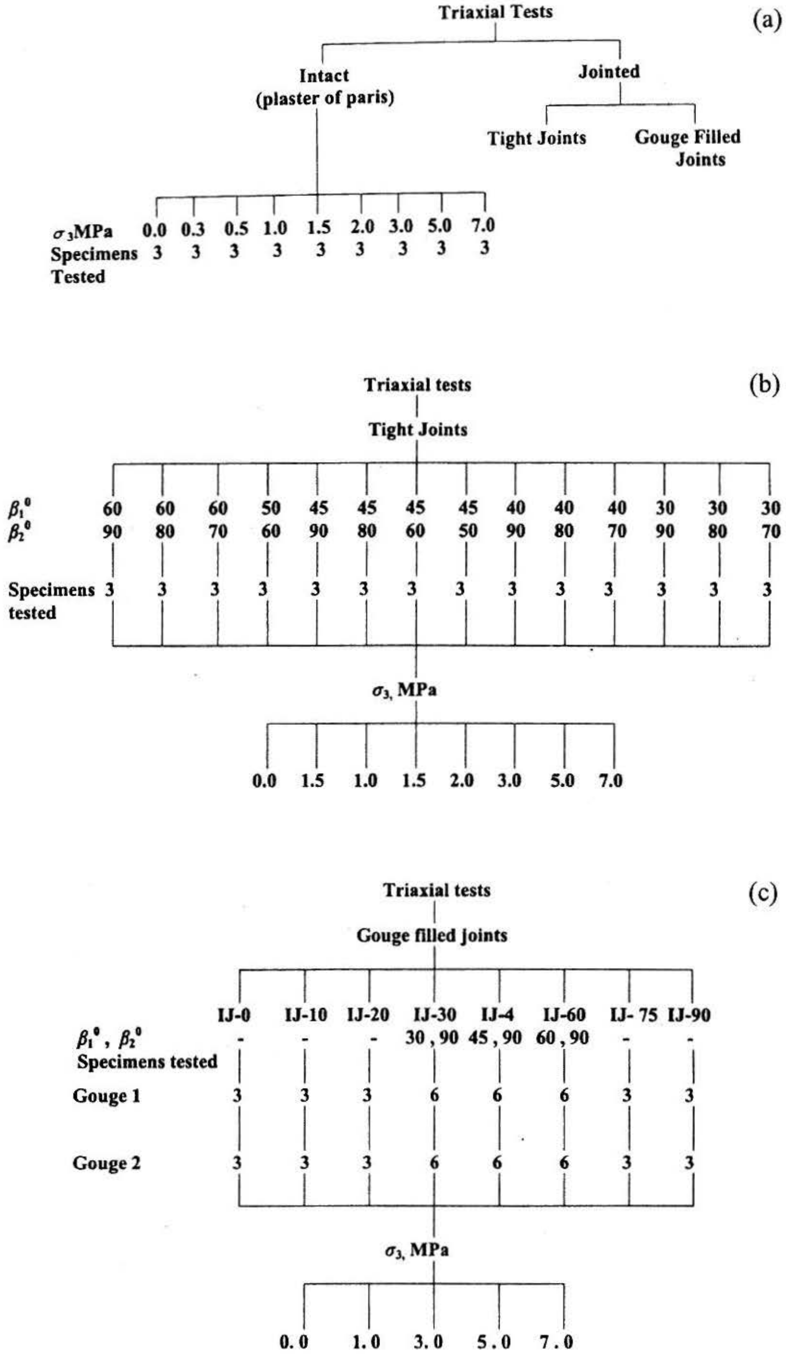


FIGURE 2 : (a) Triaxial Testing Programme; (b) Triaxial Testing for Tight Jointed Specimens; (c) Triaxial Testing Programme for Gouge Filled Joints

compression tests on intact specimens of plaster of Paris were carried out at confining pressures of 0.0, 0.3, 0.5, 1.0, 1.5, 2.0, 3.0, 5.0 and 7.0 MPa. For tight jointed specimens the tests were conducted at 0.0, 0.5, 1.0, 1.5, 2.0, 3.0, 5.0 and 7.0 MPa confining pressures. Whereas, for the gouge filled joints, the tests were carried out at 0.0, 1.0, 3.0, 5.0 and 7.0 MPa confining pressures. At each confining pressure, axial compressive load was applied and measurements were taken at regular intervals of deformation until the failure of the specimen occurred.

The triaxial tests were conducted as per the details given in Fig.2(a) to 2(c). The triaxial tests at confining pressures below 1 MPa were conducted as per Bishop and Henkel (1962). Whereas, the triaxial tests at and above 1 MPa were conducted in the high pressure triaxial cell designed and fabricated at Indian Institute of Technology, Delhi.

Results and Discussion

Joint factor, J_f may be evaluated by using the following relationship

$$J_f = \frac{J_n}{n \cdot r} \tag{1}$$

where J_n = Joint frequency, i.e. number of joints/meter depth

n = Inclination parameter for the joint

r = Strength parameter along the joint

The values of n are obtained from Table 2 for any joint orientation, $\beta°$ (Ramamurthy, 1993; Ramamurthy and Arora, 1994).

Specimens having two joints at inclination of β_1 and β_2 ($\beta_1 < \beta_2$) β_1, closer to $\left(45° - \phi_j/2\right)$ is the critical one. The values of n have been taken corresponding to β_1 in the present study for joints with and without gauge filling from Table 2. The variation of σ_{cr} $\left(= \sigma_{cj}/\sigma_{ci}\right)$ with J_f for the jointed specimens tested having one or two joints with different inclinations and with and without gouge filling, has been illustrated in Fig.3 (subscript i refers to intact and j refers to jointed specimens respectively). The variation

Table 2 : Value of n for the Orientation of Joint for U-shaped Anisotropy

$\beta°$	0.0	10	20	30	40	50	60	70	80	90
n	0.82	0.46	0.11	0.05	0.07	0.31	0.46	0.63	0.82	1.00

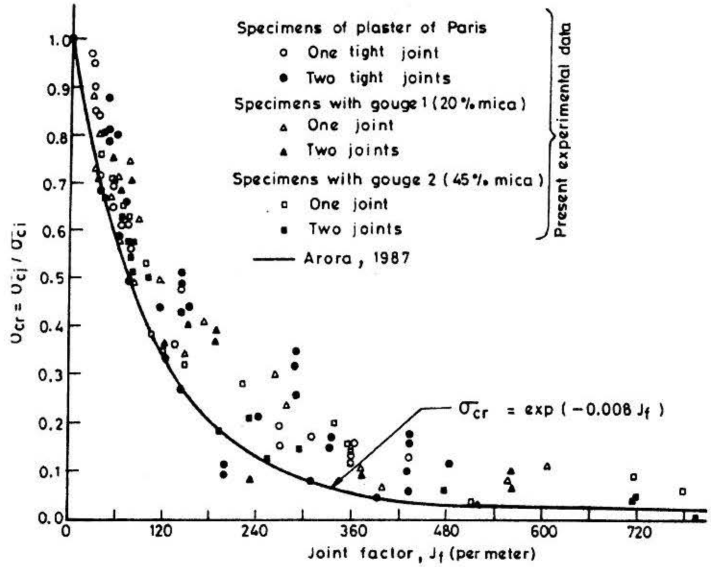


FIGURE 3 : Variation of σ_{cj}/σ_{ci} with Joint Factor, J_f

of σ_{cr} with J_f from test data of Ramamurthy and Arora (1994), Arora (1987), Yaji (1984), Einstein and Hirschfeld (1973), Brown and Trollope (1970) and Roy (1993) has been illustrated in Fig.4. Figure 4 indicates that as J_f

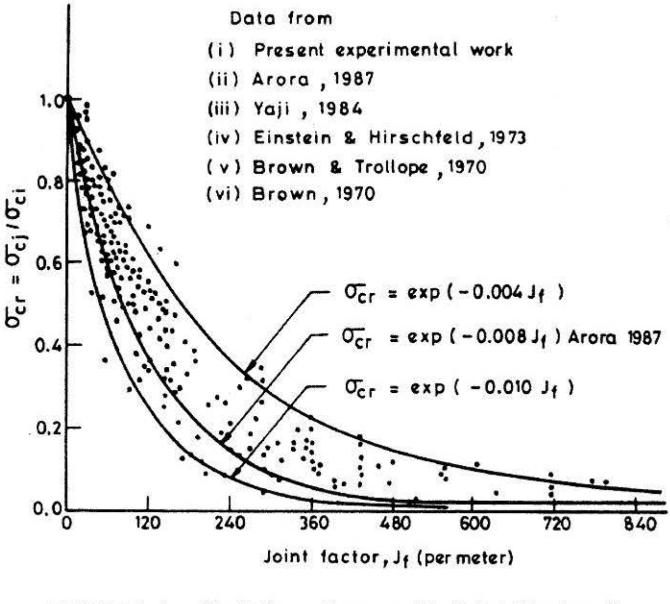


FIGURE 4 : Variation of σ_{cr} with Joint Factor, J_f

increases the corresponding uniaxial compressive strength of the jointed specimen σ_{cj} decreases as compared to the strength of intact specimen, σ_{ci}. A scatter in uniaxial compressive strength is observed due to different jointing patterns and joint roughness, developed during breaking of the specimen. The empirical relationships developed between σ_{cr} and J_f is as follows,

For upper bound

$$\sigma_{cr} = \exp(-0.004\,J_f) \tag{2}$$

For average limit (Ramamurthy and Arora, 1991)

$$\sigma_{cr} = \exp(-0.008\,J_f) \tag{3}$$

For lower bound

$$\sigma_{cr} = \exp(-0.01\,J_f) \tag{4}$$

Equations (2), (3) and (4) hold good for different rocks and rock-like materials covering a wide range of σ_{ci} (9.46 to 123.00 MPa) values. The use of Eqns.(2), (3) and (4) depends upon what factor of safety one would like to adopt to obtain σ_{cj} to apply in the field situation. The upper bound limit Eqn.(2) may be used with higher factor of safety and Eqn.(4) with lower factor of safety. Equation (3) may be adopted when the level of confidence is to fall between the upper and lower limits.

Prediction of Tangent Modulus of Jointed Specimens, E_{tj}

The modulus of elasticity in uniaxial compression has been determined from stress- strain curves at 50 per cent of the failure stress. Single tight jointed specimens at $\beta = 2°$ and $\beta = 29°$ have shown the maximum value of $E_{tj} = 781.8$ MPa and minimum value of $E_{tj} = 40.5$ MPa respectively. Whereas, two tight jointed specimens indicated maximum value of $E_{tj} = 760.0$ MPa at $\beta_1 = 63°$, $\beta_2 = 82°$ and the minimum value of $E_{tj} = 9.7$ MPa at $\beta_1 = 31°$, $\beta_2 = 63°$. The specimens filled with gouge 1 at $\beta = 90°$ and specimens with two joints $\beta_1 = \beta_2 = 90°$ have indicated maximum value $E_{tj} = 754.5$ and 420.7 MPa respectively. Whereas, the specimens with $\beta_1 = 33°$, $\beta_2 = 65°$ have shown minimum value of $E_{tj} = 22.7$ and 10.0 MPa respectively in uniaxial compression. The specimens filled with gouge 2 at $\beta = 0°$ and those with two joints at $\beta_1 = \beta_2 = 90°$ have shown a maximum value of $E_{tj} = 630.0$ and 398.7 MPa respectively. On the other hand the specimens with gouge 2 at $\beta = 35°$ and those with two joints at $\beta_1 = 31°$, $\beta_2 = 70°$ have indicated the minimum value of $E_{tj} = 7.5$ MPa and 2.0 MPa respectively in uniaxial compression. Based on these values of E_{tj} and E_{ti} empirical relationships have been established.

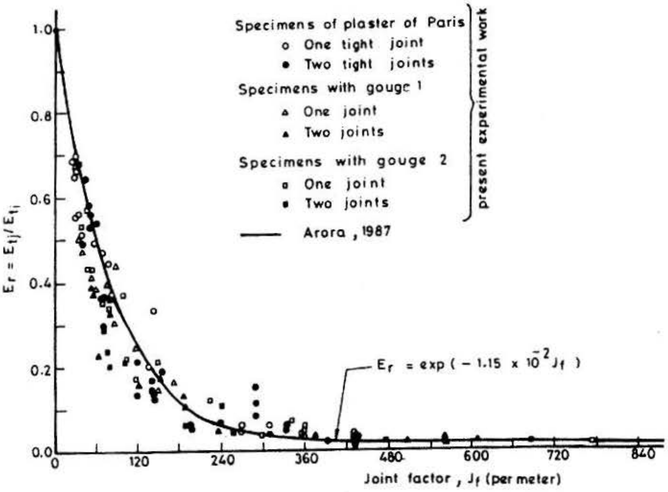


FIGURE 5 : Variation of E_r with Joint Factor, J_f

Figure 5 shows the variation of E_r $\left(= E_{tj}/E_{ti}\right)$ with J_f for jointed specimens having one or two joints with different inclinations and with and without gouge. Figure 6 illustrates the variation of E_r with J_f based on test results of Roy (1993), Ramamurthy and Arora (1991), Arora (1987), Yaji (1984), Einstein and Hirschfeld (1973), Brown (1970), Brown and Tollope (1970). Relationships between E_r and J_f are established as,

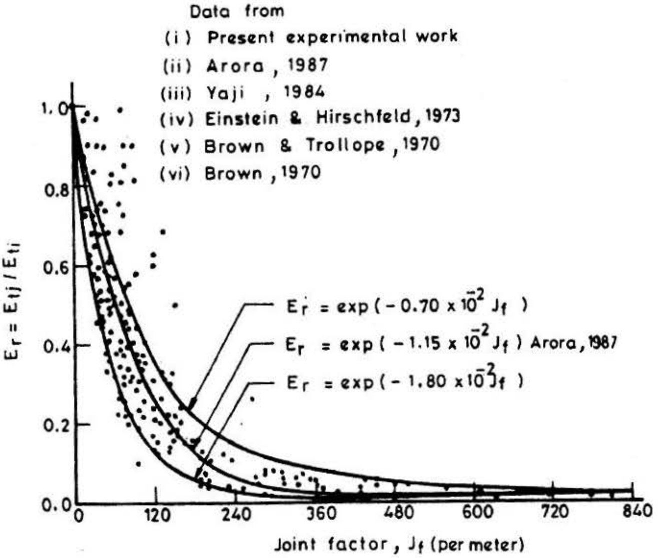


FIGURE 6 : Variation of E_r with Joint Factor, J_f

For upper bound

$$E_r = \exp\left(-0.7 \times 10^{-2} J_f\right) \tag{5}$$

For average values (Ramamurthy and Arora, 1994)

$$E_r = \exp\left(-1.15 \times 10^{-2} J_f\right) \tag{6}$$

For lower bound

$$E_r = \exp\left(-1.18 \times 10^{-2} J_f\right) \tag{7}$$

Equations (5), (6) and (7) may be used for evaluating E_{tj} depending upon the factor of safety to be applied in the field conditions.

Strength Criteria for Rocks

The strength criteria for isotropic, anisotropic intact rocks and rock masses were proposed by various researchers to quote a few Murell (1965), Bieniawski (1974), Brook (1979) and Hoek and Brown (1980). These were adequately discussed in the earlier publications (Ramamurthy 1986 and 1993) and also by other researchers. Based on the test results and analysis of published literature, Rao (1984), Ramamurthy et al. (1985) and Ramamurthy (1986) suggested the following strength criterion for intact rocks;

$$\frac{(\sigma_1 - \sigma_3)}{\sigma_3} = B_i \left(\frac{\sigma_{ci}}{\sigma_3}\right)^{\alpha_i} \tag{8}$$

where σ_{ci} = uniaxial compressive strength

σ_1 and σ_3 = major and minor principal stresses respectively

α_i and B_i = material parameters / strength parameters.

α_i is the slope of Plot between $(\sigma_1 - \sigma_3)/\sigma_3$ and σ_{ci}/σ_3 on log - log plot and B is the intercept when $\sigma_{ci}/\sigma_3 = 1$. This Eqn.(8) was later modified (Ramamurthy, 1993) to include the tensile strength for intact rocks.

Evaluation of α

Ramamurthy and co-workers (1985) found the value of $\alpha = 0.80$ for most intact rocks. Later on based on extensive experimental works, Ramamurthy and Arora (1987) had shown the variation of α value for jointed specimens. The value of α_i and α_j for intact and jointed specimens respectively are presented in Figs.7(a) and 7(b) for some of the tight jointed specimens of plaster of Paris.

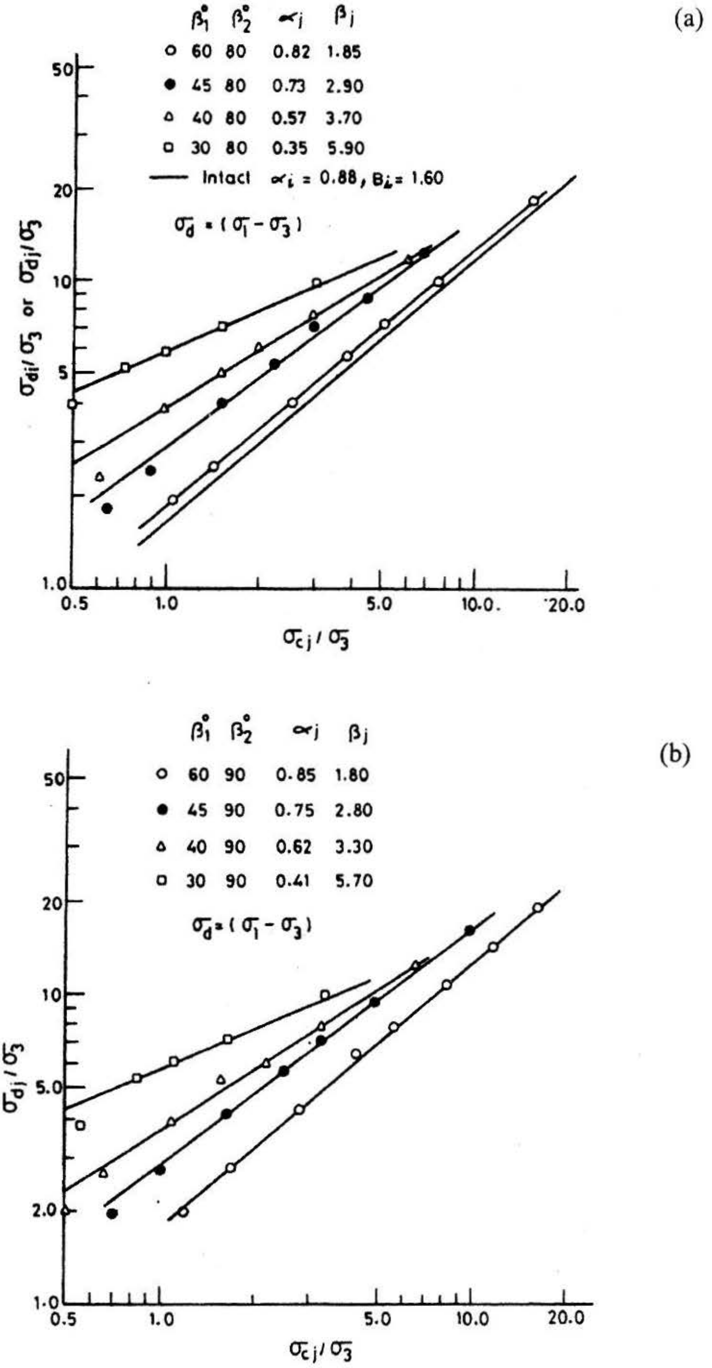


FIGURE 7 : Evaluation of α and B for Tight Jointed Specimens of Plaster of Paris

The minimum value of $\alpha_j = 0.33$ was observed for two tight jointed specimens of $\beta_1 = 30°$, $\beta_2 = 70°$ whereas maximum value of $\alpha_j = 0.85$ was in the case of specimens at joint inclination of $\beta_1 = 60°$, $\beta_2 = 90°$. The plot between σ_{dj}/σ_3 and σ_{cj}/σ_3 (where $\sigma_{dj} = \sigma_1 - \sigma_3$) for specimens with gouge 1 and gouge 2 are illustrated in Figs.8(a) to 8(d) and 9(a) to 9(d) for determination of α_j. Figures 8(a) to 8(d) indicate a minimum value of $\alpha_j = 0.46$ for the specimen $\beta = 30°$ and a maximum value $\alpha_j = 0.86$ for specimen at joint orientation $\beta = 90°$ for gouge 1 filled joints. Whereas, the maximum value of $\alpha_j = 0.75$ was observed for gouge 1 filled specimen at $\beta_1 = 60°$, $\beta_2 = 90°$ and a minimum value of $\alpha_j = 0.48$ was observed for gouge 1 filled specimen at $\beta_1 = 30°$ and $\beta_2 = 90°$. The maximum value of $\alpha_j = 0.81$ has been observed for joints with gouge 2 at $\beta_1 = 60°$, $\beta_2 = 90°$. The minimum value of $\alpha_j = 0.36$ for one joint at $\beta = 30°$ whereas, for two joints filled with gouge 2 the minimum value of $\alpha_j = 0.36$ was observed for specimen at $\beta_1 = 30°$ and $\beta_2 = 90°$.

Based on the present experimental work and the data of Arora (1987), Yaji (1984), Einstein and Hirschfeld (1973) and Brown and Trollope (1970), it is observed that there is a large variation in the values of α_j. But the variation of α_j/α_i with σ_{cj}/σ_{ci} follows a definite trend.

Figures 10(a) and 10(b) illustrate the variation of α_j/α_i with σ_{cj}/σ_{ci} from the present experimental data and the data from Arora (1987), Yaji (1984), Einstein and Hirschfeld (1973) and Brown and Trollope (1970). A further analysis of the test data presented in Fig.10(b) could be represented by the relationship for all practical use as

$$\frac{\alpha_j}{\alpha_i} = \left(\frac{\sigma_{cj}}{\sigma_{ci}}\right)^{0.50} \tag{9}$$

Evaluation of B Factor for Jointed Mass

Ramamurthy et al. (1985) defined B as a material parameter and suggested that the values of B vary from 1.80 to 3.00 depending upon the lithology of the intact rock. The present study has indicated that there is a large variation in the value of B for jointed rocks with and without gouge filling. This study indicates minimum and maximum values of B_j as 1.80 and 6.40 for two tight jointed specimens with $\beta_1 = 60°$, $\beta_2 = 90°$ and $\beta_1 = 30°$, $\beta_2 = 70°$ respectively. Similarly the minimum and maximum value of B_j are 1.80 and 4.70 for specimens with $l_j - 10$ (i.e. one joint at $\beta_1 = 10°$), $l_j - 30$ filled with gouge 1. The maximum and minimum values of B_j are 5.00 and 2.30 for two joints filled with gouge 1, for specimens having $\beta_1 = 30°$, $\beta_2 = 90°$ and $\beta_1 = 60°$, $\beta_2 = 90°$. The minimum and maximum values of B_j are 2.0 and 4.5 for specimens $l_j - 90$ and $l_j - 30$ filled with gouge 2

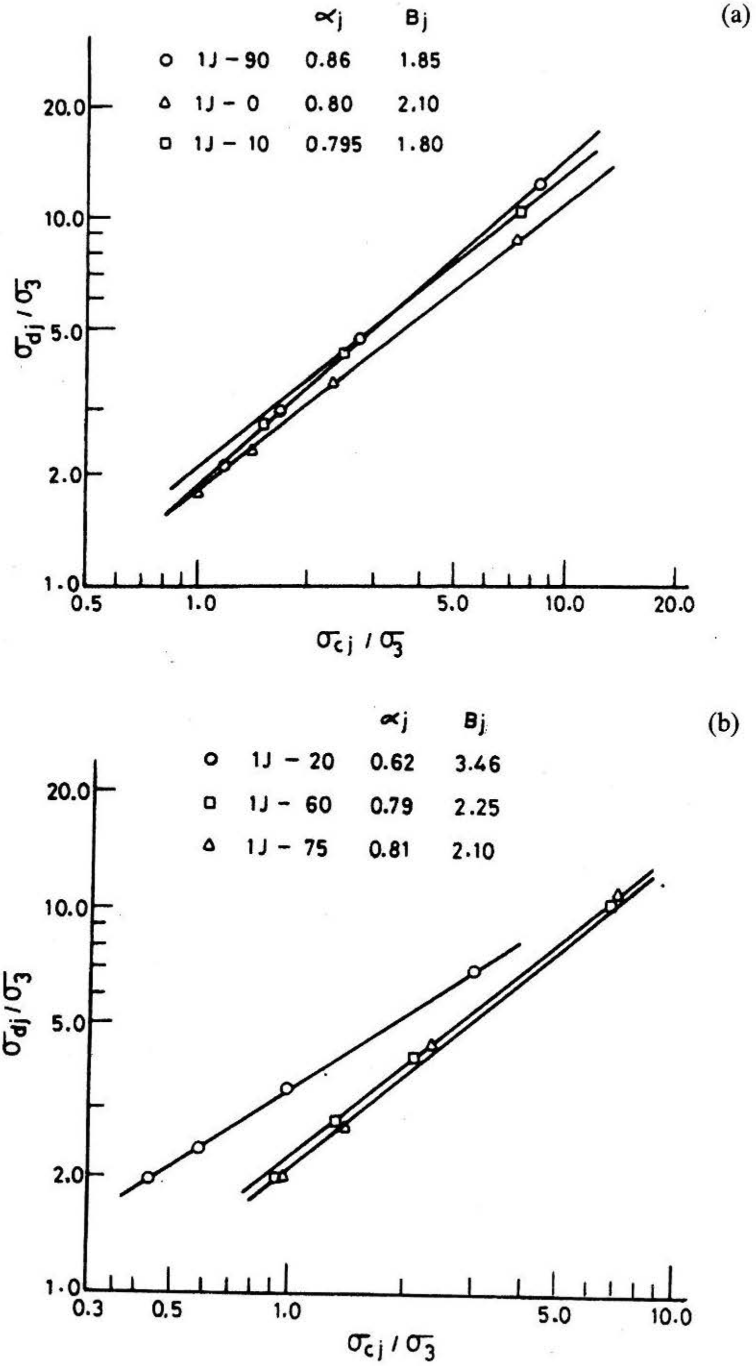


FIGURE 8 : Continued

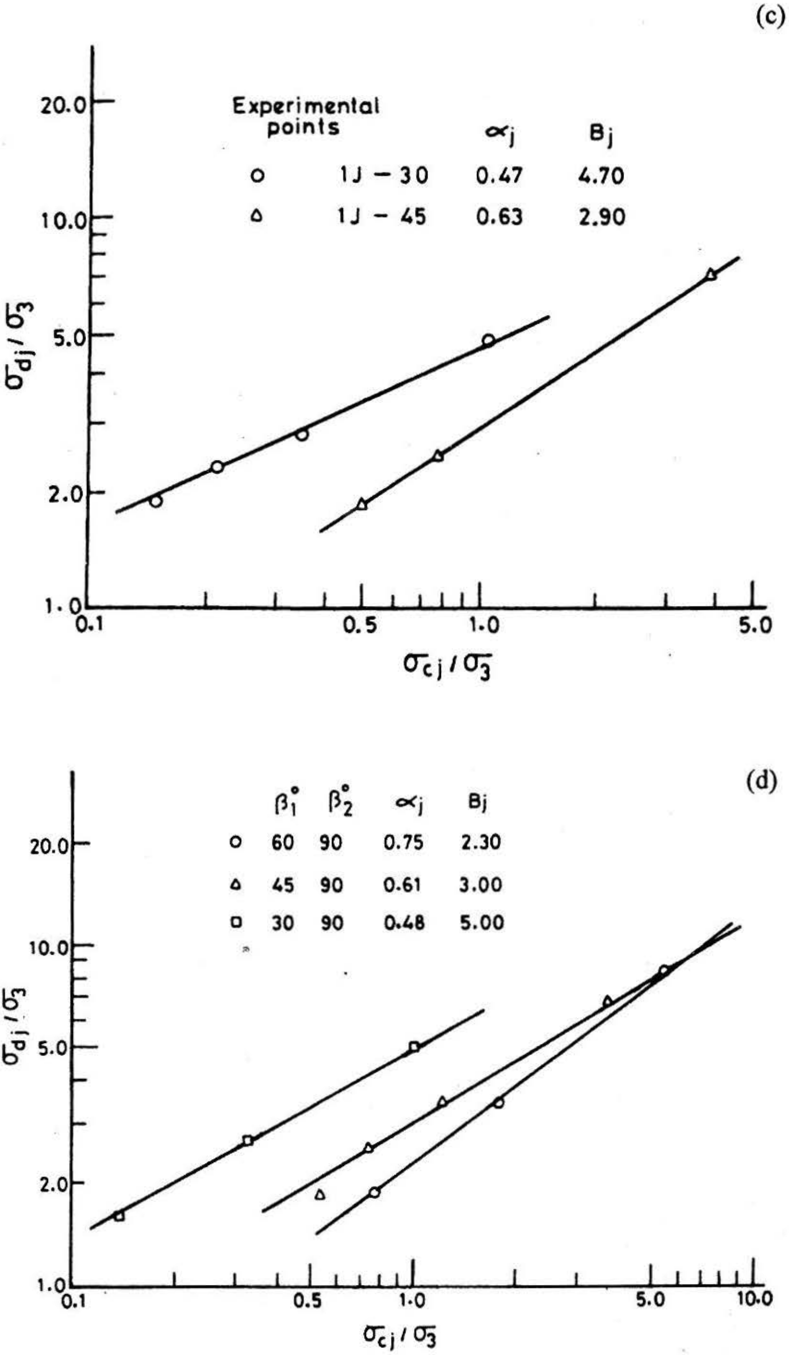
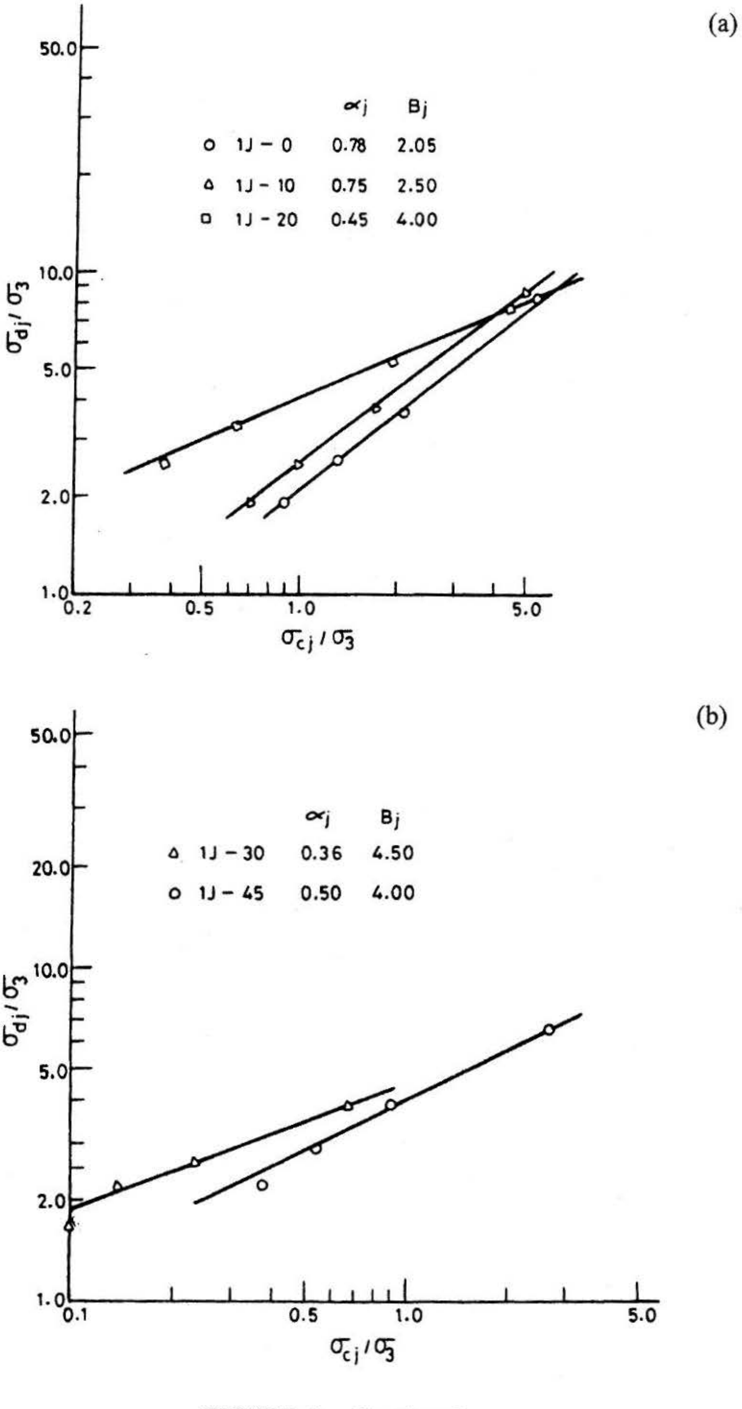


FIGURE 8 : Evaluation of α and B for Jointed Specimens with Gouge 1



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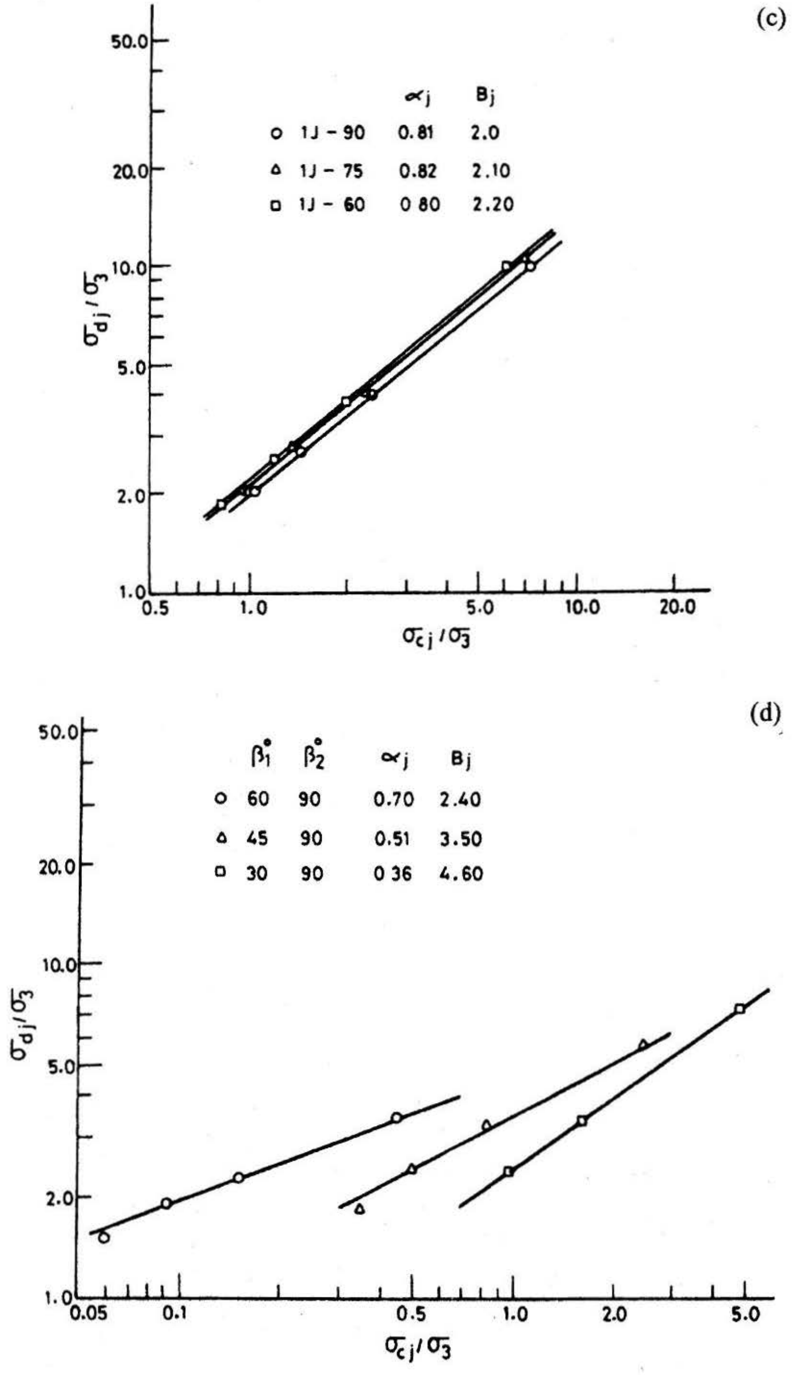

FIGURE 9 : Evaluation of α and B for Jointed Specimens with Gouge 2

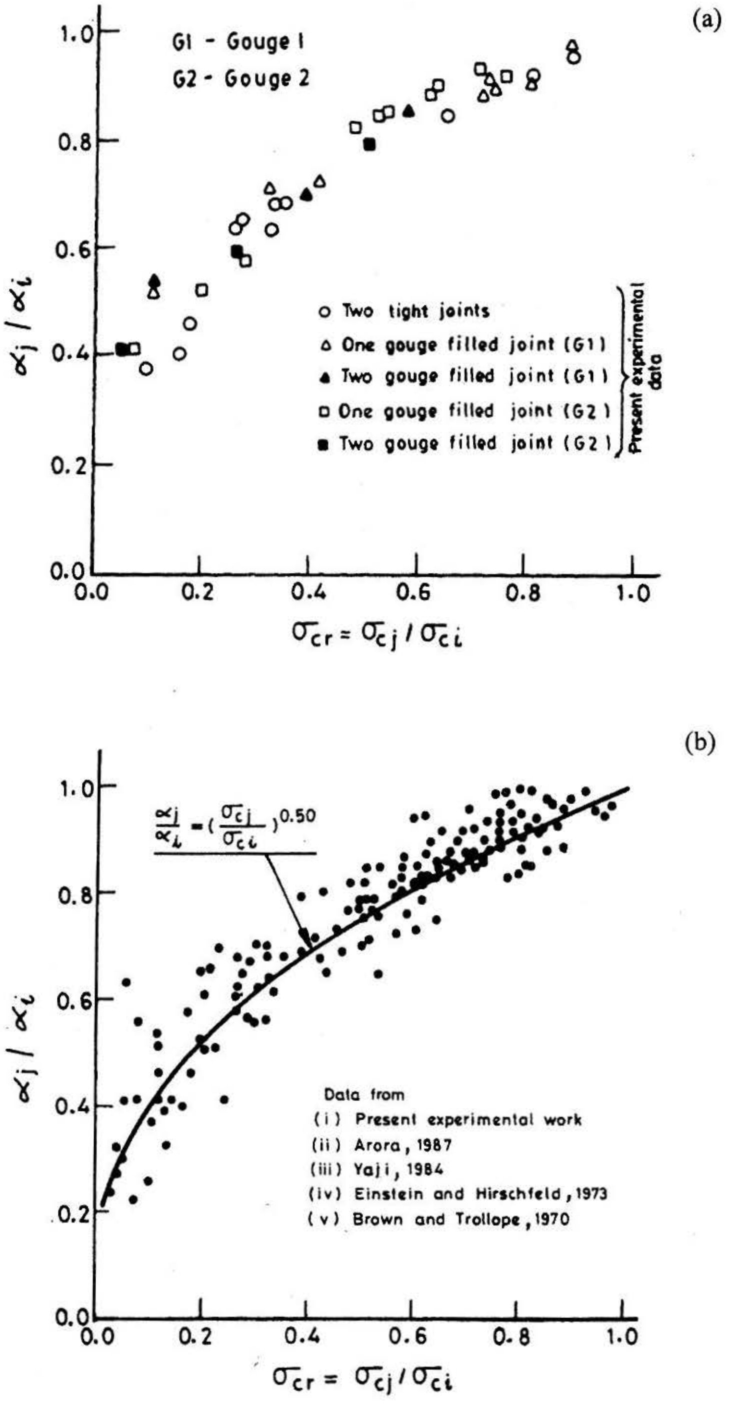

FIGURE 10 : Variation of α_j/α_i with σ_{cj}/σ_{ci}

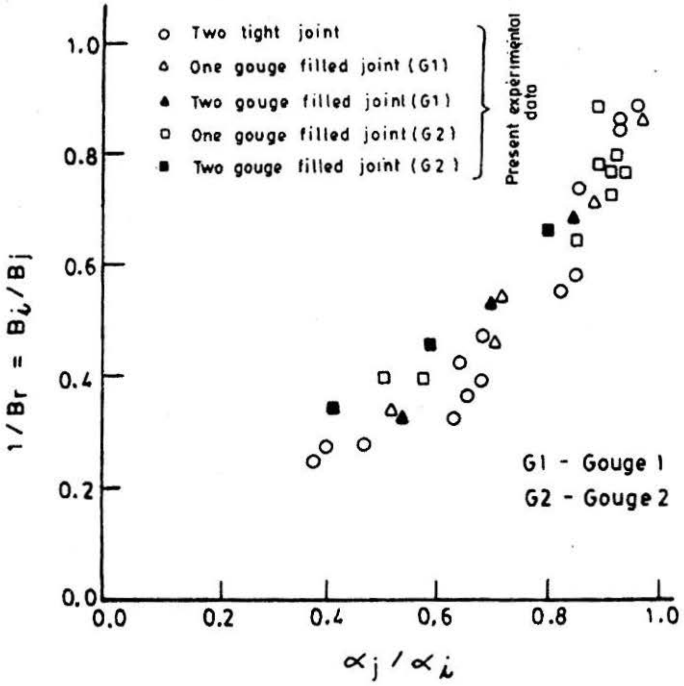

FIGURE 11 : Variation of B_i/B_j with α_j/α_i

respectively. The maximum and minimum values of B_j are 4.60 and 2.40 for two joints filled with gouge 2 specimens at $\beta_1 = 30°$, $\beta_2 = 90°$ and $\beta_1 = 60°$, $\beta_2 = 90°$.

The present study indicated that B_j is greater than B_i for the types of joints studied with and without gouge which is also confirmed by analysing the test data of Brown (1970), Brown and Trollope (1970), Einstein and Hirschfeld (1973), Yaji (1984) and Arora (1987).

Figure 11 shows the variation of B_i/B_j for the specimens tested in the present study. Figure 12 illustrates a plot between B_i/B_j and α_j/α_i incorporating the result of present work and test data of Arora (1987), Yaji, (1984), Einstein and Hirschfeld (1973) and Brown and Trollope (1970). A suitable exponential curve is fitted to the plotted data to develop a relationship between B_i/B_j and α_j/α_i. The relationship may be expressed by the following Eqn.10.

$$\frac{B_i}{B_j} = 0.13 \exp 2.04\left(\frac{\alpha_j}{\alpha_i}\right) \tag{10}$$

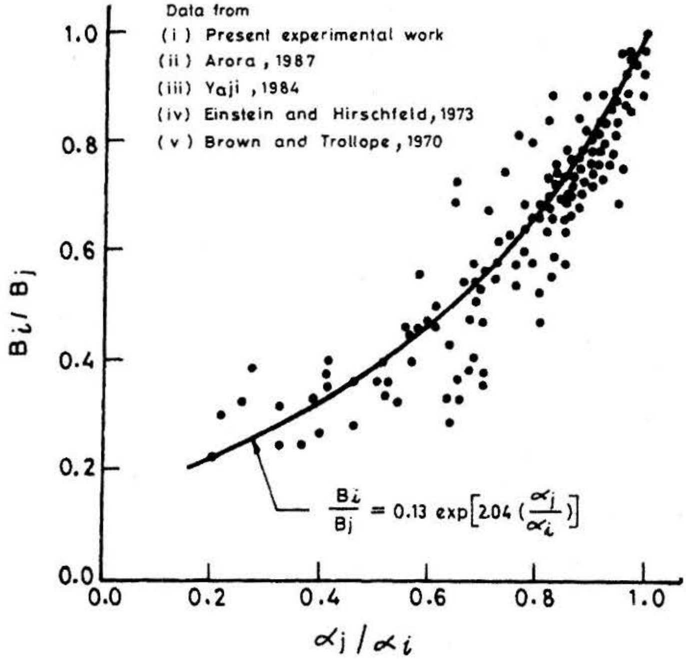

FIGURE 12 : Variation of B_i/B_j with α_j/α_i

Equation (10) may also be expressed in terms of the ratio of the uniaxial compressive strength of jointed and intact specimens as,

$$\frac{B_i}{B_j} = 0.13 \exp 2.04 \left(\frac{\sigma_{cj}}{\sigma_{ci}}\right)^{0.50} \tag{11}$$

Conclusions

1. On the basis of the experimental data, it appears that the non-linear two parametric strength criterion which was found to be applicable to intact rocks and jointed rocks and rock-like materials has also been found to be applicable in the case of jointed mass with in-filled gouge material.

2. The joint factor which takes in to account the combined influence of joint frequency, critical joint inclination and the strength along this joint has been found to be a useful parameter to define the weakness introduced by jointly / fracturing in a mass. It is useful in linking the uniaxial compressive strength, tangent modulus and strength parameters

of the criterion of intact rock to those of the corresponding values of the jointed mass.

3. The uniaxial compressive strength, the tangent modulus and the strength parameters in the failure criterion of jointed mass could now be more reliably estimated and the strength of the jointed mass can be assessed under any desired confining pressures / in-situ stress in the axisymmetric triaxial case.

Notations

E_r = E_{tj}/E_{ti} at 50% of the failure stress

E_t = Tangent modulus

J_f = Joint factor equals to $J_n/n \cdot r$; a weakness co-efficient due to jointing per meter depth

J_n = Joint frequency i.e. number of joints per meter depth

n = Inclination parameter dependent on joint orientation angle β°) with the vertical/major principal stress

r = Joint strength parameter dependant on joint condition and joint material i.e. $\tan\phi_j$, (ϕ_j = friction angle on the sliding joint).

β = Angle between orientation of joint and the major principle stress, σ_1, direction

σ_c = Uniaxial compressive strength

σ_{cr} = σ_{cj}/σ_{ci}

σ_d = Deviator stress, $\left(\sigma_1 - \sigma_3\right)$

σ_1 = Major principal stress

σ_3 = Confining pressure/minor principal stress

Note: i refers to intact rock, j refers to jointed rock.

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