TECHNICAL NOTE

DEFORMATIONAL CHARACTERISTICS OF ROCKS CONTAINING A SINGLE DISCONTINUITY

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Abstract For the purpose of exploring deformation characteristics of jointed rock masses, influence of joint inclination and confining pressure on the mechanical behavior of discontinuous rock a series of compression tests were conducted under satisfactory testing conditions on three types of sandstone from various locations. Three groups of jointed specimens were used in this research, including specimens containing saw cut planar joint, shear-surface joint and split breakage joint. The specimens were tested triaxially up to 70 MPa confined pressure. A 5 MN servo-controlled stiff testing machine was employed and a monitoring system was set up using a microcomputer controlled logger. The deformation characteristics of jointed specimens with saw cut joints were different in low and high confinements, however, in split breakage joints sliding behavior was the same in low and high confinements. Mohr envelope for 60° inclination in split breakage joints was above that of 45° in both saw cut and split breakage joints, i. e. a higher coefficient of sliding friction or a higher shear strength across the joint for this orientation.

Key Words Discontinuous Rock, Saw Cut Joint, Split Breakage Joint, Confining Pressure, Deformation

چکیده به منظور ارزیابی خصوصیات توده‌های سنگی درزدار و ناپیوسته، مطالعه اثر جهت و زاویه ناپیوستگی و نیز تاثیر فشار جانبی بر رفتار مکانیکی سنگ‌های ناپیوسته، تحقیقات آزمایشگاهی بر روی نمونه‌های استوانه‌ای چند نوع سنگ انجام گردید. آزمایش‌های سه محوری با استفاده از دستگاه بارگذاری الکترونیکی و با سختی زیاد و تحت شرایط کنترل شده و با فشار جانبی تا MPa ۷۰ اجرا شد. اطلاعات حاصل از بارگذاری طی آزمایش توسط دستگاه الکترونیکی جمع‌آوری اطلاعات ضبط و توسط برنامه‌ای کامپیوتری پردازش و تحلیل گردید. نمونه‌های سنگی به صورت استوانه و با نسبت ارتفاع به قطر ۲ و با قطر ۷۵ میلیمتر تهیه گردید. سه نوع درز بر روی نمونه‌ها ایجاد گردید. نوع اول درز اره‌ای است که با سطح صاف و تقریباً صیقلی بودند و نوع دوم درزهای کششی که قابل مقایسه با درزهای طبیعی که در توده‌های سنگی هستند بودند و نوع سوم درزهای برشی بودند که نمونه بکر تحت بار در امتداد صفحه‌ای شکسته می‌شد و سپس به عنوان درز مورد مطالعه قرار می‌گرفت. ناپیوستگی نسبت به محور افقی نمونه با زوایای °۱۵، °۳۰، °۴۵ و °۶۰ ایجاد شدند. خصوصیات تغییر شکل‌پذیری نمونه‌های درزدار با درز اره‌ای تحت فشار جانبی کم متفاوت با رفتار نمونه‌های درزدار تحت فشار جانبی بالا بود. لیکن در درزهای کششی رفتار لغزشی و اصطکاکی تحت فشار کم و زیاد تفاوتی نداشت. پوش موهر برای زاویه °۶۰ و با درز کششی بالاتر از پوش زاویه °۴۵ با درز کششی و یا اره‌ای قرار می‌گرفت. یعنی زاویه اصطکاک لغزشی بیشتر یا مقاومت برشی بیشتر برای درزهای زبر و طبیعی تحت زاویه °۶۰ اتفاق می‌افتد.

1. INTRODUCTION

After Von Carman [1] who pioneered the triaxial testing of rocks. It appears that the application of this test in the study of deformation behavior of rock, was first used by the US Bureau of Reclamation [2] for testing the bond strength between concrete and rock. It was adopted for measurement of friction between the surface of a joint by Jaeger [3], and has since been used extensively for investigating different aspects of discontinuous rock without giving enough attention to the end-specimen condition particularly to the problem of change of the specimen geometry when sliding commences.

It has been shown (Fahimifar [4]) that the type and configuration of seat and platen in the cell specimen system have significant effects on the deformation characteristics of the joint surface.

Among several configurations, including a spherical seat at the top and a platen in the bottom which is often the case, the most satisfactory end-specimen condition was a configuration, in which pairs of hardened steel discs were polished and lubricated with a molybdenum disulphide grease and placed at the top and bottom of specimens. On the basis of this modification experimental research was performed to investigate the sliding and frictional characteristics of rock types containing a single plane of weakness under triaxial testing condition.

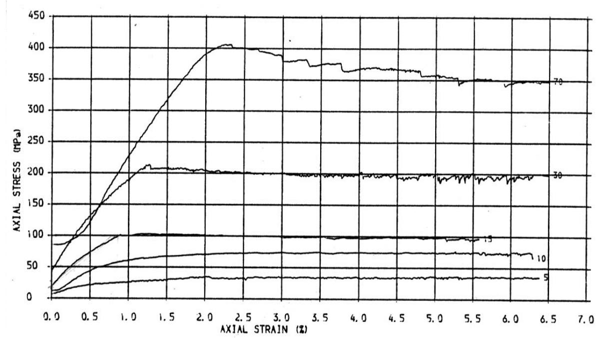

Figure 1. Stress–strain plots for sandstone with saw cut joints, joint angle = 45°, confining pressures = 5, 10, 15, 30 and 70 MPa.

2. EXPERIMENTAL PROCEDURES

The experiment was carried out by a 5 MN servo-controlled stiff testing machine in the same way as described by Fahimifar [4]. The procedure used for the preparation of test specimens was in accordance with the ISRM suggested methods (Brown [5]). The specimens were cored to a nominal diameter of 75 mm and length of 150 mm.

Three groups or types of jointed specimens similar in size and shape were used in this experiment. The first type of joint was saw cut in which after preparation of cylindrical cores, each of them was cut into two pieces with a diamond saw. The cuts were perfectly plane surfaces at angles 15, 30, 45 and 60° with respect to the direction of minor principal stress. The second joint type, i.e, the shear-surface joint was established by shear fracture of solid specimens in confining pressures of zero (uniaxial) and 10 MPa. For the jointed specimens produced in this way, it was not possible to obtain predetermined joint orientations. The third joint type used in this experiment is an attempt to simulate natural joints. The cylindrical specimens with this type of joint were drilled from a block containing a split breakage (tension joint) at an inclination of 30, 45 and 60°. Preparation of this type of specimen was very difficult and time consuming.

A multi channel analogue data acquisition unit capable of interfacing with a microcomputer and with the servo-controlled system was used. The triaxial cell has sufficient internal space to allow large lateral displacement when sliding takes place along the joint surface. It has been designed for confining pressure up to 70 MPa. A continuously operating electric pumping unit applied lateral confining pressure hydraulically.

3. DISCUSSION OF RESULTS

Examination and observation of the tables and plots reveal that several parameters affect the stress-strain and stress at failure-joint inclination, and the deformational characteristics of the rocks tested.

a) Confining Pressure Effects Confining pressure had significant effects upon the stress-strain properties of the rocks tested with any orientation. The axial stress-strain curves as presented (Figure 1), all show that increased confining pressure both strengthens the intact and jointed rocks, and results in an eventual transition from strain softening to hardening behavior for the intact specimens. There is also an increase in the axial strain to failure and often a shallower post-failure curve as confining pressure increases.

Effects of increased confining pressure on the jointed rock having orientations of 45 and 60° namely the orientations in which failure occurs by sliding along the joint surfaces, is more remarkable

TABLE 1. Strength Reduction Factors for Sandstone Specimens With Saw Cut Joints.

Confinig Pressure (MPa)	Joint orientation angle (deg.)					Intact compressive strength (MPa)
	0	15	30	45	60	
0	0.924	0.898	0.189	0	0	79
5	0.809	0.796	0.757	0.194	0.074	154.5
10	0.945	0.921	0.837	0.391	0.181	166
15	0.839	0.829	0.771	0.424	0.171	205
30	0.990	0.973	0.996	0.604	0.292	289
70	-	-	-	0.761	0.450	440

(Figures 2 and 3). Comparison of the peak stresses for these orientations with those of the intact specimens in the same confining pressure shows that the increased confining pressure decreases the joint effect significantly, even in the critical orientations (Figure 4). In other words, it may be concluded that increased confining pressure, eventually results in the diminishing of the weakness plane effect on the rock strength.

Table 1 illustrates the strength reduction factors (the ratio of the strength of jointed specimen to that of the intact) for sandstone specimens with saw cut joints. Comparison of the ratios for 45° orientation shows that increase in confining pressure from 15 to 30 and then to 70 MPa resulted in an increase in the ratios from 0.424 (15 MPa) to 0.604 (30 MPa) and to 0.761 (70 MPa). This implies that the strength of the jointed specimens becomes nearer to the strength of the intact specimens in proportion to the increase in the confining pressure. The same trend is observed for 60° orientation and the other joint types. For 60° orientation (Table 1 for instance) the ratio on 15 MPa confining pressure is 0.171. It has increased to 0.292 for 30 MPa and to 0.450 for 70 MPa.

The effect of confining pressure on the sliding characteristics of joints at low confining pressures seems to be different from that of the higher confining pressures. As Figures 1 (plots 5 and 10) and 2 (plots 5 and 10) illustrates up to 10 MPa

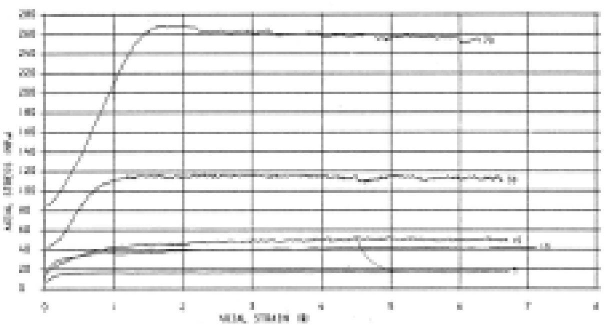

Figure 2. Stress–strain plots for sandstone specimens with saw cut joints, joint angle = 60°, confining pressures = 5, 10, 15, 30 and 70 MPa.

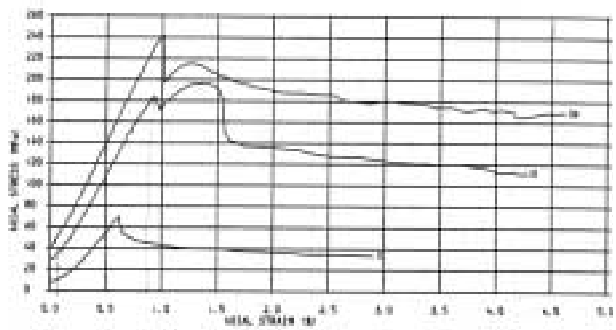

Figure 3. Stress–strain plots for sandstone specimens with natural joints, joint angle = 45°, confining pressures = 5, 10, 15 and 30 MPa.

TABLE 2. Strength Reduction Factors for Sandstone Specimens With Saw Cut Joints.

Confinig Pressure (MPa)	Joint orientation angle (deg.)			Intact compressive strength (MPa)
	30	45	60	
0	0.433	0.050	0	60
5	0.787	0.685	0.190	108.5
10	0.949	0.744	0.317	137
15	0.906	0.768	0.262	160
30	-	0.640	0.400	250

TABLE 3. Strength Reduction Factors for Sandstone Specimens with Saw Cut Joints.

Confinig pressure (MPa)	Joint orientation angle (deg)			Intact compressive strength (MPa)
	30	45	60	
5	0.945	0..414	0.213	154.5
15	0.893	0.756	0.615	205
30	0.882	0.678	0.644	298

confining pressure (5 and 10) sliding has continued asymptotically with a slightly ascending order of magnitude, or nearly at a constant stress level, however, with an increase in confining pressure from 15 to 30 and then to 70 MPa, sliding has continued in a descending order, so that the rate of reduction has increased with increased confining pressure.

The behavior of sliding in split breakage joints seems to be the same in both low and high confining pressures, after dropping the stress to a residual value sliding continues in a descending order at all levels of confining pressures (Figure 3). The reason for the difference in sliding manner in low and high confining pressures, and also in saw cut and split joints may be explained as follows: In the saw cut joints at low levels of confining pressures, the rate of damage due to sliding is very low in comparison with high confining pressure, therefore, the amount of debris material produced during sliding is much less than that of high pressures: Examination of the specimens after tests

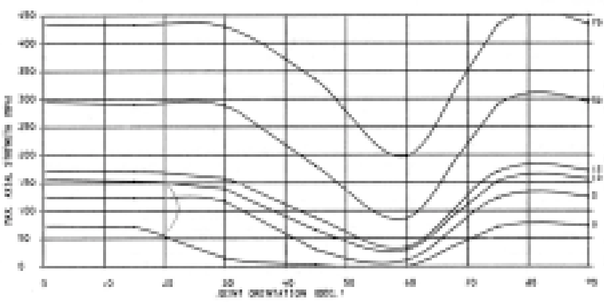

Figure 4. Stress–joint orientation plots for a sandstone, joint angles: 0, 15, 30, 45, 60, 75 and 90°, confining pressures = 0, 5, 10, 15 , 30 and 70 MPa.

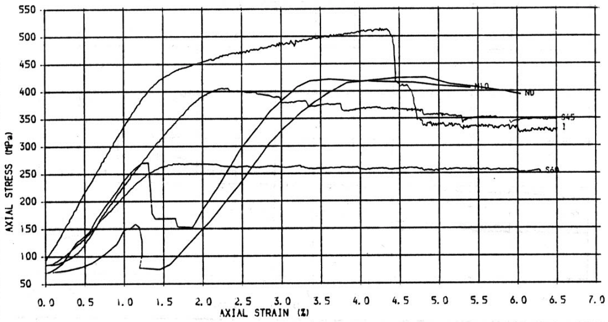

Figure 5. Stress–strain plots for intact and jointed sandstone specimens, saw cut with 45 and 60°, and shear-surface joints (at 0 and 10 MPa), confining pressure 70 MPa.

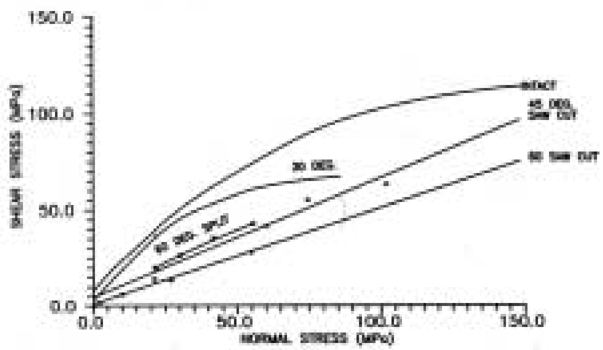

Figure 7. Mohr envelopes for intact and jointed (saw cut and split) sandstone specimens (type II).

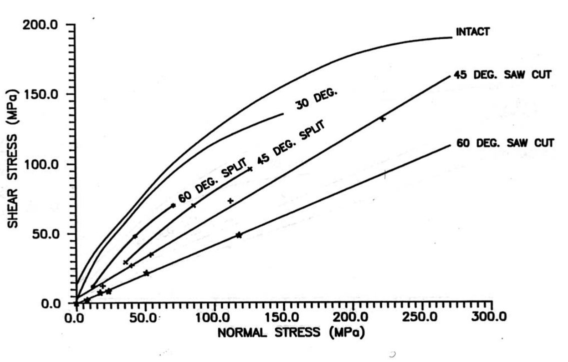

Figure 6. Mohr envelopes for intact and jointed (saw cut and split) sandstone specimens (type I).

confirmed that a rather thick layer of pulverized material coated the surfaces of sliding in high confining pressures, it was very thin, however, in low pressures. Because of such a layer of wear over the sliding surface it may be postulated that a filled joint has been formed which is much weaker than the rock material. With continuation of sliding the wear becomes thicker, and therefore, a further reduction in the stress level results.

In the split breakage joints because of the high degree of surface roughness, as sliding is initiated, at first the tips of asperities start fracturing, and with continuation of sliding further asperities fracture and bring about a thick layer of wear material. This process results in a permanent reduction in the residual stress value until a complete slickensided surface is produced which in this case the residual stress reaches a nearly constant value.

In jointed specimens with higher angles of orientations (45 and 60°) in which the mechanism of deformation is dominated by frictional sliding, the behavior seems to be different. For lower confining pressures a near to constant value, or a gradual increase in the stress is observed as sliding progresses (Figures 1 and 2 plots 5 and 10). With an increase in confining pressure (Figures 1 and 2 for 30 MPa and higher pressures) when sliding continues the stress decreases gradually, and the rate of decreasing becomes higher with confining pressures. This dual behavior is very important in engineering practice, where it is planned to construct a structure in a jointed rock mass. Whether the structure is confined by a low or high stress level, the deformational behavior of the structure for the critical joint orientations (45 to 65°) will be different. It is therefore important to pay attention to the magnitude of deformation before and after peak stress, and in fact, the maximum magnitude of allowable strain should be determined in addition to the maximum stress. For this reason selecting a failure criterion that employs only peak stress may be wrong.

b) Effects of Discontinuity Inclination Joint inclination has pronounced effects on both failure strength and strain. The failure strength tends to be reduced when joint inclination exceeds 15° and with further increase in inclination failure strength decreases more noticeably. This is at its minimum at about the inclination of 60° (Figure 4). When width/height ratio is equal to 0.5, the curve rises steadily near to the intact strength at the line

TABLE 4. Summary of the Shear and Normal Stresses Through the Joint in Sandstone Specimens With Saw Cut and Split Joint for 45 and 60 Degrees Orientations (Type I).

Confinig pressure (MPa)	Joint angle (deg.)	Joint type	Normal stress (MPa)	Shear stress (MPa)	Ratio of shear to normal stresses
5	45	Split	35.66	29.27	0.82
15	45	//	85	70	0.823
30	45	//	126	96	0.761
5	60	//	12	12.12	1.01
15	60	//	42.75	48.06	1.12
30	60	//	70.5	70.14	0.995
5	45	Saw cut	18.89	12.45	0.659
10	45	//	42.02	27.18	0.679
15	45	//	53.97	34.77	0.644
30	45	//	111.78	73.29	0.655
70	45	//	221.85	131.39	0.592
5	60	//	7.69	2.25	0.292
10	60	//	7.15	7.58	0.442
15	60	//	23.25	8.66	0.372
30	60	//	50.85	21.6	0.424
70	60	//	117.87	48.67	0.413

of 60° inclination.

A better understanding of the effects of joint inclination on the failure strength of the rocks tested may be obtained by the strength reduction factors (the proportion of the compressive strength of the specimen containing joint to that of the intact specimen) as in Tables 1, 2, and 3 for both saw cut and split joints in different orientations for the three rocks tested.

Examination of the tables show that the effect of joint inclination on the peak strength of the specimens having zero and 15° orientations are not significant, however as the joint inclination increases to 30° and more, reduction in peak strength accelerates so that at zero confining pressure for 30° orientation the strength has reduced to 18.9% of the intact rock. The strength coefficients for 45 and 60° orientations in zero confining pressure are very near to zero however, with an increase in confining pressure the strength factor increases up to 45% for 60° orientation in 70MPa confining pressure (Table 1).

Comparison of the strength reduction factors for saw cut joints, shear-surface, and split breakage joints reveal that the joint inclination has had the highest effect on the failure strength of the specimens containing saw cut joint with 60° orientation. However, the effects on the split breakage joints were minimum (Table 1 and 2). Stress level during sliding on the saw cut joints with 60° inclination at all levels of confining pressures applied (0-70 MPa) is below the stress level in other types of joints with any orientation in the same confining pressure (Figure 5, for instance). It is also under the residual stress level in the intact specimens at different confining pressure levels applied in this experiment (Figure 5).

TABLE 5. Summary of the Shear and Normal Stresses Across the Joint in Sandstone Specimens With Saw Cut and Split Breakage Joint and Inclinations of 45 and 60 Degrees (Type II).

Confinig pressure (MPa)	Joint angle (deg.)	Joint type	Normal stress (MPa)	Shear stress (MPa)	Ratio of shear to normal stresses
5	45	Split	40.91	34.51	.843
15	45	//	61.5	46.5	.756
10	60	//	21.5	19.92	.926
15	60	//	30.25	26.41	.837
30	60	//	55.5	42.86	.77
5	45	saw cut	41.88	35.45	.822
10	45	//	60.24	41.74	.692
15	45	//	74.52	55.16	.74
30	43	//	101.83	63.3	.621
5	60	//	10.02	6.27	.625
10	60	//	21.18	14.23	.671
15	60	//	27.04	13.61	.503
30	60	//	54.85	28.11	.512

Significance of joint surface roughness may be evaluated by studying the Mohr envelopes for rough surfaces (split joint) as in Figures 6 and 7. In these figures, for both sandstones, Mohr envelopes for 60° orientation containing split breakage joint (rough surface joint) are above those of 45° in both saw cut and slit joints, that is to say, a higher coefficient of sliding friction and therefore a higher shear strength across the joint in this case. It is necessary to note that this trend does not imply that for the same confining pressure the shear strength on 60°orientation is higher than that of45°. Tables 4 and 5 show the ratios of the shear to normal stresses, namely the coefficient of sliding friction for each pair of principal stresses for the two orientations of 45° and 60°. Although the magnitudes of the shear and normal stresses for 60° orientation with rough surface for the confining pressures of 5, 15 and 30 MPa are lower than those of 45°, however, the ratios of each pair of shear to normal stress for 60° orientation are considerably higher than those of 45°.The mean of the ratios of τ/σ for 60 orientation is 0.994, whereas that of 45° is 0.741. This trend, however, for saw cut joints (smooth surface) is not observed, and the mean of the τ/σ for 45°orientation is 0.584 which is higher than 0.416 of the 60°. It implies that a rough sliding surface through a critical joint orientation (60°, for instance) provides a higher coefficient of friction with respect to a lower orientation such as 45°.

Examination of Tables 1 and 3 which illustrate the strength reduction factors for saw cut and split joints with different orientations show that the degree of joint surface roughness in a joint with 60° orientation has a greater importance than in a joint with 45° orientation. The strength factors for saw cut joints in 45° and 60° orientation for 5 MPa confining pressure as in Table 1 are 0.194 and 0.074, and in the same confining pressure, for split joint (rough surface) as in Table 3 are 0.414 and 0.213 respectively. The ratio of the strength coefficients for 45 and 60° for two cases of saw cut and split thus obtained is 0.141/0.194 = 2.13 and

0.213/0.074 = 2.87 respectively which demonstrates clearly that the ratio for 60° (2.87) is greater than the 45° (2.13). At 15 and 30 MPa the ratio for 45 and 60° orientations are 1.78 and 3.59 (in 15 MPa) and 1.22 and 2.2 (in 30 MPa) respectively which shows that the 60° ratios are greatly higher than those of the 45°. This implies that in the same condition (the same rock and under the same confining pressure) a rough joint surface plays a more important role in a critical joint orientation (60°) than the other orientations (45°, for instance). This behavior may be explained in Table 4.

The main reason may be attributed to the non-planarity of the sliding surface in the split breakage joints. When the sliding surface is smooth and completely planar (saw cut joint), distribution of shear stress throughout the joint surface will be homogeneous. In a split breakage joint with rough sliding surface, however, the joint can be non-planar and therefore, distribution of shear stress may not be homogeneous. Such a difference in behavior in planar and non-planar joint may result in different behaviors in the shear resistance of a non-planar joint at various inclinations. That is to say, when joint inclination increases and reaches a critical (say 60°) orientation, the joint shear resistance in a non-planar joint against a shear stress increases in a greater proportion with respect to the joint shear resistance with a lower orientation (say45°). In fact, in the case of 60° orientation because of the convenient direction of sliding a higher degree of interlocking asperities is provided through a rough surface. This leads to the failure of asperities from their bases rather than the tops or the middles, and therefore a greater shear resistance results. Increased confining pressure also causes further intrusion of asperities into the others and therefore, a stronger bond is produced through the bases of asperities leading to higher coefficient of friction in the case of critical orientation such as 60°.

The shape of the split joint envelopes is typical of those reported for rock types tested by direct shear apparatus (Patton [6] and Barton and Chouby [7]).

4. SUMMARY AND CONCLUSIONS

For assessment of mechanical characteristic of discontinuous rock masses a series of triaxial compression tests were performed on cylindrical jointed specimens under satisfactory end-specimen conditions.

Test results reveal that joint inclination has significant effects on failure strength. The failure strength tends to be reduced when joint inclination exceeds 15°. This being at its minimum at about the 60° orientation. Mohr envelope for 60° orientation containing split joint shows higher coefficient of sliding friction. This may be ascribed to the non-planarity of the sliding surface in the split breakage joints.

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