Geol. Bull. Univ. Peshawar, 1987, Vol. 20, pp. 77–97

AN EXPERIMENTAL STUDY OF THE MECHANICS OF FRACTURE CLOSURE

SAIFULLAH KHAN TANOLI[1] and ROBERT M. STESKY[2]

[1] National Centre of Excellence in Geology, University of Peshawar, Pakistan.
[2] Tuzo Wilson Research Laboratories, Erindale College, University of Toronto, Mississauga, Ontario, L5L 1C6, Canada.

ABSTRACT

Fracture closure under uniaxial stress to 30 MPa was studied in the simulated fractures with controlled fracture surface roughness, obtained by lapping with # 240 and # 80 grit powders, within cylindrical cores. These cores were drilled from rock samples of Barre granite, metagabbro, granodiorite, metabasalt, altered pyroxene granulite, and dolomitic marble. The amount of fracture closure at a given normal stress depends largely on rock type as well as on fracture surface roughness. Most of the closure occurred at low stresses and the fracture became stiffer with increase in normal stress. At high normal stresses, the fracture stiffness, i.e. change in normal stress for unit displacement, was greatest in rocks containing hard, strong minerals. In rocks containing weak minerals, failure of surface irregularities or asperities, occurred causing the high-stress stiffness to be less than in strong rocks where asperities deformation was dominantly elastic. The amount of permanent closure due to asperity failure increased consistently from stronger to weaker rocks as well as from relatively smoother to rougher surfaces. Surface roughness has a proportionally greater effect on fracture closure for rocks containing strong minerals than those containing weak minerals.

INTRODUCTION

Fracture is a general term used for any break in rock whether or not it causes displacement due to mechanical failure by stress. Fractures are a common and an important structural feature of crustal rocks. They may form in both tectonic and non-tectonic environments (Drummond, 1964). Tectonic fractures develop during folding or faulting and non-tectonic fractures develop without accompanying diastrophism. Currie and Nwachukwu (1974) suggested that both fracture types form in response to release of confining pressure either upward or laterally as a result of unloading process through erosion.

Fractures determine zones of weakness in rock and in many cases play an important role in controlling the movement of groundwater, petroleum, ore-fluids, and magma. They have a considerable significance in many engineering problems concerned with rock masses, specifically in big constructions like dams, tunnels, etc. The fracture characteristics, such as the roughness, fracture orientation and their density etc., are important since they affect the ability of fractures to influence physical properties of rocks and to control the distribution of fluids and hydrothermal ores. For instance, with the increase in density of fractures, the rock porosity will increase and resistivity and wave velocities will decrease. The fracture orientations can play a dominant role in the migration and consequent accumulation of geologic fluids at some suitable locations. In permeability studies, the parallel plate model has been used to measure the flow through fractures. But in nature fractures do not have idealized smooth surfaces but instead are generally very rough. The fluid transmitting and storage capacity of a fracture depends upon the opening between two fracture faces called as fracture aperture. The larger the aperture, the greater would be its effect. Since the joint conductivity is proportional to the square of the mean fracture aperture (Roegiers *et al.*, 1979), therefore a small change in fracture aperture may lead to a major variation in permeability.

The response of the fracture under stress and confining pressure is similar. Under low stresses the fracture is more compliant and at high stresses the fracture becomes increasingly stiffer. This stiffening with normal stress is the result of a greater number of asperities or irregularities on the fracture surfaces coming into contact as the stress is increased.

The present study was undertaken to examine fracture closure under applied normal stress and the influence of fracture surface roughness and rock type on this closure. This investigation assumes that rock composition and fracture surface roughness are two important factors determining fracture closure. It will examine these variables and also the permanent deformation accompanying fracture closure. Physical properties of the rocks studied are given in Table 1.

APPARATUS

Uniaxial stress-displacement experiments apparatus consisted of a double action hydraulic jack with a maximum capacity of hundred tons, a piston overlying the jack with four mounted strain gages to record the stress, a DCDT (Direct Current Differential Transformer) fixed on the upper steel column and placed on the piston to measure the displacement and two pumps, one hand and the other screw pump, were used to apply the pressure (Fig. 1). The power supply to both the strain gages and the DCDT was 10 volts. The power supply

TABLE 1. A LISTING OF THE AVAILABLE PROPERTIES OF THE ROCKS USED. (NOTE: MOH'S HARDNESS IS A ROUGH ESTIMATE AND WAS CALCULATED FROM VISUAL ROCKS COMPOSITIONS).

Rock Type	Unconfined Compressive strength (MPa)	Porosity	Bulk Density (gms/cm³)	Compressional velocity at 4 MPa (Km/sec)	Compressional velocity at 200 MPa (Km/sec)	Shear Velocity at 4 MPa (Km/sec)	Shear Velocity at 200 MPa (Km/sec)	Average Moh's Hardness
Barre Granite (BG)	100	0.0062	2.63	4.45	6.16	2.9	3.86	~ 5.8
Metagabbro (MG)	108	0.0005	3.02	6.85	7.15	4.0	4.27	~ 5.7
Granodiorite (GD)	—	0.0025	2.71	5.45	6.43	—	—	~ 4.9
Metabasalt (MB)	—	0.002		6.67	6.94	—	—	~ 5.5 (?)
Altered Pyroxene Granulite (PG)	295	0.0010	2.87	5.97	6.2	—	—	~ 4.4
Dolomitic Marble (DM)	437	0.0052	2.85	5.3	7.4	3.13	4.275	~ 3.5

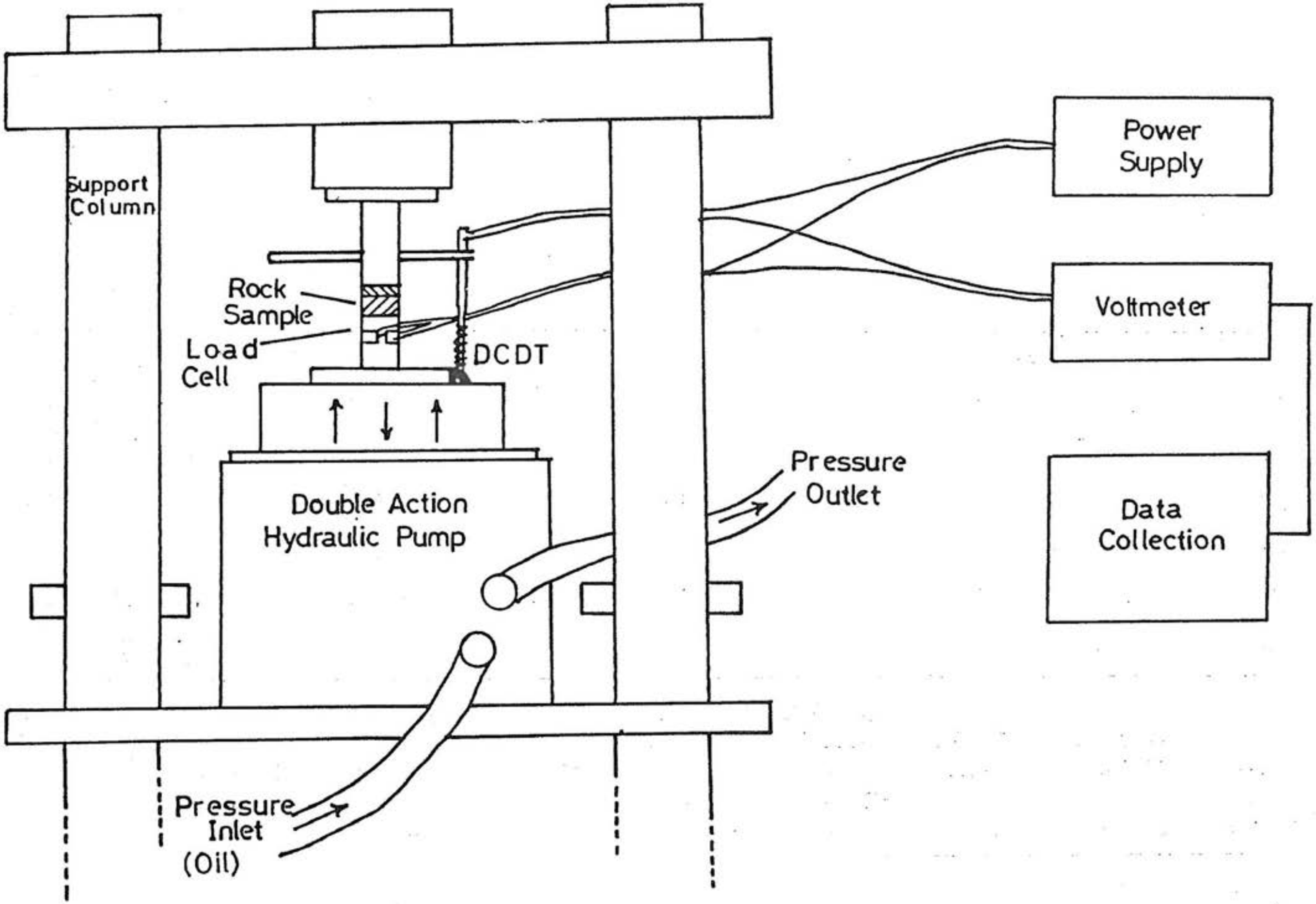

Fig. 1. Schematic diagram of apparatus used for normal stress-displacement experiments.

was controlled by a high precision voltmeter. Both the stress and the displacement (the DCDT output) were recorded on two separate digital voltmeters which were connected through an interface to a computer for the purposes of direct data collection.

EXPERIMENTAL METHOD

Cylindrical rock cores of diameter 1.25cm and length more or less 2.5cm were used in the uniaxial stress experiments. Simulated fractures were introduced at right angle to the core axes by the diamond saw cuts after loading the intact cores several times to 25 to 30 MPa stress. This intact cycling of the cores to maximum stress tended to minimize the irrecoverable deformation in the rocks surrounding the fracture. Both faces of the simulated fracture were polished to remove irregularities before lapping with # 240 grit or # 80 grit, as desired, to get the controlled fracture surface roughness. The core was reassembled and normal stress-displacement experiment was performed. Up to four runs were performed. Experiments were done in duplicate or triplicate for each type of core and different cores from the same specimen.

To examine permanent deformation within the fracture surfaces two types of experiments were done: (1) load cycling to the maximum stress for both # 240 grit and # 80 grit fracture surface roughnesses, and (2) loading to various peak stresses less than the maximum stress but the last run, for both kind of roughnesses.

The displacements measured after inducing simulated fractures were those, for the fracture, rock mass, and machine together. Since the displacements for the intact cores represented the rock mass and machine, therefore the difference between the two, before and after the induction of fracture, gave the displacement for fracture alone. Due to uncertainties in initial loading point, common to both type of runs, the accuracy in stress is approximately 0.163 MPa and in displacement approximately 2 to 3 microns, slightly greater in few cases.

OBSERVATIONS

Results reported here are based on the two types of observations. The first is fracture closure vs. stress as a function of rock type and roughness. There may be a number of other parameters affecting the fracture closure as stress is applied but the present evaluation is based on two factors which may control, to a large extent, the rate and amount of closure. The second type of observation deals with permanent fracture closure as a function of rock type and fracture surface roughness.

Fracture Closure : Dependence of Rock Type

Figure 2 and Table 2 show the fracture displacement (closure) under uniaxial stress for various rock types, with surfaces lapped with # 80 grit powder. All the rocks are compliant at stresses up to 2 MPa and show almost

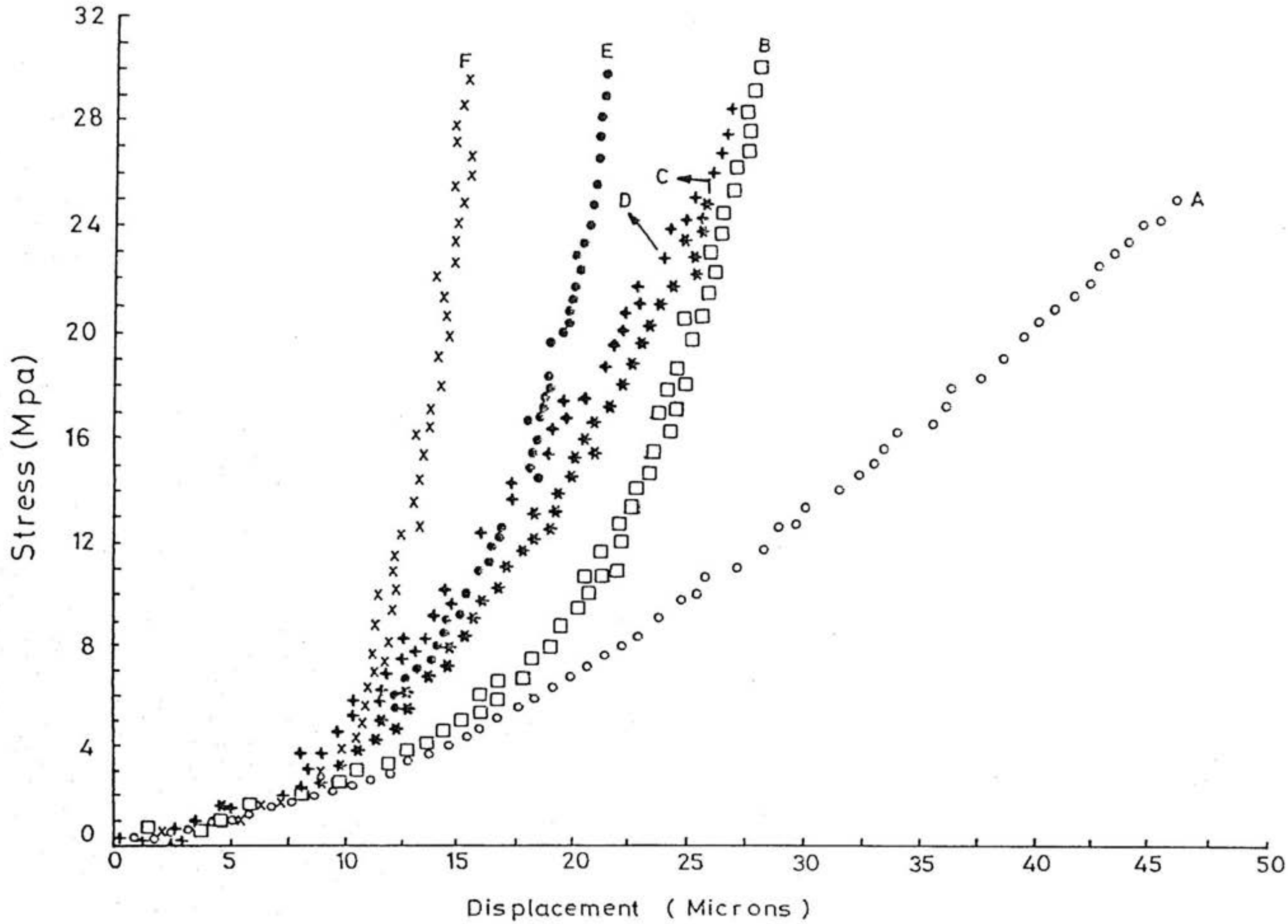

Fig. 2. Stress-displacement plots of the cores with a simulated fracture, both the faces of which were lapped with # 80 grit powder. A = dolomitic marble, B = metabasalt, C = granodiorite, D = altered pyroxene granulite, E = metagabbro, F = Barre granite.

TABLE 2. FRACTURE CLOSURE AT VARIOUS STRESS LEVELS FOR THE SIX ROCKS USED IN THIS STUDY. THE FRACTURES WERE LAPPED WITH # 80 GRIT POWDER.

Stress (MPa)	Fracture Displacement (Microns)					
	Dolomitic marble	Barre granite	Altered pyroxene granulite	Meta-gabbro	Meta-basalt	Grano-diorite
2	9.8	8	7.3	7.5	7.3	9
5	16.8	10.7	10.6	11.6	11.9	15.6
10	25	12.2	15	15.5	16.5	20.5
15	32.6	13.6	18.6	17.8	19.8	23.5
20	39.2	14.6	22.5	19.5	23	25.2
25	46	15	25.3	20.8	26	26.6
30	—	15.2	27.9	21.5	—	27.8

the same displacement. At higher stresses considerable differences occur. Two extremes in mechanical behaviour are exhibited by dolomitic marble and Barre granite. The fracture in Barre granite shows most of its displacement below 2 MPa stress and this displacement is about 53% of the total displacement attained up to 30 MPa. In case of dolomitic marble, most of the fracture displacement took place above 2 MPa. The displacement up to 2 MPa in this rock contributes only 21% of the total displacement achieved up to 25 MPa stress.

An interesting observation from Figure 2 is the shape of the curves. There is a progression in high-stress stiffness (i.e. the slope of the curve at high stresses) from the Barre granite, the stiffest, through metagabbro, granodiorite, metabasalt, altered pyroxene granulite, to dolomitic marble, the most compliant. This sequential arrangement of rocks according to stiffness is similar to the arrangement based on average Moh's hardness (Table 1) with the exception of metabasalt. Since the average hardness is computed from visual estimates of modal composition and does not take into account other factors, such as grain size, the significance of this exception is not clear.

Fracture Closure : Dependence of Surface Roughness

Fracture closure was measured in all six rocks with surfaces lapped with # 80 grit and # 240 grit powders. Table 3 shows how fracture closure varies with surface roughness. The results demonstrate that the amount of closure is greater for the rougher surfaces than the smoother ones.

Fig. 2. Stress-displacement plots of the cores with a simulated fracture, both the faces of which were lapped with # 80 grit powder. A = dolomitic marble, B = metabasalt, C = granodiorite, D = altered pyroxene granulite, E = metagabbro, F = Barre granite.

TABLE 3. FRACTURE CLOSURE VALUES IN MICRONS AT VARIOUS STRESSES FOR SURFACES LAPPED WITH # 240 GRIT AND # 80 GRIT POWDERS.

Stress (MPa)	Dolomitic marble # 80 grit	Dolomitic marble # 240 grit	Barre granite # 80 grit	Barre granite # 240 grit	Altered pyroxene granulite # 80 grit	Altered pyroxene granulite # 240 grit	Metagabbro # 80 grit	Metagabbro # 240 grit	Metabasalt # 80 grit	Metabasalt # 240 grit	Granodiorite # 80 grit	Granodiorite # 240 grit
2	9.8	10	8	6.2	7.3	4.2	7.5	7.5	7.3	7.8	9	9.8
5	16.8	14	10.7	7.6	10.6	6.8	11.6	9.8	11.9	8.7	15.6	12.7
10	25	21.4	12.2	8.4	15	10.8	15.5	12.1	16.5	10.6	20.5	15.5
15	32.6	27.6	13.6	9	18.6	14	17.8	13.3	19.8	12.8	23.5	16.8
20	39.2	33.5	14.6	9.4	22.5	17.1	19.5	14.4	23	14.5	25.2	18.1
25	46	39.5	15	9.7	25.3	19.6	20.8	14.7	26	17.4	26.6	19.2
30	—	—	15.2	9.9	27.9	22	21.5	15.2	—	—	27.8	20

The effect of roughness is examined by comparing the closure values for both # 240 grit and # 80 grit fracture surfaces for all the six rocks between 5 MPa and 25 MPa stress. The value of 5 MPa stress was chosen as a base because, in some cases, it is possible that initial seating may be affecting the displacement values at low stresses (for example, granodiorite). The percentage difference in closure for # 240 grit and # 80 grit fracture surface is calculated as:

$$\frac{\text{Closure for \# 80 surface} - \text{Closure for \# 240 grit surface}}{\text{Closure for \# 240 grit surface}} \times 100$$

This will give the percentage increase in closure for # 80 grit fracture over the # 240 grit fracture.

The rocks in Table 4 are listed in order of increasing percentage difference of closure. This order is exactly the reverse of the order found for the effect of rock type, or average Moh's hardness, on closure displacement. Thus, surface roughness has a relatively greater effect on the amount of closure with stress for rocks composed of relatively hard, strong minerals. For weak rocks, the difference in displacement related to surface roughness is relatively minor, for an equivalent difference in roughness. Although different rocks respond differently when lapped with the same size powder (Coulson, 1970), the extreme variations in percentage closure are probably related more to the mechanics of closure rather than differences in surface roughness.

PERMANENT CLOSURE

When the normal stress is released, a fracture does not usually recover all of the deformation caused by the stress. Generally a certain amount of permanent closure occurs that depends on rock type and surface roughness. To examine these effects, two types of observations of permanent closure were made; one by cycling to the maximum stress and the other by cycling to successively higher peak stresses. The cores were not moved between the cycles.

Dependence of Permanent Closure on Rock Type

(a) *Cycling Observations.* An example of typical cycling plots is shown in Figure 3.

The maximum applied stress for dolomitic marble was 25 MPa and for all other three rocks was of 30 MPa. The permanent closure data for three cycles is shown in the Table 5. This data suggests that the greatest amount of closure takes place in the first cycle in all the rocks. However, this closure amount varies for different rocks, and is highest in dolomitic marble and least in Barre granite. The decrease in permanent closure from first to second cycle and from second to third cycle is greatest in dolomitic marble and least in Barre granite rock. Similarly, the total permanent closure is greatest in dolomitic marble

TABLE 4. FRACTURE CLOSURE AND PERCENTAGE-DIFFERENCE FOR TWO TYPES OF FRACTURE ROUGHNESS.

Rock Type	Dolomitic marble		Altered pyroxene granulite		Metabasalt		Granodiorite		Metagabbro		Barre granite	
Surface roughness	# 80	# 240	# 80	# 240	# 80	# 240	# 80	# 240	# 80	# 240	# 80	# 240
Fracture closure 5–25 MPa (Microns)	29.2	25.5	14.7	12.8	14	9	11	6.5	9.2	4.6	2.8	1.3
Percentage difference	14.5%		15%		55%		69%		100%		115%	

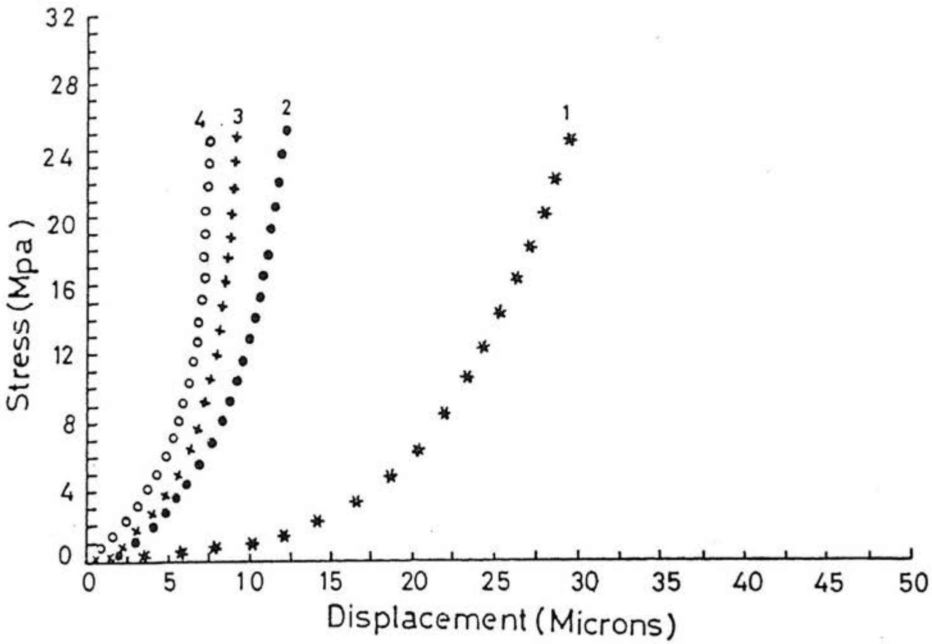

Fig. 3. An example of cycling experiments in a dolomitic marble core after inducing a simulated fracture. Curves 1, 2, 3 and 4 represent first, second, third and fourth cycle respectively.

and least in Barre granite. These rocks can be arranged in order of increasing amount of permanent closure: Barre granite (the least), metagabbro, altered pyroxene granulite, and dolomitic marble. This order is also one of decreasing average Moh's hardness (Table 1) suggesting that the amount of permanent closure is less for rocks composed of strong minerals than those with relatively weaker minerals.

TABLE 5. PERMANENT FRACTURE CLOSURE OBSERVED FROM CYCLING EXPERIMENTS. THE FRACTURES WERE LAPPED WITH # 80 GRIT POWDER.

	Average Permanent Deformation (Microns)			
Rock name	First cycle	Second cycle	Third cycle	Total
Barre granite	6.5	3.4	2.7	12.6
Metagabbro	8.5	3.7	2.0	14.2
Altered pyroxene granulite	14	4.0	2.5	20.5
Dolomitic marbie	19	7	2.5	28.5

In all the rocks, the curves show a progressive increase in fracture stiffness with increase in number of cycles. The relative increase in stiffness seems to depend on the average mineral hardness, since the weakest, dolomitic marble, shows the largest increase, while Barre granite shows the least. In any case, the fracture in Barre granite remains the stiffest.

(b) *Peak Stress vs. Permanent Deformation.* The data in Table 6 shows that as in the cycling tests, the greatest amount of closure in successively higher peak stress experiments takes place for dolomitic marble and the least for Barre granite rock. A large increase in permanent closure occurs during the first 5 MPa of compression, with lesser increases at higher peak stresses. Plotting the cumulative permanent closure against the peak stress (Fig. 4) shows that after the initial increase below 5 MPa, the amount of closure increases nearly linearly with the peak stress. Interestingly, linear lines fitted to the points on this plot all have a common intercept around 3 to 4 microns. Thus the initial seating of the surfaces seems to be the same for all fractures and seems to be accomplished during the first few MPa of applied normal stress. The amount of increase in permanent closure at higher stresses depedns markedly on the mineral strength or hardness and presumeably is caused by some form of failure of the surface asperities. Curiously, the total amount of permanent closure achieved in these increasing peak-stress cycles is much greater than that found after even three cycles to maximum stress (19.9 vs. 12.6 microns for Barre granite and 41.7 vs. 28.5 microns for dolomitic marble). Indeed, the cumulative permanent closure is a significant fraction of the total closure at maximum normal stress. This result strongly suggests that the surface deformation is path-dependent or history-dependent, perhaps, through some cyclical fatigue or static fatigue process. This conclusion is supported by the observation of a continued increase in permanent closure with each load cycle to maximum normal stress (Table 5).

TABLE 6. PERMANENT CLOSURE OBSERVED AT VARIOUS PEAK STRESSES FOR THE FRACTURES GROUND WITH # 80 GRIT POWDER.

Peak stress (MPa)	Average Permanent Deformation (Microns)		
	Barre granite	Metagabbro	Dolomitic marble
5	5.8	6.5	13.5
10	3.7	3.9	6.8
12	—	—	6
15	3.2	2.5	5.8
18	—	—	5.2
20	2.7	2.7	4.4
25	2.4	3	—
30	2.1	2.5	—
Total Permanent Deformation	19.9	21.1	41.7

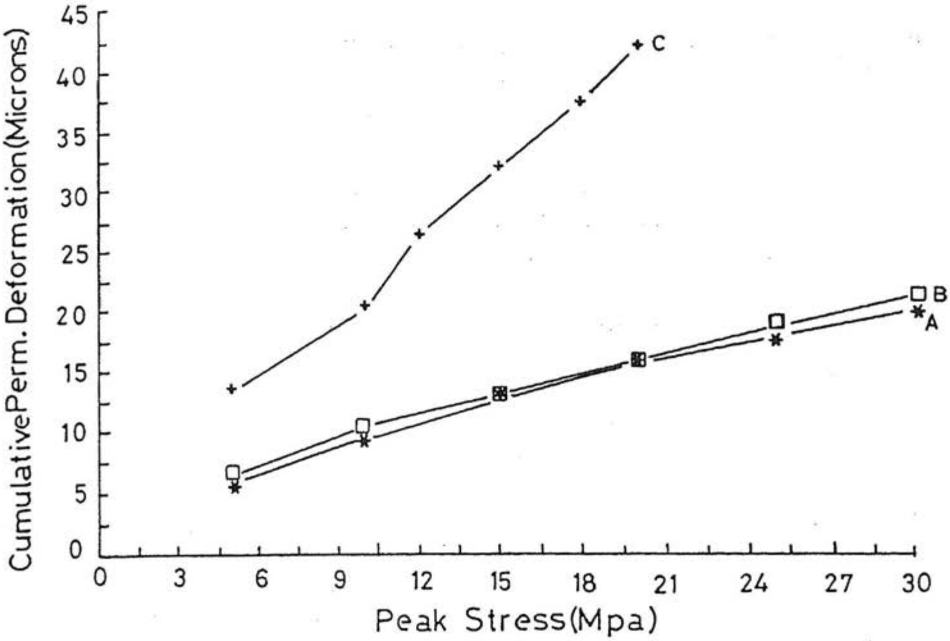

Fig. 4. Plots of cumulative permanent deformation with various peak stresses. The fracture faces were ground with # 80 grit powder. A = Barre granite, B = metagabbro, C = dolomitic marble.

Dependence of Roughness on Permanent Closure

(a) *Cycling Observations.* The measurements of permanent closure after cycling to maximum stress are shown in Table 7. The data shows that more permanent closure occurs with rougher surfaces. An effect seen earlier for fracture

TABLE 7. COMPARISON OF THE AMOUNT OF PERMANENT FRACTURE CLOSURE OF FRACTURES LAPPED WITH #80 GRIT POWDER, WITH THOSE LAPPED WITH # 240 GRIT POWDER.

	Average Permanent Deformation (Microns)							
	First cycle		Second cycle		Third cycle		Total	
Rock name	# 80 grit	# 240 grit	# 80 grit	# 240 grit	# 80 grit	# 240 grit	# 80 grit	# 240 grit
Barre granite	6.5	3.06	3.4	1.8	2.7	1.3	12.6	6.1
Metagabbro	8.5	5	3.7	2.3	2	1.8	14.2	9.1
Altered pyroxene granulite	14	10.5	4	2	2.5	1.5	20.5	14
Dolomitic marble	19.5	16.4	3.5	4.5	3	2	26	22.9

stiffness is seen again here: surface roughness has a proportionally greater influence on the amount of permanent closure in rocks with hard, strong minerals (for example, Barre granite) than in those with weak minerals (for example, dolomitic marble).

(b) *Peak Stress vs. Permanent Deformation.* Table 8 and Figure 5 show the measurements of permanent closure at zero stress for # 80 and # 240 grit surfaces after cycling to successively higher peak stresses. As with the # 80 grit surfaces, the cumulative permanent closure for # 240 grit surfaces increased linearly with the peak cycling stress with a larger increase during the first loading to 5 MPa. The initial seating displacement is approximately the same for the three rocks (about 0–2 microns), less than that found for the #8 0 grit surfaces (about 3–4 microns). Above 5 MPa, the cumulative permanent closure increased less rapidly with peak stress for the # 240 grit surfaces than did that for the # 80 grit surfaces. As in the cycling tests, surface roughness had a proportionally greater influence on the cumulative permanent closure for the rocks composed of hard minerals than that for the rocks with soft minerals. Again, the cumulative permanent closure is greater than the total permanent closure after three cycles to maximum stress (compare Tables 7 and 8).

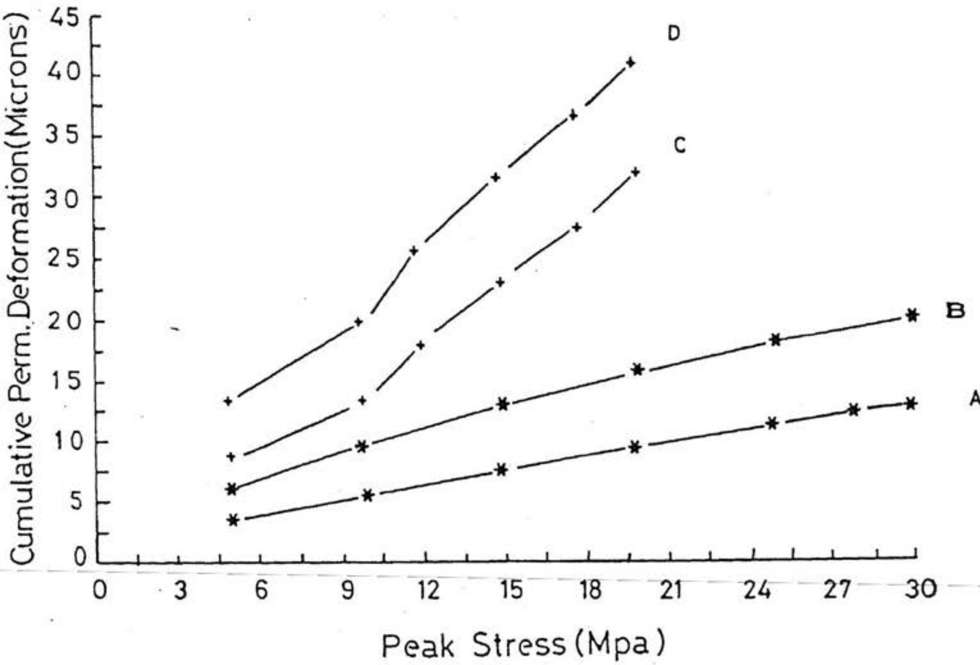

Fig. 5. Plots of cumulative permanent deformation with various peak stresses for relatively smooth and rough surfaces for cores from two extreme mechanical behaviour rocks for the purposes of inter- and intra-comparison. A = Barre granite, # 240 grit lapping, B = Barre granite, # 80 grit lapping, C = dolomitic marble, # 240 grit lapping, D = dolomitic marble, # 80 grit lapping.

TABLE 8. COMPARISON OF THE PERMANENT FRACTURE CLOSURE FOR FRACTURES LAPPED WITH # 80 GRIT AND # 240 GRIT POWDER AT VARIOUS PEAK STRESSES.

	Average Permanent Deformation (Microns)					
	Barre granite		Metagabbro		Dolomitic marble	
Peak Stress (MPa)	# 80 grit	# 240 grit	# 80 grit	# 240 grit	# 80 grit	# 240 grit
5	5.8	3	6.5	3.5	13.5	8.5
10	3.7	2.2	3.9	2	6.8	5.2
12	—	—	—	—	6	4.8
15	3.2	2	2.5	1.8	5.8	5
18	—	—	—	—	5.2	4.7
20	2.7	1.9	2.7	1.85	4.4	4.3
25	2.4	1.7	3	1.7	—	—
28	—	1.2	—	—	—	—
30	2.1	.5	2.5	1.9	—	—
Total permanent deformation	19.9	12.5	21.1	12.75	41.7	32.5

ANALYSIS OF THE RESULTS

(a) Fracture Stiffness

The fracture stiffness, that is the slope of the normal stress-displacement curve, depends upon normal stress, rock type, and fracture surface roughness (Table 9). Plots of fracture stiffness versus stress for two rocks with extreme mechanical behaviour, i.e. Barre granite and dolomitic marble, are shown in Figure 6.

All the rocks used in this study appear to have negligible or no stiffness at zero stress and the stiffness increases with an increase in stress. This increase in stiffness is approximately linear for Barre granite, metagabbro, and granodiorite, the rate of increase being greater for smoother surfaces. For dolomitic marble, altered pyroxene granulite, and metabasalt, there is a rapid increase in stiffness up to 5 MPa and at higher stresses, the increase is less rapid. Thus, for both surface roughnesses in these rocks, the increase in stiffness is non-linear.

In general, the rocks which are composed of strong minerals, such as quartz and feldspar, showed higher stiffness values than those rocks containing weak minerals, such as dolomite and fine grained alteration minerals (see Aver-

TABLE 9. SUMMARY OF REPRESENTATIVE FRACTURE STIFFNESSES FOR # 240 GRIT AND # 80 GRIT FRACTURE SURFACES AT VARIOUS STRESS LEVELS.

Stress (MPa)	Fracture Stiffness (MPa/microns)											
	Barre granite		Metagabbro		Granodiorite		Metabasalt		Altered pyroxene granulite		Dolomitic marble	
	# 80 grit	# 240 grit	# 80 grit	# 240 grit	# 80 grit	# 240 grit	# 80 grit	# 240 grit	# 80 grit	# 240 grit	# 80 grit	# 240 grit
2	.65	1.2	.4	.75	.3	.55	.42	1.73	.6	.76	.19	.24
5	1.9	3	.9	1.6	.65	1.2	.85	2.47	.97	1.1	.35	.41
10	4	6.3	1.7	3.2	1.45	2.48	1.26	2.58	1.25	1.43	.52	.59
15	5.9	8.8	2.6	4.6	2.25	3.55	1.48	2.65	1.32	1.57	.64	.7
20	7.8	11.8	3.4	6.5	3.05	4.4	1.56	2.7	1.55	1.8	.73	.79
24	9.2	15	4.15	7.5	3.6	4.6	1.62	2.73	1.65	1.95	.8	.86

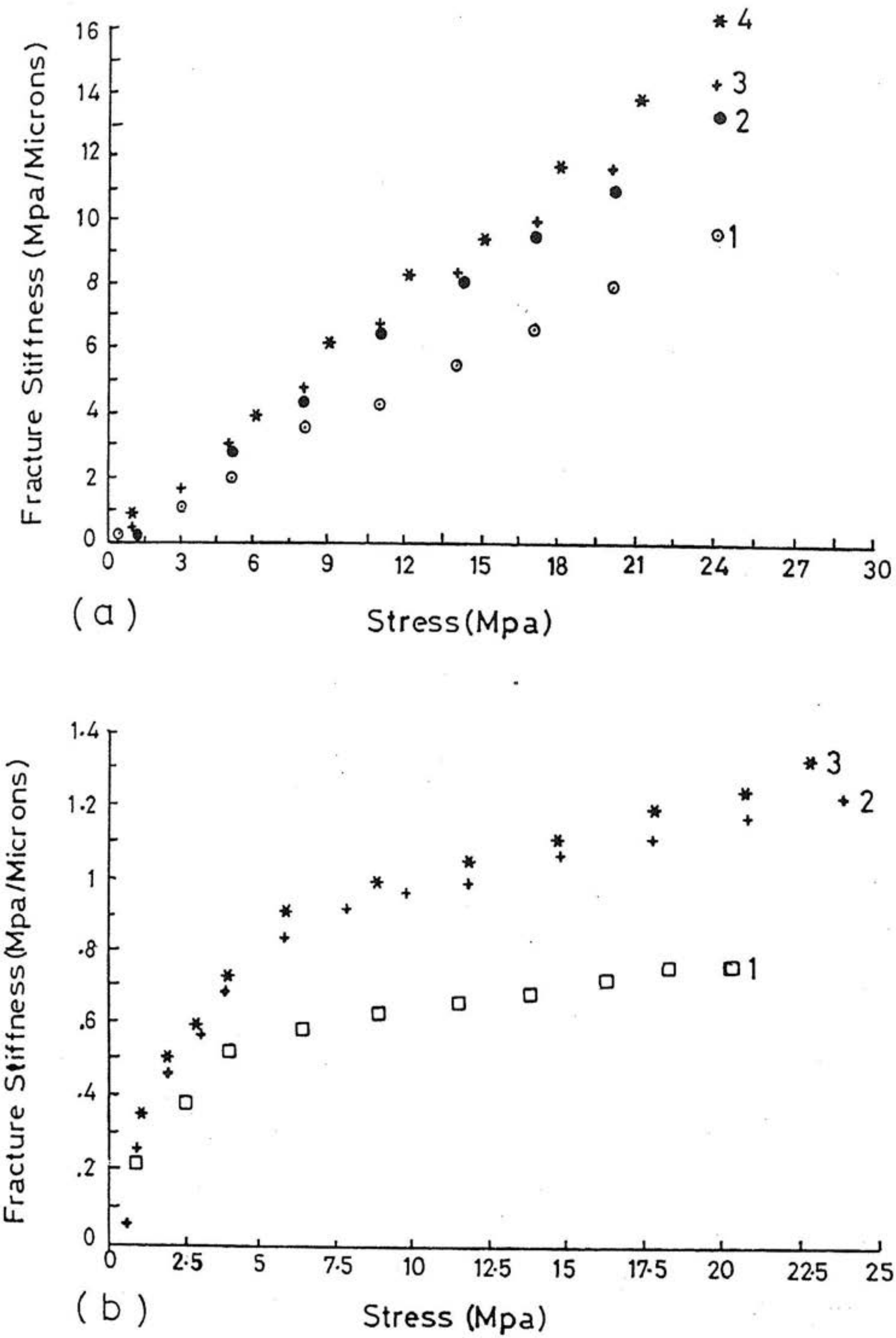

Fig. 6. Plots showing the fracture stiffness with stress for cycling experiments for the two rocks with extreme behaviour. The fracture faces were lapped with # 80 grit powder. (a) Curves 1–4 represent first to fourth cycle respectively for the dolomitic marble. (b) Curves 1–3 represent first to third cycle respectively for the Barre granite.

age Moh's hardness, Table 1). Surface roughness also has an effect: the rougher surfaces have a lower stiffness at the same stress. As suggested earlier, roughness has a proportionately greater effect on Barre granite than it does on the dolomitic marble.

The explanation for these results lies in the fact that two surfaces in contact, in general, do not touch over their entire surface. Rather the surfaces are irregular with many asperities, or surface undulations of a variety of heights, that impinge on each other. When the surfaces are in initial contact with no normal stress, very few asperities are in contact between the surfaces, these asperities most likely being the highest. During compression two effects occur: the asperities already in contact become deformed increasing their contact area and secondly, more asperities come into contact, causing a further increase in total contact area. Initially, the small contact area allows considerable closure displacement to occur because the contact stresses between asperities can become quiet high. However, as the contact area increases, the contact stresses do not increase as rapidly as does the normal applied stress. Thus less deformation occurs and the fracture becomes stiffer. Rougher surfaces have fewer asperities in contact and require larger closure displacements to bring other asperities into contact. Thus rougher surfaces have a lower stiffness. This explanation for the increase in fracture stiffness with applied normal stress was originally proposed by Greenwood and Williamson (1966).

When the minerals in the rock are weak, asperities may fail, producing an additional amount of closure deformation beyond that produced by elastic compression. Thus the bulk fracture stiffness will not increase as rapidly with applied stress as when the deformation is entirely elastic. During cycling experiments, asperities that fail during a first cycle will be less likely to do so on subsequent loadings. Thus there is an increase in fracture stiffness upon reloading. Evidence for asperity failure and its possible mechanisms is discussed in more detail below.

(b) Permanent Closure

Permanent fracture closure refers to the permanent reduction in fracture aperture after application of a normal stress. The amount of permanent closure increases with the magnitude of applied normal stress, by an amount that depends on rock type and surface roughness. Greater permanent closure occurs with rougher surfaces and with rocks containing softer, weaker minerals. Surface roughness for permanent closure is comparatively more important for the rocks containing strong minerals like Barre granite. In all rocks a large amount of permanent closure occurs below 5 MPa. In strong rocks, much less develops at higher stress (less than 50%), while in weaker rocks, the permanent clŏsure is still significant.

Several explanations are possible for this behaviour, including asperity interlocking, indentation, and failure. Interlocking would occur with all rocks and likely be more prominent for rougher surfaces. Asperity indentation would be more important where the rock contains a mixture of strong and weak minerals and failure by crushing or ductile flow would occur where the minerals are weak. Both indentation and failure should be more prominent for rougher surfaces because of fewer asperities in contact and hence greater contact stresses.

Partial evidence for asperity failure being significant, at least in the weaker rocks, comes from a sequence of scanning electron microscope photographs of surfaces in Barre granite and dolomitic marble before and after compression up to 100 to 200 MPa. Although these stresses are considerably greater than that used in this study, the observations reveal that asperity failure does occur and is more prominent in rocks containing weak minerals. Asperity failure shows up by the presence of loose debris and flattened asperity tips. The granite showed none of these characteristics, while asperity failure was abundant in the dolomitic marble.

Thus we can postulate the following sequence of events occurring during compression of rock surfaces. Initially, closure occurs by elastic compression of the asperities and by interlocking, perhaps accompanied by shearing off of some asperity tips. At higher stresses, little further interlocking occurs, but elastic compression continues. In hard, strong rocks, the majority of the deformation is elastic, while interlocking contributes a relatively small amount to the closure. In rocks containing weak, soft minerals, asperity failure and indentation may take place at high stresses. The mechanism for this deformation depends on the minerals present. Failure could occur by crack growth, probably aided by cleavage, by twinning, kinking, or ductile flow. A consequence of this behaviour is that permanent closure will be time-dependent, because the mechanisms of failure are time-dependent. Indeed, asperity failure was used to explain the time-dependent increase in friction strength of rock surfaces held under constant normal stresses (Scholz and Engelder, 1976). Thus where non-elastic deformation accounts for a significant portion of the asperity deformation, the long-term fracture closure could be considerably underestimated in a short-term test.

(c) Relation Between Permanent Closure and Fracture Stiffness

Fracture stiffness is a measure of the increase in normal stress needed to produce an increment in total displacement. Thus where the elastic deformation is supplemented by permanent closure, the stiffness will be lower than where only elastic deformation takes place, other things being equal. This relationship can be seen in Figure 7, where the stiffness at high normal stress is

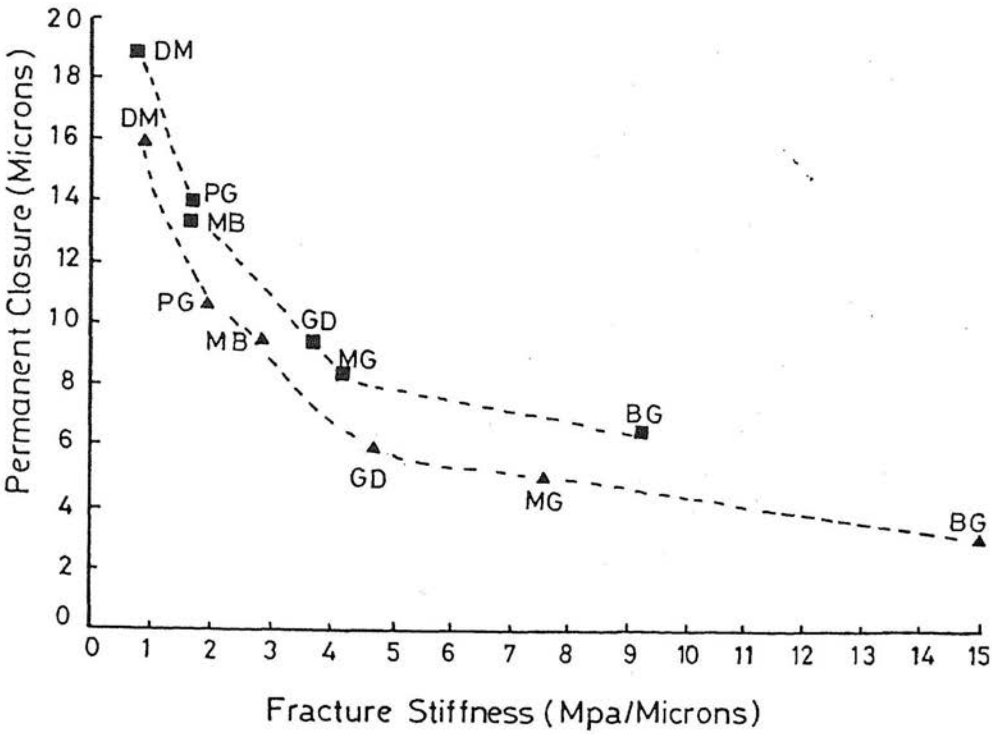

Fig. 7. **First-cycle permanent closure after unloading versus fracture stiffness at 25 MPa stress for various rocks. The squares represent # 80 grit and triangles # 240 grit lapped fractures. DM = dolomitic marble, PG = altered pyroxene granulite, MB = metabasalt, GD = granodiorite, MG = metagabbro, BG = Barre granite.**

plotted against the relative amount of permanent closure. The weaker marble shows a large amount of permanent closure and low stiffness. When the fracture in the marble is re-loaded a second or third time, the relative permanent closure is much less and the fracture is considerably stiffer. Notice also the influence of surface roughness (Fig. 7). The rougher surfaces show more permanent closure and low stiffness as compared to smooth surfaces. As noted earlier, roughness has a greater effect on these properties for stronger rocks, such as Barre granite.

CONCLUSIONS

1. The fracture surfaces asperities composed of stronger minerals dominantly deform elastically under compression. The asperities of weaker minerals, on the other hand, tend to deform elastically at lower stresses and fail by crushing or ductile deformation at higher stresses.

2. The amount of permanent closure increases with an increase in surface roughness for any rock. However, under similar conditions for fractures having

approximately the same surface roughness, the closure is greater along fractures in weaker rocks than in stronger rocks. Generally, surface roughness has a proportionally greater effect on the amount of closure as the mineral hardness increases.

3. The amount of permanent closure and fracture compliancy decreases with increasing load cycles. A repeatedly stressed fracture may show wholly elastic deformation even in weaker and softer rocks unless the prior stress level is exceeded.

4. During compression initially the deformation takes place chiefly due to elastic compression of the asperities while interlocking of the two surfaces contributes a certain amount of permanent closure. This interlocking occurs for all rocks and is more prominent along rougher surfaces.

5. In rocks containing stronger minerals, deformation is mainly elastic and interlocking is minor except at low stresses.

6. In weaker rocks, asperity failure and indentation may take place at higher stresses. Failure could occur by crack growth aided by cleavage, by twinning, kinking, or ductile flow. The asperity indentation should be more important in rocks containing a mixture of strong and weak minerals. Indentation and failure is expected to be more pronounced for rougher surfaces because fewer asperities are in contact and, hence, contact stresses will be higher.

REFERENCES

Coulson, J.H. 1970. The effects of surface roughness on the shear strength of joints in rock. Technical Report No. MRD-2-70, Missouri River Division, Corps of Engineers, Omaha, 283p.

Currie, J.B. and Nwachukwu, S.O. 1974. Evidence of incipient fracture porosity in reservoir rocks at depth. Bull. Can. Petrol. Geol. 22, 42—58.

Drummond, J.M. 1964. An appraisal of fracture porosity. Bull. Can. Petrol. Geol. 12, 226—245.

Greenwood, J.A. and Williamson, J.B.P. 1966. Contact of nominally flat surfaces. Proc. Royal Soc. London A295, Series A, 300—319.

Jaeger, J.C. and Cook, N.G.W. 1976. Fundamentals of rock mechanics. Chapman Hall Ltd., and Science Paperbacks.

Roegiers, J.C., Curran, J.H. and Bawden, W.F. 1979. Numerical modelling of flow in fractured rock masses. Technical Report, Department of Civil Engineering, University of Toronto, Canada.

Scholz, C.H. and Engelder, J.T. 1976. The role of asperity indentation and ploughing in rock friction — 1. Asperity creep and stick slip. Int. J. Rock Mech. and Mining Sci. 13, 149—154.

Tanoli, S.K. 1982. A study of the mechanics of fracture closure. Unpublished M.Sc. thesis, University of Toronto, Canada, 153p.