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Effects of Strain Rate on Rock Joint Deformation

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Summary For the purpose of studying the effects of strain rate on deformational characteristics of rock specimens containing a single joint when subjected to gradually increasing compressive loading, a series of triaxial tests was conducted at constant strain rates of 2.08 x 10^{-6}/s (slow rate), and 8.33 x 10^{-4}/s (fast rate). Triaxial tests were performed under satisfactory end-specimen condition on two types of sandstone by a 5 MN servo-controlled stiff testing machine up to 30 MPa confining pressure. Increased strain rate decreased the reduction in volume or a slower strain rate resulted in a further closure of the joint. A faster strain rate led to a higher Poisson's ratio. Poisson's ratio decreased to a lower magnitude both at fast and slow rates due to an increase in confining pressure. Lateral strain increased as strain rate changed from fast to slow.

1. INTRODUCTION

The influence of time on discontinuities is important in many geotechnical applications in rock slope stability for calculation and estimation of slope movements, study of earthquake mechanisms (time-dependent of stick-slips) and dynamic loading over short time periods (blast and seismic loads).

Strain rate effects on frictional behaviour of joints and faults have been of great interest to geophysicists and seismologists attempting to understand the mechanism and prediction of earthquakes. These studies have been mostly concentrated on the stick-slip characteristics and dependence of frictional sliding on the slip velocity. A detailed investigation was given by Fahimifar (1991 and 1994).

There is a large number of research projects on the effects of strain or displacement rates on the axial stress-strain curves of intact specimens from laboratory compressive and tensile tests which have been mostly reviewed by Paterson (1978). Although the general agreement amongst workers is that the peak strength of rock specimens increases with increasing strain rates, there is not a uniform time-dependent characterisation for different rock types in wide ranges of strain rates for different confining pressures.

The majority of the work on time-dependent frictional resistance in jointed rocks were conducted with high confinement (to study earthquake mechanisms) and only a few investigations have been undertaken at stress levels applicable to engineering structures (confining pressures or normal stresses up to 15 MPa). These experiments have been conducted mainly using the direct shear apparatus.

Schneider (1977) performed a direct shear test experiment on a weak clay rock (a shale with a uniaxial strength of 3 MPa) to determine the time dependent behaviour of rock joints. The joints were established by a diamond saw cut parallel to the bedding. The frictional resistance was measured for each specimen at the same level of normal load, but at six different shear displacement rates (0.01, 0.1, 1, 10, 100 and 200 mm/min). He showed that in the tests with the same normal stress the frictional resistance is larger at higher shear rates. He concluded that the frictional resistance depends upon the normal stress and shear displacement rate.

Crawford and Curran (1981) conducted an investigation to determine the effects of the rate of shear displacement on the frictional resistance of rock discontinuities, using a direct shear test pertinent to this experiment. Four rock types were selected containing saw cut joints with various degrees of surface roughness under normal stresses up to 3 MPa. They concluded that the frictional resistance of rock surfaces can be significantly influenced by the rate of shear displacement. The magnitude of the rate effect is dependent on the rock type and normal stress level.

At low normal stresses the soft material, dolomite, exhibited an increase in shear resistance. At higher normal stresses the resistance remained constant until it reached the displacement rate at break point, where upon it decreased.

For the granite specimen, of intermediate hardness, the frictional resistance was essentially independent of shear velocity, whereas for the hardest rocks, the syenite and sandstone specimens showed significant variations of shear resistance with the rate of shear displacement.

2. EXPERIMENTAL PROCEDURES

The experiment was carried out using a 5 MN servo-controlled, stiff testing machine in the same way as described by Fahimifar (1994). The procedure used for the preparation of test specimens was in accordance with the ISRM suggested methods (Brown, 1986). The specimens were cored to a nominal diameter of 75 mm and length of 150 mm. They were smooth and free of any abrupt irregularities, with size parallel to each other to within 0.01 mm and at right angles to the longitudinal axis.

The type of joint was saw cut and, after preparation of cylindrical cores, each of them was cut into two pieces with a diamond saw. The cuts were perfectly plane surfaces at an angle 30° with respect to direction of major principal stress. The nominal height of the jointed specimens was taken to be the same as the intact specimens (i.e. 150 mm), however, the height decreased slightly when the intact specimen was cut by the diamond saw for establishing the joint.

The surface texture of the joints were kept similar for all specimens, so that it can be reasonable assumed that all the joint surfaces are similar in frictional characteristics.

A multi-channel analogue data acquisition unit capable of interfacing with a microcomputer and also with the servo-controlled system was used. This unit enables the use of a microcomputer to acquire data from a number of analogue signal sources and transmit it digitally.

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 a maximum confining pressure of 70 MPa. The lateral confining pressure was applied hydraulically by a continuously operating electric pumping unit. The tests were performed triaxially with confining pressures up to 30 MPa.

3. SELECTION OF TYPE OF ROCK

Two different sandstones were selected for investigation and their thin petrological sections were also studied. Rock materials were selected from various locations in an attempt to allow the testing of more than one type of rock, so that conclusions of a general nature could be reached.

4. VOLUME CHANGE MEASURING APPARATUS

The apparatus used was that of Price (1979) which was capable of coping with the large anticipated volume changes and fast rates of volume change.
The apparatus incorporates a pressure relief valve with a specified operating range of 7-70 MPa, but which, in practice, proved capable of operating even at zero pressure. This valve is mounted in series with the triaxial cell and a Bourdon-type hydraulic pressure gauge. The pressure gauge was used both for the setting of the relief valve and for monitoring the confining pressure during the test. An inlet valve is used for closing off the system from the confining pressure pump once the desired test pressure is reached.

Once the required confining pressure is reached, the relief valve is finely adjusted, if needed, and the inlet valve closed (system closed). It should be noted that the operating level of the relief valve is initially set before the experiment, whilst disconnected from the triaxial cell. Once the system is closed, any further axial loading of the specimen will cause an increase in the confining pressure and thus operate the relief valve. The oil displaced in this manner is collected and its volume recorded manually with an accuracy of 0.5 cc against the axial strain. The axial displacement (axial strain) and axial load (axial stress) are continuously monitored by means of an LVDT and a load cell respectively, and recorded on both an X-Y plotter and the microcomputer data logger facilities. Thus, at any given moment during the test the volumetric strain of the specimen can be calculated (Fahimifar, 1995) as a function of the displaced oil and the axial displacement.

5. JOINT DEFORMATIONAL BEHAVIOUR

Effects of strain rate on sliding characteristics and deformational behaviour of jointed specimens in which sliding freely occurs along the joint surface are very pronounced. Figure 1 illustrates volumetric strain-axial strain curves for saw cut jointed sandstone specimens at slow and fast rates and confining pressures 5 and 15 MPa. It is observed that increased strain rate decreases the reduction in volume, or increased strain rate decreases the joint closure. A change in the strain rate, for instance, from slow to fast, for 5 MPa confinement, reduced the change in volume from an average of 0.35% to 0.1%, and for 15 MPa, from 0.4% to 0.25%.

It may be concluded that a slower strain rate results in a further closure of the joint. This finding is important in the long-term behaviour of structures, such as a dam constructed on a jointed rock mass, dependent on whether it is built in a short or long period of time and whether it is loaded at a fast or slow rate (such as sudden flow of water to the dam because of a high rainfall). This may lead to subsidence beneath the dam. As is observed in Figure 1, an increased confining pressure decreased the difference in the volumetric strain between two slow and fast rates, from the average of 0.25 (0.35 - 0.1 = 0.25) to 0.15 (0.4 - 0.25 = 0.15), namely about 40% ([0.25 – 0.15]/0.25 × 100) reduction.

Comparison of the plots in Figure 1 shows a distinct difference between the curves corresponding to the slow rate with those of the fast rate. A peak value is observed in the slow rate plots for both 5 and 15 MPa confinements which is related to a slight

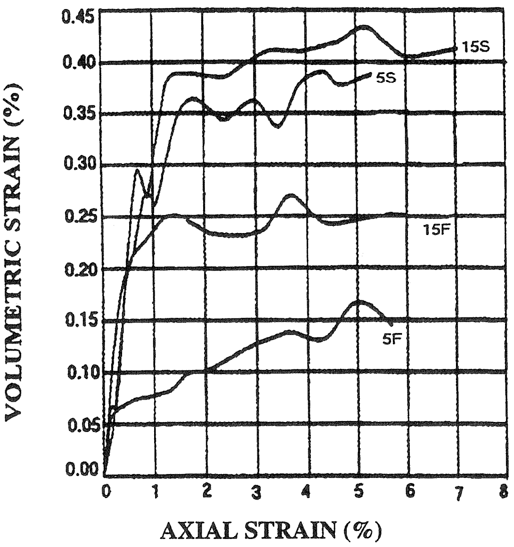

Figure 1. Volumetric strain-axial strain plots for sandstone specimens. (Slow and fast strain rates, joint angle = 60°, confining pressure = 5 and 15 MPa).

relative increase in volume, or in fact slight dilation of the joint at that point. In the plots corresponding to the fast rate, however, a relative expansion (increase in volume) is not observed at all, but there is a uniform reduction in volume throughout the test. It is necessary to differentiate between the concept of volumetric strain in the intact and jointed specimens, particularly when the mechanism of deformation is dominated by sliding movement along the joint. In this case volumetric strain is directly a measure of joint closure (joint normal displacement or joint shortening; Barton, 1986) or joint dilation (joint normal displacement or joint thickening; Goodman, 1976) and joint shear displacement. There is not an absolute increase in specimen volume at all during the deformation process, but relative increases in volume at some portions which are an indication of dilation at those positions. It is also necessary to note that occasional fluctuations in the sliding portion of the volumetric strain-axial strain curves, particularly those related to saw cut joints (as in Figure 1), are mainly due to errors in reading the displaced oil by eye. As the magnitude of volume change in the jointed specimens was very low (less than 1%) it was very sensitive to a small error in reading the oil level from the graded cylinder. For instance, a change of 0.2 cc in the amount of oil dripping through tbe relief valve affects the calculations considerably.

The strain rate also significantly affected the instantaneous Poisson's ratio. As is observed in Figure 2, the faster strain rate resulted in a higher Poisson's ratio. The increased confining pressure decreased the strain rate effect so that the instantaneous Poisson's ratio decreased to a lower magnitude, both at fast and slow rates, due to an increase in the confining pressure from 5 to 15 MPa.

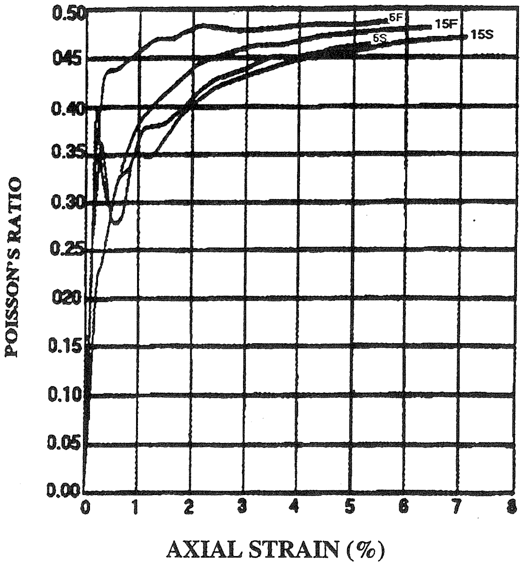

Figure 2. Axial strain-instantaneous Poisson's ratio plots for sandstone specimens. (Slow and fast strain rates, joint angle = 60°, confining pressure = 5 and 15 MPa).

An interesting point in Figure 2 is that the plots of the instantaneous Poisson's ratio, for both the 5 and 15 MPa confinements at a slow strain rate, dropped to a lower level, increased again, and then continued asymptotically. This discrepancy is better seen in Figures 3 and 4 which show the axial stress-Poisson's ratio plots for both 5 and 15 MPa confining pressures. There is no sirnilar observation, however, in the fast strain rate plots in any of the Figures 2, 3 and 4.

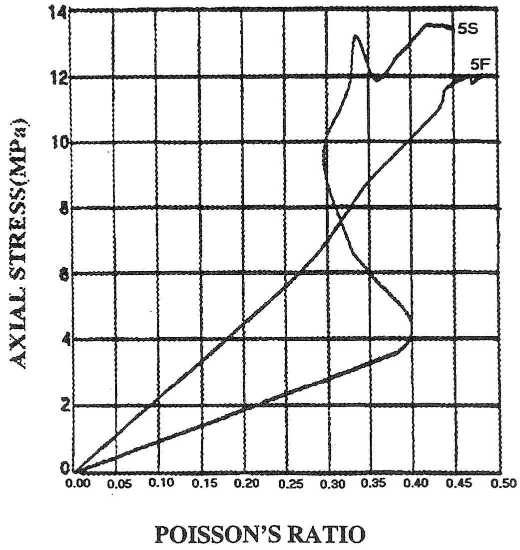

Figure 3. Axial stress-instantaneous Poisson's ratio plots for sandstone specimens. (Slow and fast strain rates, joint angle = 60°, confining pressure = 5 MPa).

This behaviour indicates that, for slow rate of strain, at a certain interval of axial stress, which is at the onset of sliding over the joint surface, the rate of change of axial strain becomes greater than the rate of change of lateral strain (taking into account that

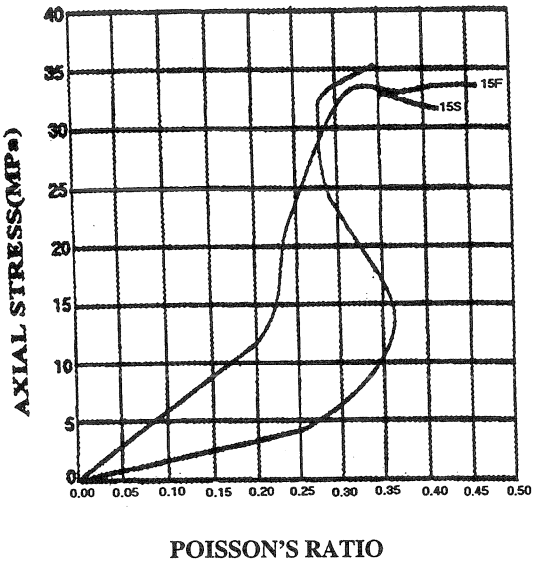

Figure 4. Axial stress-instantaneous Poisson's ratio plots for sandstone specimens. (Slow and fast strain rates, joint angle = 60°, confining pressure = 15 MPa).

the instantaneous Poisson's ratio = $\varepsilon_2/\varepsilon_1$). This is due to the fact that, at the initiation of sliding, a slight dilation occurred and resulted in the percentage increase in axial strain (because of normal displacement of the joint) being greater than the percentage increase in lateral strain.

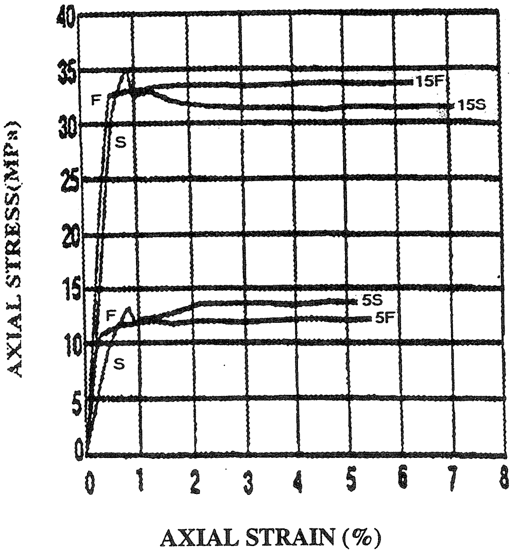

Figure 5. Axial stress-strain plots for sandstone specimens. (Slow and fast strain rates, joint angle = 60°, confining pressure = 5 and 15 MPa).

For the fast strain rate, because of a lower degree of interlocking asperities, there is no dilation at the onset of sliding. For this reason a peak stress is not observed in the stress-strain plots corresponding to the fast rate for both 5 and 15 MPa confinements (Figure 5 plots 5F and 15F).

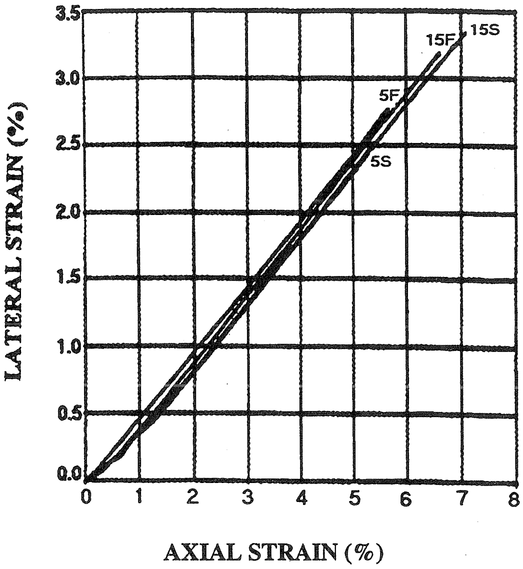

Figure 6. Lateral strain-axial strain plots for sandstone specimens. (Slow and fast strain rates, joint angle = 60°, confining pressure = 5 and 15 MPa).

Effects of strain rate on lateral strain are very pronounced as is observed in Figures 6 and 7. In Figure 6, which indicates the axial strain-lateral strain relationship of sandstone jointed specimens with 60° inclination, it is observed that at a certain amount of axial strain (at 2% on the x-axis, for instance) the corresponding lateral strain for the fast rate is higher than for the slow rate, for both 5 and 15 MPa confining pressures. Increased cofinement reduced this effect. In Figure 7 (axial stress-lateral strain plots), which clearly shows the variation of the lateral strain from the beginning of loading, it is observed that the lateral strain increased when the strain rate changed from fast to slow. The increase, for the lower confining pressure (5 MPa), is greater than that for the higher confinement (15 MPa) at a certain level of stress (at 5 MPa axial stress, for instance, as in Figure 7).

The influence of strain rate on the deformational behaviour and frictional resistance of rock joints may be ascribed to the fact that the change in strain rate causes the real area of asperity contacts to change. Teufel and Logan (1978) showed that, with a decrease in the displacement rate from 10^{-2} to 10^{-6} cm/s, the real area of contact increased from about 5 to 14% of the apparent area. This behaviour affects both sliding resistance and deformational characteristics of rock joints. In fact, as the strain rate decreases, further interlocking asperities will result. It is for this reason that, in Figure 5, a change in strain rate, from slow to fast, the sliding stress decreased to a lower level at the beginning of sliding. In addition, because of a reduction in the interlocking asperities (due to a decrease in real contact area), the occurrence of a peak stress disappeared in both the 5 and 15 MPa confining pressures in the plots corresponding to the fast rate, and also in Figures 1, 2 and 5, for the same reason, the deformational characteristies of jointed specimens have been affected. It is clearly observed

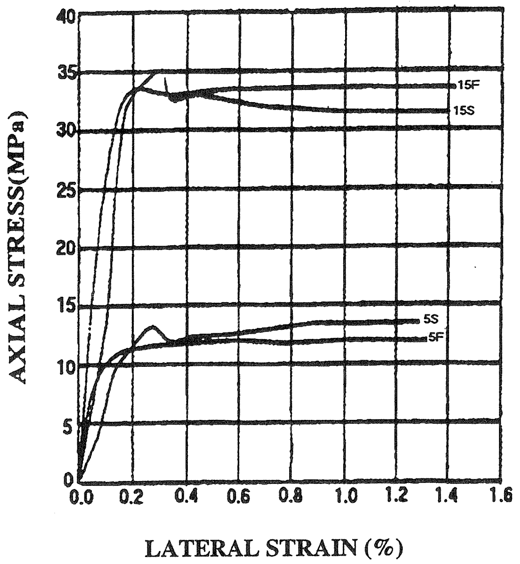

Figure 7. Axial stress-lateral strain plots for sandstone specimens. (Slow and fast strain rates, joint angle = 60°, confining pressure = 5 and 15 MPa).

in Figure 1, for instance, that when the strain rate was increased to a fast rate, due to a reduction in the interlocking asperites (or a reduction in the real contact area over the joint surface), the damage to the sliding surfaces reduced. This means that the joint closure decreased and therefore, a reduction in the volumetric strain became less than that at the slow rate.

Because of further asperity damage, with the continuation of sliding when a slow strain rate is applied, the amount of gouge material over the sliding surfaces increases considerably compared with that procuced at the fast rate. This behaviour becomes more significant at higher confining pressures. The gouge material, in this case, acts as a layer of filling material which reduces the sliding resistance to a level lower than that observed at the fast rate, as is seen in the upper plots (15S and 15F) for 15 MPa confinement, in Figure 5. This behaviour is, of course, affected by other factors such as the type of rock and the order of magnitude increase or decrease in strain rate.

6. CONCLUSIONS & RECOMMENDATIONS

An experimental investigation was conducted to evaluate the significance of strain rate on the deformational characteristics of rock with a single joint. The most important remarks may be summarised as follows:

1. Increased strain rates decreased the reduction in volume of the specimens, or a slower strain rate resulted in further closure of the joints. Increased confining pressures reduced this effect.
2. The strain rate significantly affected the instantaneous Poisson's ratio. The faster strain rate resulted in a higher Poisson's ratio. Increased confining pressures decreased this effect. At a slow strain rate and at the initiation of sliding the rate of change of axial straining became higher than the rate of change of lateral straining, which was an indication of joint dilation at that position.
3. Increased strain rates resulted in greater lateral strains within the jointed specimen. Increased confining pressures decreased this effect.

During straining of the specimens, the displaced oil from the triaxial cell was measured in a graded cylinder, with a maximum accuracy of 0.5 cc. This was insufficient to achieve precise volumetric strain obtained by calculation for the jointed specimens in which sliding over the joint plane is predominant. This problem led to occasional fluctuations in the volumetric strain-axial strain plots in the sliding portions. The servo-controlled amplifier apparatus, which would be able to measure the displaced oil automatically, is likely to overcome this problem. It is recommended that a series of tests be conducted using this device and comparing the results with those described in this paper.

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