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Frictional behaviour of sandstone: A sample-size dependent triaxial investigation

Hamid Roshan [a], [*], Hossein Masoumi [b], Klaus Regenauer-Lieb [a]

[a] *School of Petroleum Engineering, UNSW Australia, Sydney, NSW, 2052, Australia*
[b] *School of Mining Engineering, UNSW Australia, Sydney, NSW, 2052, Australia*

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ABSTRACT

Frictional behaviour of rocks from the initial stage of loading to final shear displacement along the formed shear plane has been widely investigated in the past. However the effect of sample size on such frictional behaviour has not attracted much attention. This is mainly related to the limitations in rock testing facilities as well as the complex mechanisms involved in sample-size dependent frictional behaviour of rocks.

In this study, a suite of advanced triaxial experiments was performed on Gosford sandstone samples at different sizes and confining pressures. The post-peak response of the rock along the formed shear plane has been captured for the analysis with particular interest in sample-size dependency. Several important phenomena have been observed from the results of this study: a) the rate of transition from brittleness to ductility in rock is sample-size dependent where the relatively smaller samples showed faster transition toward ductility at any confining pressure; b) the sample size influences the angle of formed shear band and c) the friction coefficient of the formed shear plane is sample-size dependent where the relatively smaller sample exhibits lower friction coefficient compared to larger samples.

We interpret our results in terms of a thermodynamics approach in which the frictional properties for finite deformation are viewed as encompassing a multitude of ephemeral slipping surfaces prior to the formation of the through going fracture. The final fracture itself is seen as a result of the self-organisation of a sufficiently large ensemble of micro-slip surfaces and therefore consistent in terms of the theory of thermodynamics. This assumption vindicates the use of classical rock mechanics experiments to constrain failure of pressure sensitive rocks and the future imaging of these micro-slips opens an exciting path for research in rock failure mechanisms.

1. Introduction

Triaxial experiments are used to characterize and quantify the mechanical response of materials under simulated in-situ conditions (Bésuelle et al., 2000; Chang and Jumper, 1978; Khan et al., 1991, 1992; Klein et al., 2001; Niandou et al., 1997; Parry, 1960; Sulem and Ouffroukh, 2006a; Wasantha et al., 2014).

Little emphasis however has been placed on the size effect of the triaxial response of the investigated materials. Size effects are particularly pronounced for geological loading conditions where the behaviour of a sample from initial stage of loading to shear displacement along formed shear plane at different confining pressures is of interest. Size effects have been demonstrated under different loading/stress conditions including uniaxial compressive test (Baecher and Einstein, 1981; Darlington and Ranjith, 2011; Masoumi et al., 2014; Mogi, 1962; Panek and Fannon, 1992; Pratt et al., 1972; Thuro et al., 2001a), point load test (Broch and Franklin, 1972; Brook, 1980; Forbes et al., 2015; Greminger, 1982; Hawkins, 1998; Thuro et al., 2001b) and indirect tensile or so called Brazilian test (Andreev, 1991a, b; Butenuth, 1997; Çanakcia and Pala, 2007; Carpinteri et al., 1995; Elices and Rocco, 1999; Thuro et al., 2001a). Also, a limited number of studies have included size effect under triaxial condition (Aubertin et al., 2000; Hunt, 1973; Medhurst and Brown, 1998; Singh and Huck, 1972) while neither has reported the full stress-strain response from the initial stage of loading to shear displacement beyond the peak

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* Corresponding author.
E-mail address: h.roshan@unsw.edu.au (H. Roshan).

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stress. This has led to shortcoming in understanding of size effects on a) the rate of transition from brittle to ductile response, b) the formation of shear bands and c) the post-peak shear response along the formed shear plane particularly in sedimentary rocks.

Understanding the mechanisms involved in the transition from brittleness to ductility in sedimentary rocks is a vital aspect of the petroleum geomechanics, in particular reservoir production (Wong et al., 1997). In addition, the formation of shear band is of great interest in many disciplines from structural geology to petroleum geomechanics such as prediction of the fluid transmissivity along faults (Sulem and Ouffroukh, 2006b). Further, the friction coefficient of fractures is generally assumed size independent. However, a number of investigations have shown that the sample size influences the friction coefficient of rock discontinuities e.g. faults and fractures (Bandis, 1980; Bandis et al., 1981; Barton and Bandis, 1982; Carpinteri and Paggi, 2005; Schellart, 2000).

These investigations have proposed some form of descending size effect model for the friction coefficient. However, the studies were restricted to a statistical description and not aimed at gaining insight into the origins of the size effect. Consequently no universal law was derived and the proposed models did not seem to be able to suitably predict the sample-size dependent behaviour of the friction coefficient over the wide range of laboratory scales especially at relatively smaller sizes. A profound knowledge of the sample-size effect is particularly important in petroleum geomechanical projects where relatively small core samples are often retrieved from deep locations and available for the laboratory experiments.

In this study, a number of triaxial laboratory experiments were performed on Gosford sandstone samples at three different sample diameters with complete stress-strain behaviour from the initial stage of loading to shear displacement along the formed shear planes. Because of homogeneous porosity structure of Gosford Sandstone and its uniform mechanical response (Baud et al., 2000; Edmond and Paterson, 1972; Forbes et al., 2015; Masoumi et al., 2016; Ord et al., 1991; Roshan et al., 2016a; Sufian and Russell, 2013), it was used for a first systematic study to shed light on the origins and character of the sample-size effect for shear deformation. We present a first study that characterises the size effects on a) the rate of transition from brittle to ductile response in rock over a wide range of confining pressures, b) the formation of shear bands and c) the friction coefficient of the formed shear planes. We interpret the results by a novel thermodynamic homogenization approach (Regenauer-Lieb et al., 2014) using the upper bound method to derive a representative volume element for mechanical deformation of Gosford sandstone.

2. Sample preparation and experimental methodology

The laboratory triaxial experiments were conducted on Gosford sandstone samples with diameters of 25, 50 and 96 mm. Gosford sandstone forms a unit within the massive (290 m thick) Triassic Hawkesbury sandstone of the Sydney Basin (Ord et al., 1991) on the east coast of New South Wales, Australia (Fig. 1).

The Gosford sandstone used in this study was obtained from Gosford Quarry, Somersby, New South Wales, Australia. Samples were carefully selected to be as homogeneous as possible visually with no macro defect with a unified colour. Roshan et al. (2016b) conducted an X-ray computed tomography scan on the same batch of Gosford sandstone used in this study and reported its porosity to be approximately 16.0%. The maximum grain size of Gosford sandstone was estimated as 0.6 mm from sieve analysis. In addition, the mineralogy of the sample was measured as 86% quartz (SiO2), 7% illite (Al2 H2 K0.7 O12 Si4), 6%, kaolinite (H4 Al2 O9 Si2) and 1% anatase (TiO2) by X-ray diffraction analysis. All samples with length to diameter ratio of 2 (ASTM, 2000) were oven dried for 24 h at 105° C. To make the end surfaces flat, the cores were grounded carefully to about 0.003 mm tolerance according to ISRM (2007).

A servo-controlled loading frame system with maximum loading capacity of 300 tonnes was used to perform the triaxial experiments. A GCTS triaxial cell with the maximum axial loading capacity of 200 tonnes and 70 MPa confining pressure was employed (Fig. A1 in the Appendix). The triaxial cell came with three sets of platens at 100, 50 and 25 mm diameters. A manual hydraulic pump with maximum pressure capacity of 100 MPa was utilized to provide the confining pressure. An additional digital gauge manufactured by Geotechnical Digital Systems (GDS) with accuracy of ±0.01 MPa was used to control the confining pressure during the experiment. Two axial and one circumferential Linear Variable Differential Transducers (LVDT) were utilized to log the axial and radial deformations of the sample, respectively (Fig A2 in the Appendix). Subsequently the average of the axial deformations was used for data interpretation. Several experiments were conducted on each size (25, 50 and 96 mm) and confining pressure (10, 20 and 30 MPa) to account for possible scatters.

The deviatoric stress is defined as $q = \sigma_1 - \sigma_3$ where σ_3 is the confining pressure and σ_1 is the axial stress. The shear band angle (β) is referred to the angle between the formed shear plane and the horizon which is measured after complete failure of the sample. The residual deviatoric stress in the stress-strain curve is also referred to the final permanent deviatoric stress level, in which the shearing occurs along the shear plane with no change in the deviatoric stress.

3. Results

Examples of one set of conventional triaxial deviatoric stress (q) versus axial strain for 25, 50 and 96 mm diameter samples under three confining pressure (10, 20 and 30 MPa) are shown in Fig. 2. The mean peak and residual deviatoric stresses as well as the shear band angles (β) at different sizes and confining pressures are extracted from the experimental data and reported in Table 1.

Shear band angles were attained according to the method proposed by El Bied et al. (2002) where attempts were made to conduct the measurement at the centre of the shear plane to minimise the effect of deviated shear angles close to the end surfaces. The measured shear band angles at different confining pressures for all three diameters are presented in Fig. 3. The photos of the formed shear bands for a set of triaxial tests on each sample size at different confinements are additionally presented in Appendix (Figs. A3-A5).

Fig. 3 shows that an increase in confining pressure leads to decrease in shear band angle for all three diameters with different degree of sample-size dependency. The data obtained from triaxial testing at different sample sizes are used to investigate the effect of sample size on a) the rate of transition from brittle to ductile response, b) shear band angle, and c) the friction coefficient of formed fractures.

3.1. *Sample-size effect on the rate of transition from brittleness to ductility*

The mean peak and residual deviatoric stresses reported in Table 1 for 10, 20 and 30 MPa confining pressures are used to investigate the size effect on the rate of transition from brittle to ductile response e.g. ductile response is defined as where the incremental stress shows no softening with strain. A relationship, so called the transition index (TI), is defined to study this process: