Shear Strength of Some Rock Forming Powdered Minerals Under High Confining Pressure

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ABSTRACT

The published literature on the experimental and theoretical observations concerning the frictional behaviour of rock forming minerals is reviewed. Experimental data on the behaviour of four rock forming minerals; viz. Quartz, Calcite, Talc and Biotite, in powdered form, when subjected to triaxial stresses under a range of confining pressures up to 630 kg/cm^2 (63 MPa) is presented. It has been observed that for Calcite and Talc, the modified Mohr-Coulomb envelope is a straight line leading to an angle of shearing resistance of 34^{o} and 26.5^{o} respectively. However, for Biotite and Quartz, a decrease in the slope of the Mohr-Coulomb envelope has been observed when the confining pressures were increased to the higher values. In case of Quartz, up to a confining pressure of 112 kg/cm^2 (11.2MPa), the angle of shearing is 38.5^{o}. However, when the confining pressure is increased beyond 112 kg/cm^2 (11.2MPa), angle of shearing resistance falls to 34.5^{o}. In case of Biotite, up to a confining pressure of 210 kg/cm^2 (21MPa), angle of shearing resistance is about 25.5^{o}. When the confining pressure is increased beyond 210 kg/cm^2 (21MPa), angle of shearing resistance falls to 20^{o}. It has been observed that the cohesion intercept for all the minerals is nearly zero.

Keywords: Rock forming minerals, frictional characteristics, triaxial stress, crystalline structure, modified Mohr-Coulomb envelope.

1. INTRODUCTION

A detailed study of frictional characteristics is of considerable importance in rock mechanics. Frictional forces between joints, cracks and fault surfaces have to be estimated. Knowledge of friction between individual grains of rock pieces is important. Further, on a small scale, friction between the minute Griffith cracks in a rock requires to be estimated.

A rock mass is not a uniform body but is broken up by a network of joints and faults. The properties are, therefore, controlled by the properties of the intact portions of the rock and by joints as well as the geometry of the joint system. A displacement in the joint system may change the position of the rock elements and result in the development of highly localized stresses in them, which may lead to failure by crushing.

The range of stresses involved in various problems in rock mechanics is very large. Near the abutments of arch dams, the stresses may be as high as 100kg/cm^2 (10MPa), whereas in rock slopes, the stresses may be of the order of 4 to 5 kg/cm^2 (0.4 to 0.5 MPa) only.

The coefficient of friction 'μ' is dependent on the nature of materials and the roughness of the surfaces in contact. According to Amonton's law (Bowden and Tabor, 1950), the magnitude of 'μ' is considered to be independent of the value of the normal stress 'σ_n'. Bowden and Tabor have explained the existence of contacts at very few points between even highly polished natural surfaces. The normal stress at these contact points would be high and may exceed the yield strength of the material. The frictional force can be separated into "shearing" and "ploughing" components. At a larger number of contacts, the stress will be very different so that deformation at some contacts would be plastic whereas at others it may be elastic.

Archard (1958) considers the law of friction to follow a power law

$$\tau = k.\sigma_n^m, \tag{1}$$

$$\mu = k.\sigma_n^{m-1}, \tag{2}$$

where m varies between 2/3 to 1.0. Experimental results of sliding of joints of andesite and mica have led to the following expressions (Jaeger, 1971).

$$\tau = 1.2\sigma_n^{0.9} \tag{3}$$

$$\tau = 5.2\,\sigma_n^{0.7} \tag{4}$$

Jaeger has also indicated the use of the expression

$$\tau = \tau_o + k.\sigma_n^m, \tag{5}$$

which is similar to the Coulomb law of

$$\tau = c + \sigma_n \tan\phi, \tag{6}$$

as applied in soil mechanics. It has been noticed that with an increase of σ_n, the value of c increases (Byerlee, 1967). If the area of a block of material is A and the area of contact is A_c, then we may have

$$\tau = c_c\left(\frac{A_c}{A}\right) + \mu_c.\sigma_n \tag{7}$$

wherein cohesion c_c is proportional to A_c/A. Byerlee (1967) gave results of tests on granite cylinders of 1.67 cm in diameter tested in triaxial cells at confining pressures of 1050 to 15750 kg/cm^2 (105 to 1575 MPa). The surfaces were ground and pressed together under a hydrostatic pressure of 105 MPa before a tangential stress was applied. The results indicated

$$\tau = 9000 + 0.6\sigma_n \tag{8}$$

in the range of σ_n from 210 to 1575 MPa. It was concluded that A_c was equal to A and the value of 63MPa was for intact material. For an ordinary contact at low normal stresses, A_c/A might be of the order of 0.01 leading to a cohesion value of 6.3 kg/cm^2, as was usually reported. Results presented by Jaeger and Cook (1970) of tests on sliding of nearly spherical contacts on trachyte with varying areas of contact and high normal stresses yield c_c= 7MPa and μ_c= 0.32 for high normal stresses and values of c_c=10 and μ_c= 0.48, indicating the area of contact to be small.

Broken rock has been tested in triaxial cell of large size. Fumigalli (1970) and Coates (1963) present the experimental data. Terzaghi (1962) quoted measurements giving angle of shearing resistance of crushed aggregate as 65°. Jaeger and Cook (1969) also quoted measurements of Snowy Mountains Authority giving value of ϕ=40° for crushed aggregate. It has been found that the results of these tests depend greatly on the possibility of the porosity of the aggregates. Interlocking of the aggregates is also involved. The Mohr envelopes are usually curved so that a power law representation can be made.

It is difficult to test a finely jointed rock in the laboratory. It has been noted that Calcite has an uneven thermal expansion, and heating it caused the grain boundaries to crack. Rosengren and Jaeger (1968) conducted triaxial tests on marble previously heated to 500°C. The strength of this marble has been found to increase rapidly with confining pressure. The Mohr envelope is curved which can be represented by

$$\tau = 40\sigma^{0.8} \text{ psi.} \tag{9}$$

Jaeger (1970) tested six-inch diameter cores from a closely jointed rock. The fractures were at a spacing of .127cm to 2.54cm. The Mohr envelope is curved at high pressures and the material fails along a definite plane of failure. Interlocking accounted for considerable gain in strength.

Karman's (1911) investigation on the strength of marble indicated that at low confining pressures, marble failed in a brittle way along a single inclined shear fracture. Strength increased progressively with increasing confining pressure and the rock failed as a barrel shaped specimen at high confining pressures. This deformation was due to sliding across a large number of intersecting shear failures and is not a true plastic deformation.

2. SHEAR STRENGTH OF CRYSTALLINE MINERALS

Many studies have been made concerning the frictional properties of various substances, but little attention has been given to minerals. Possibly, the first study pertaining to frictional characteristics of mineral surfaces was made by Terzaghi in 1925. He found that the application of water between two previously dried smooth surface of Quartz resulted in a substantial increase in the coefficient of static friction. Tschebotarioff and Welch in 1948 investigated the influence of surface moisture variation on the frictional properties of Quartz, Calcite and some other minerals. Their investigation also showed that water acted as an anti-lubricant when applied to smooth surfaces of Calcite as well as those of Quartz, but lubricated the surface of minerals, which has layer lattice structures. In addition, they found that the frictional characteristics of minerals in a moist state and those of completely submerged minerals were virtually the same. Penman (1953) provided further confirmation of anti-lubricant effect of water in the case of Quartz. A detailed study was made by Horn and Deere (1962). They found that the presence of fluids on sliding surfaces of minerals greatly increased the frictional coefficients of minerals having massive crystal structures such as Quartz and Feldspar and decreased the coefficient in the case of minerals having layer-lattice type of structures, such as mica and chlorite.

Horn (1960) also performed drained direct shear tests on ground muscovite and showed that submergence in water of a dry muscovite powder reduces the angle of shearing resistances from 27° to 20°, whereas in the case of Quartz powder the angle of shearing resistance remained constant at 28°.

3. SHEAR STRENGTH OF CRYSTALLINE MINERALS UNDER HIGH PRESSURE

Baumann (1941) conducted compaction tests on freshly quarried materials and observed considerable breakdown of sharp corners of particles. A comparison of the material before and after compaction indicated a change in the percentage of large size particles but the percentage of fine particles remained unaltered. The breakdown of sharp angularities did not appear to affect the strength of the material, as straight-line failure envelopes were obtained from shear tests up to a cell pressure of 63 kg/cm^2 (6.3 MPa). Hall and Gordon (1963) tested some soils in triaxial cells up to a confining pressure of 45.5 kg/ cm^2 (4.55 MPa) and found that the slope of the Mohr envelope for sandy and gravelly soils decreases with an increase in confining pressure, but the same was not true for clayey or silty soil. Hirschfeld and Poulos (1963) also tested silts and sands up to a confining pressure of 42 kg/ cm^2 (4.2 MPa) and found that Mohr rupture envelope was curved throughout the stress range investigated. Vesic and Barksdale (1963) tested sand specimen under high confining pressures. Their results suggested that the curvature of rupture envelope was restricted to initial pressure range up to 63 kg/ cm^2 (6.3 MPa) and beyond this pressure range the envelope was a straight line. Bishop et al. (1965) and Bishop (1966) indicated breakdown of particles and curved rupture envelopes at high confining pressures. On the basis of laboratory and field studies, Sowers et al. (1965) indicated that a major part of settlement in rockfills was the result of crushing of highly stressed points of contact between the particles, which increased under wetting. Marsel (1967) tested rockfill materials under confining pressures of 25 kg/cm^2. These samples were large in size and had a diameter of 115 cm and a height of 250 cm. These results also suggested curved rupture envelope and breakdown of particles. Vesic and Clough (1968) tested sand under confining pressure up to 630 kg/ cm^2 (63 MPa). They found that at very low pressure (below 1 kg/cm^2) very little crushing was observed and effects of dilatancy gradually disappeared as the confining pressures were increased. As the confining pressure increased beyond 105 kg/ cm^2 (10.5 MPa) the effects of initial porosity were not observed.

Ramamurthy and Lal (1970) conducted an extensive study on the crushing phenomenon of sands. They used Delhi Quartzite sand (Badarpur sand) for investigations. They varied the cell pressure up to 70 kg/ cm^2 (7.0 MPa). Their results indicated that the mode of failure as depicted by the stress-strain curves appeared to be of brittle type at low cell pressures and tended towards plastic behaviour at high pressures. An important observation made by them was that the Mohr failure envelope was curved up to a confining pressure of 14 kg/ cm^2 (1.4 MPa) only and beyond that the Mohr envelope was a straight line with constant effective angle of shearing resistance.

4. OBJECTIVES OF THE STUDY

This study forms a part of the overall programme of conducting research work in understanding the mechanism of shear deformations of rock forming minerals under high pressure. In this study, results of experimental observations conducted on finely powdered Quartz, Calcite, Talc and Biotite have been reported.

These minerals were finely powdered. Both the Talc and Calcite samples pass completely through 2.36mm IS Sieve. The Quartz samples pass 100 percent through 425-micron IS Sieve and 50 percent through 2.36mm IS Sieve. In the case of Biotite, the sample passes 100 percent through 600-micron IS Sieve and 50 percent through 2.36mm IS Sieve.

5. EXPERIMENTAL PROCEDURE

Suitable equipment for the pressure range used is not readily available. Therefore, the required equipment had to be specially fabricated. The cell is designed for triaxial compression tests of a standard 3.81 cm diameter specimen having a length of 7.62 cm. It can take fluid pressure up to 1050 kg/cm^2 (105 MPa). Details of the cell and the other components have been shown in Fig.1.

The fluid pressure was developed through a special pumping unit (Fig. 2). To maintain the pressure constant a loading ram is introduced in the system. Friction is eliminated by rotating this ram. The excess fluid goes back to the pumping unit and the pressure in the cell is maintained constant.

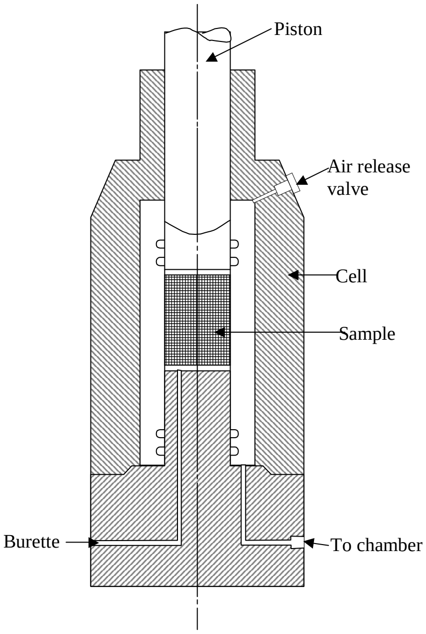

Fig. 1- The triaxial cell for 3.81cm (1.5inch) diameter samples under high confining pressure

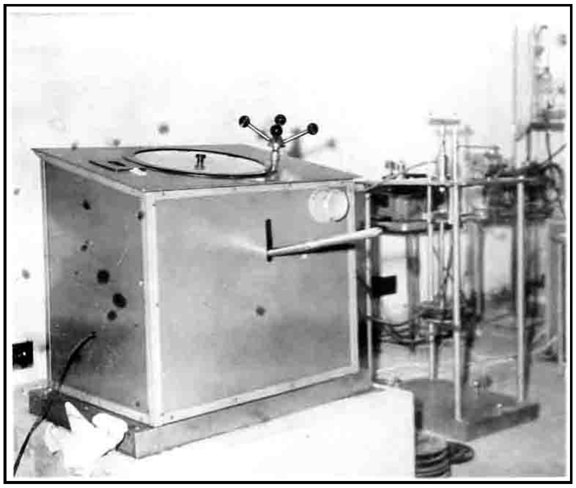

Fig. 2 – Oil pumping unit

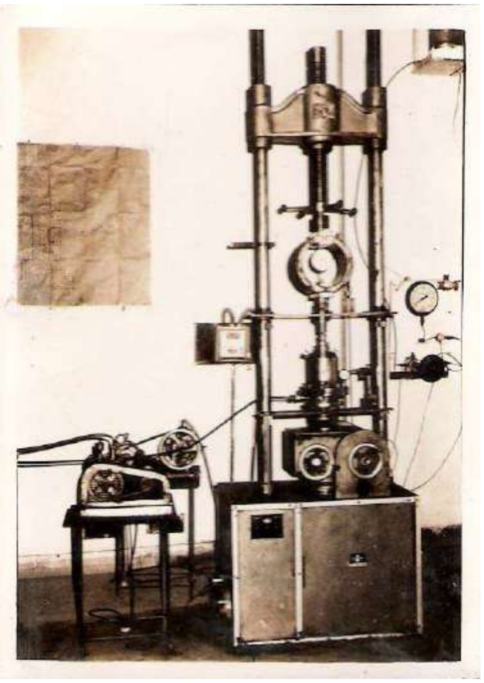

Fig. 3 – 50 ton compression machine with high pressure cell and pressure maintaining system

The loading system consisted of an electrically operated loading frame of 50-ton capacity (Fig. 3) having variable speed and the samples were sheared at a strain rate of 0.0105 cm/min.

The samples of the minerals were prepared with high initial water content and the mixture was placed carefully in suitable moulds wherein the samples could be subjected to consolidation. Initial consolidation was achieved by subjecting the samples to pressure in a one-dimensional consolidation frame.

The samples were extruded from the moulds and subjected to further consolidation at the desired cell pressure in the triaxial cell. Subsequently, the samples were sealed in two rubber membranes with the help of suitable O-rings and the cell was filled with low viscosity oil.

The cell pressure was raised in steps and the samples were allowed to drain completely. During the shearing process, readings of volume change were recorded and the quantity of water expelled from the samples was observed carefully.

All samples were sheared till a strain of 20 percent was reached or otherwise till the samples collapsed.

6. OBSERVATIONS AND DISCUSSION

A comparison of the axial stress-strain diagrams for all consolidated drained tests are shown in Figs. 4 to 7. From this data, it has been observed that failure strain to reach failure increases as the confining pressure increases.

It has been observed that the Quartz samples failed at a strain of 3 to 4 percent under low pressures but the failure strain increased considerably with an increase in cell pressure. At a high cell pressure of 560 kg/cm^2 (56 MPa),, the failure strain was of the order of 18 to 19 percent (Fig. 4).

The stress-train behaviour of the Calcite samples indicated that at the highest pressure which has been adopted here, i.e. 560 kg/cm^2 (56 MPa), the plot does not reach an upper limit of stress up to 20 percent strain (Fig. 5). The samples continued to take load even after that.

On the other hand in the case of samples of Talc and Biotite, tests were carried out up to a strain of 20 percent and the stress-strain plots indicate that the samples continued to take very small increments of load even at 20 percent strain (Figs. 6 & 7). Therefore, it is concluded that all the samples of Talc and Biotite failed at a strain of 20 percent irrespective of the magnitude of the confining pressure. These particles are flaky type compared to the nearly equi-dimensional particles for Quartz and Calcite. Therefore, under shearing strain, the particles continuously have a tendency to reorient and rearrange themselves. This results in continuous yielding of the mass, which leads to gradual deformation, and a well-defined peak in the stress-strain plot is not seen.

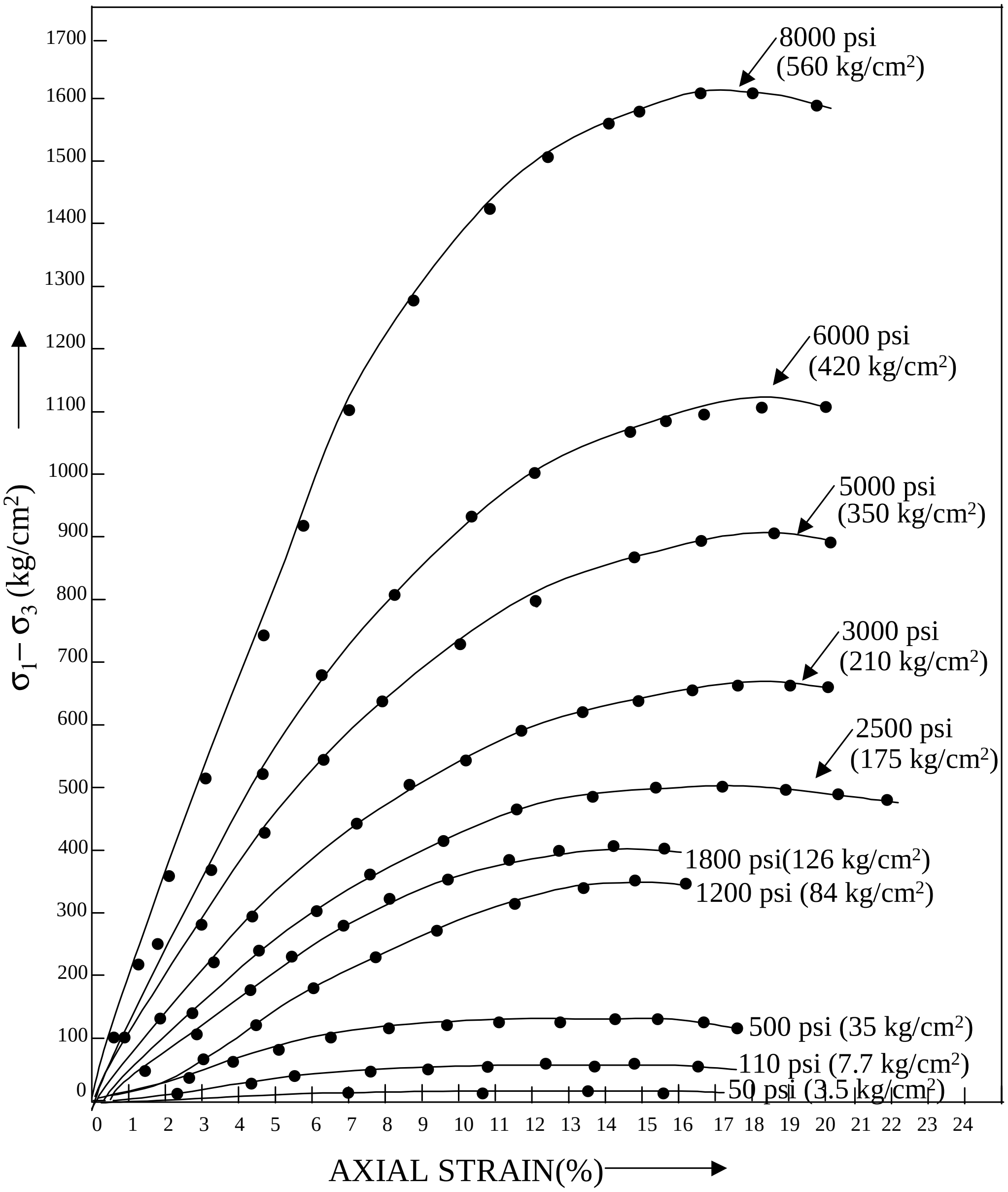

Fig. 4 - Stress-strain plots for quartz samples

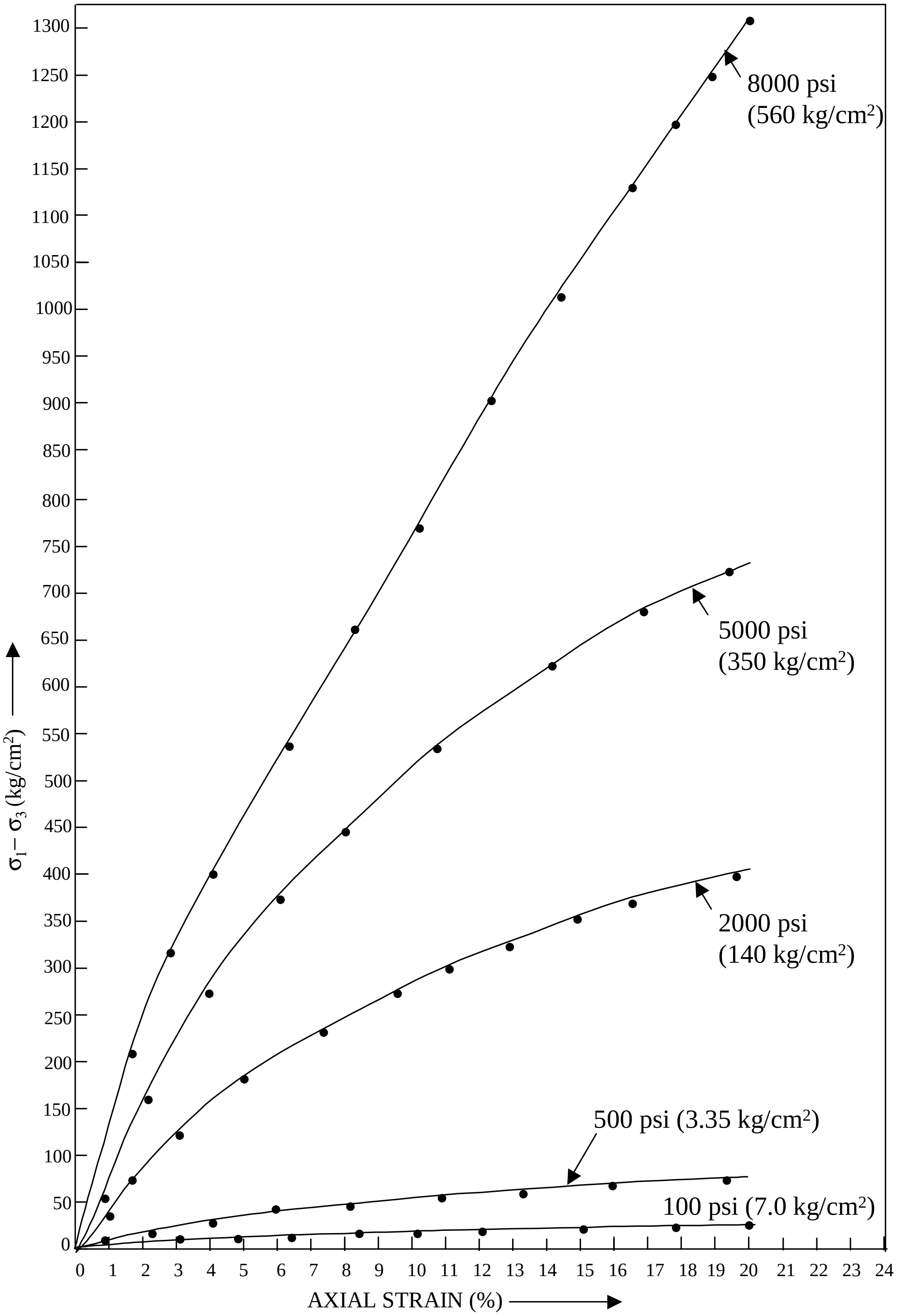

Fig. 5 - Stress-strain plots for calcite samples

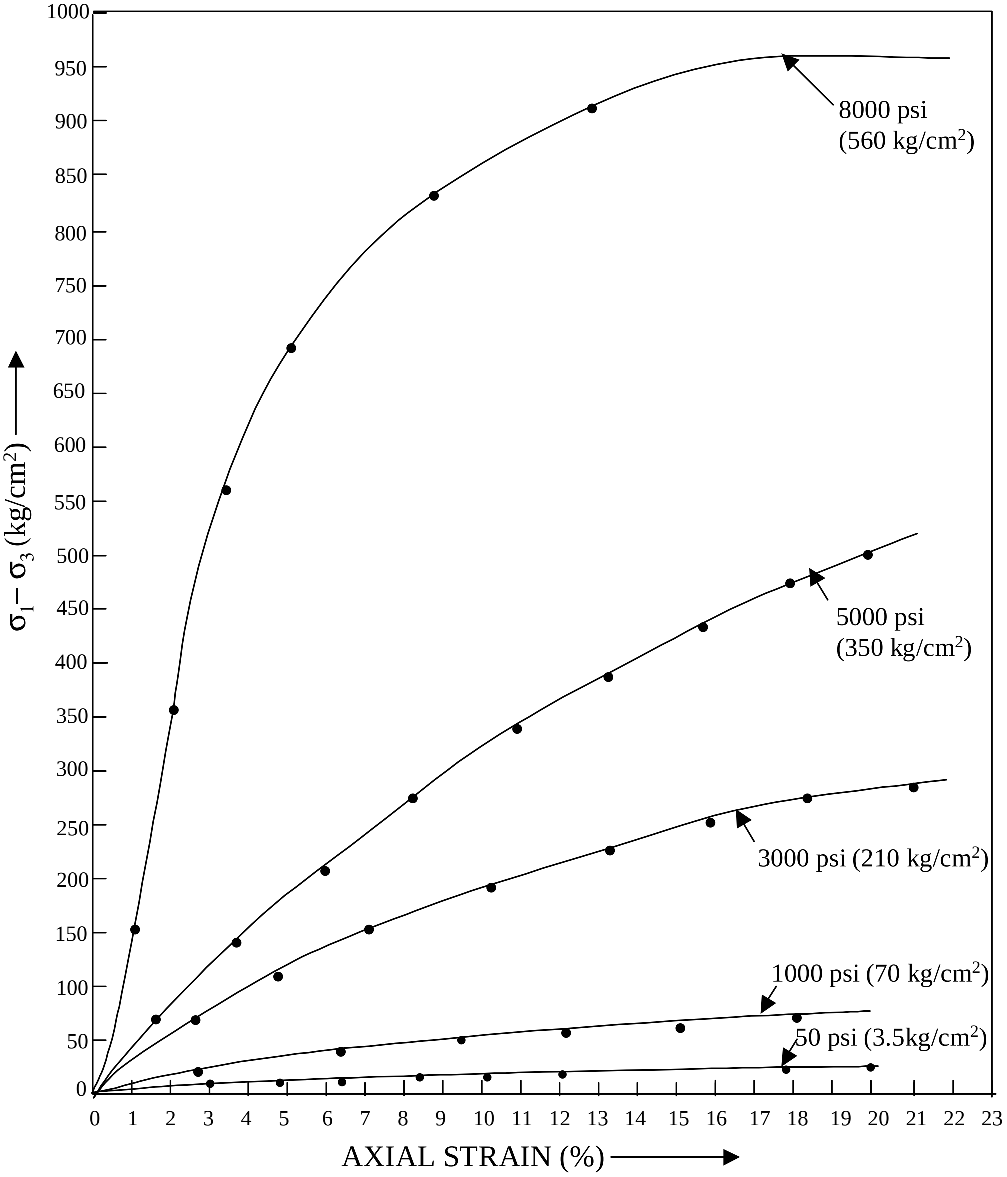

Fig. 6 - Stress-strain plots for talc samples

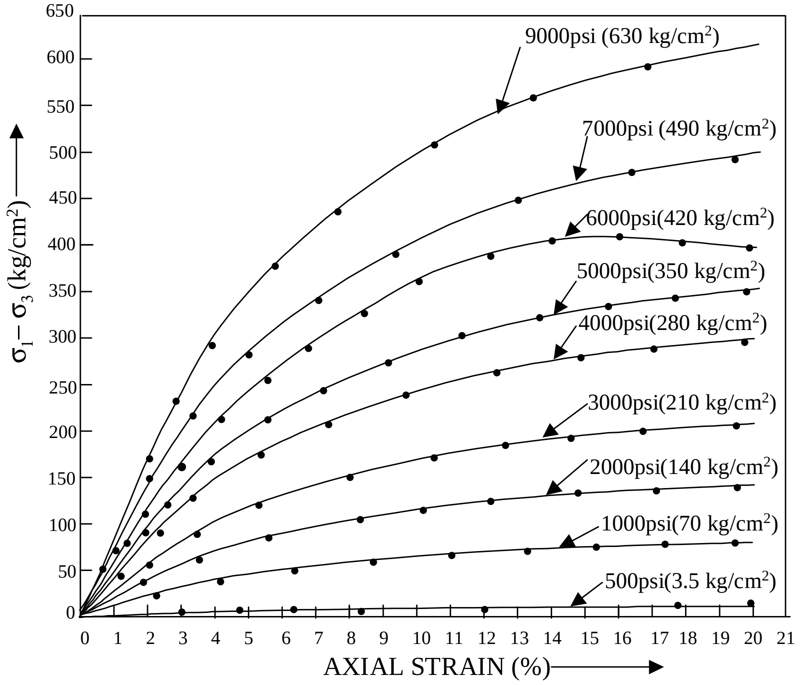

Fig. 7 - Stress-strain plots for biotite samples

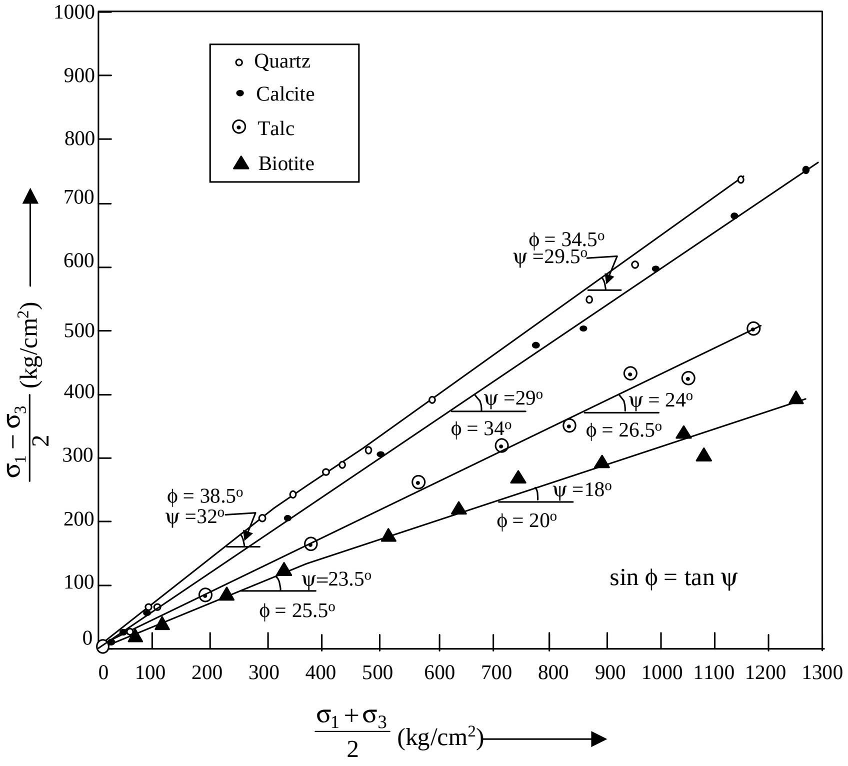

Fig. 8 - Modified Mohr envelopes

To understand failure mechanism, modified Mohr envelopes have been plotted in Fig. 8. Failure envelopes for all the minerals pass through the origin i.e. cohesion intercept is zero for all the minerals. In case of Quartz and Biotite, a change in the slope of the Mohr envelope was observed when confining pressures were increased from lower range to higher range. The slope at the higher pressure is flatter. In case of Quartz, up to a confining pressure of 112 kg/cm^2 (11.2 MPa), the angle of shearing resistance is 38.5^o. However, when the confining pressure is increased from 112 kg/cm^2 to 560 kg/cm^2 (11.2 to 56 MPa), the angle of shearing resistance falls to 34.5^o. In case of Biotite, up to a confining pressure of 210 kg/cm^2 (21 MPa), the angle of shearing resistance is about 25.5^o. When the confining pressure is increased from 210 kg/cm^2 to 560 kg/cm^2 (21 to 56 MPa), the angle of shearing resistance is 20^o.

However, in the case of samples of Calcite and Talc, it has been observed that the angle of shearing resistance remains to be constant for the entire cell pressure range adopted. The angle of shearing resistance for the Calcite is 34° and for the Talc 26.5°.

7. CONCLUSIONS

The frictional characteristics of rock forming minerals present a complex problem. The failure mechanisms under low pressures and at high pressures seem to be quite different. At high pressures, not only the crushing of grains but also the surface characteristics and the crystalline structure of the particles seem to be quite important.

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