Tu-17-04

True Triaxial Strength Testing of Sandstones

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SUMMARY

Laboratory rock mechanical tests allow estimation of rock strength and deformation behaviour under stress states similar to the in-situ conditions. In general, the in-situ stresses are described by three principal stresses, the vertical, maximum and minimum horizontal stresses. However, most of rock mechanical properties are obtained using only two different stresses, as in conventional triaxial tests where an axial load and an isotropic confining pressure are applied on a cylindrical rock sample. Also the most commonly used failure criterion, the Mohr-Coulomb criterion, is usually applied using only the maximum and minimum applied stresses and thus ignores the effect of the intermediate stress. Experimental and theoretical studies of rocks under true triaxial stress conditions have proved that describing their mechanical properties while ignoring the effect of σ , cannot reflect the rock behaviour under true stress states. In this paper the lab results of an on-going study on deformation behaviour of synthetic sandstones in a true triaxial cell are presented. The effect of both σ and σ has been examined by conducting compressional tests in different stress levels and σ /σ ratios. The results show the impact of changing stress magnitudes and anisotropy on rock strength and deformation behaviour.

Introduction

Laboratory rock mechanical tests allow estimation of rock strength and deformation behaviour under stress states similar to the in-situ conditions. In general, the in-situ stresses are described by three principal stresses, the vertical, maximum and minimum horizontal stresses. However, most of rock mechanical properties are obtained using only two different stresses, as in conventional triaxial tests where an axial load and an isotropic confining pressure are applied on a cylindrical rock sample. Also the most commonly used failure criterion, the Mohr-Coulomb criterion, is usually applied using only the maximum (σ_1) and minimum (σ_3) applied stresses and thus ignores the effect of the intermediate stress (σ_2). In 1971, Mogi designed a true triaxial cell for testing hard rocks and developed true triaxial failure criteria based on the experimental results of different rock types. His experiments on several carbonate and silicate rocks indicated that the intermediate stress has a significant effect on rock strength when its magnitude is changed from $\sigma_2 = \sigma_3$ to $\sigma_2 = \sigma_1$.

After Mogi (1971), different laboratories worldwide developed polyaxial testing machines and true triaxial experiments were conducted on different rock types (e.g. Takahashi & Koide, 1989; Haimson & Chang, 2000; Popp & Salzer, 2007). In addition, various theoretical predictions and numerical studies have been devoted to characterize the effect of applied stresses on rock failure (Haimson, 2006). Significant progress has been made in this regard which proves that describing rock deformation and failure properties while ignoring the effect of the intermediate stress, cannot reflect the rock behaviour under true stress state.

In this paper, laboratory results of an on-going study on deformation behaviour of synthetic sandstones in a true triaxial cell are presented. The effect of both minimum and intermediate stresses has been examined by conducting compressional tests in different stress levels and σ_2/σ_3 ratios (1, 2, 2.19 and 3.29). The results show the impact of changing stress magnitudes and anisotropy on rock strength and deformation behaviour.

Experimental method

The tests have been conducted in a true triaxial stress cell (TTSC), in which three independent stresses were applied on cubic rock samples of size 5cm by three solid pistons. The TTSC is designed to load cubic samples as large as 30 cm, thus in order to load 5cm rock cubes in it, metal spacers are positioned around the sample to transfer the load from steel plates of the cell to the rock.

Samples are dry synthetic sandstones with a uniaxial compressive strength (UCS) of ~23.5 MPa. All samples are assumed to be isotropic and homogeneous rocks, although some minor heterogeneity in sample cementation would be expected.

The experiments conducted so far consist of eight tests under two constant levels of minimum principal stress (σ_3 = 2.3, 6.3 MPa). For the tests under σ_3 = 6.3 MPa, four levels of the intermediate principal stress (σ_2 = 6.3, 12.6, 13.8, 20.7 MPa) have been used and for the ones under σ_3 = 2.3 MPa, two different levels (σ_2 = 4.6, 7.6 MPa) have been examined to date. After inserting each sample into the cell, loading was conducted by first hydrostatically increasing the stress in all 3 directions until the predetermined magnitudes of the intermediate and minimum stress were reached. These two stresses were then kept constant while maximum principal stress (σ_1) was increased monotonically until failure occurred. Loading in σ_1 direction was done with an average stress rate of 1.28 MPa/min which imposed an average strain rate of ~3.7E-6/s.

Measuring and recording the rock displacement along all three principal stress directions during a true triaxial test is necessary to evaluate the rock strength and elastic properties. Deformation measurements during the experiments were done using linear variable differential transformers (LVDT) mounted on spacers around the sample.

Results

The applied stresses and obtained strength from true triaxial tests for different samples are presented in Table 1. Here, σ_1 is the axial stress at failure and σ_f is the true triaxial strength which is defined by the maximum differential stress (σ_1-σ_3) at failure.

Figure 1 shows an example of the stress-strain curves obtained from a true triaxial experiment on sample 1-8. In general, the lateral deformation ε_3 is larger than ε_2. This can be interpreted as the microcracks opening perpendicular to the minimum stress direction (Kwaśniewski et al., 2003). From this plot the rock mechanical properties such as Young's modulus (E) and Poisson's ratio (ν) can also be obtained using the slope of linear elastic part of the curves. Based on ASTM standard-D5407-95 (reapproved 2000), E and ν were calculated at 40-60% of the final strength. However since the Poisson's ratio is calculated by dividing the slope of axial to lateral stress-strain curves, it is significantly affected by even slight changes in slope and thus the values obtained for E using this method are more reliable. The average Young's modulus obtained for this sandstone is about 3.67 GPa. There was some variation in the magnitude of E obtained from different tests which could be due to heterogeneity in cementation of these synthetic sandstones, as rock stiffness strongly depends on cementation at grain contacts.

Sample No.	**1-9**	**1-8**	**1-8'**	**1-10**	**1-11**	**1-12**	**1-7**	**1-6**
σ_3 (Mpa)	6.3	6.3	6.3	6.3	6.3	6.3	2.3	2.3
σ_2 (MPa)	6.3	12.6	12.6	13.8	20.7	20.7	4.6	7.58
σ_1 (MPa)	93.33	82.58	77.58	118.74	148.15	146.94	57.75	71.87
σ_f (MPa)	86.99	76.18	71.19	112.28	141.77	140.54	55.44	69.53

Table 1 *True triaxial test data for the synthetic sandstones.*

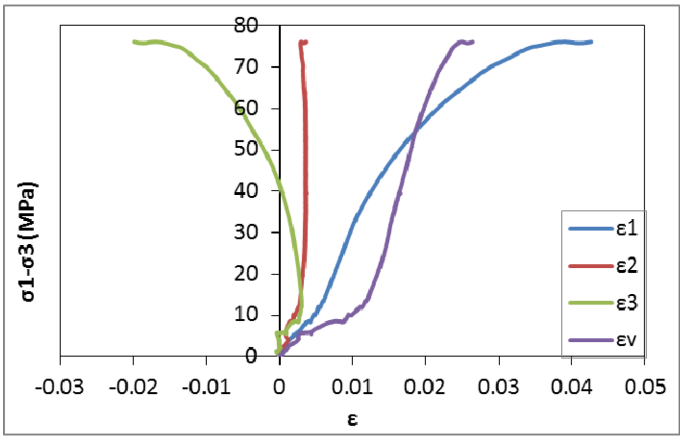

Figure 1 *Plot of the maximum differential stress (σ_1-σ_3) vs. strain for sample 1-8. ε_1, ε_2 and ε_3 are the strains along three principal stresses and ε_v is the volumetric strain.*

The differential stress versus axial strain curves for all the tests are plotted in Figure 2. There is a general increase in failure strength in different curves with increasing σ_2. Here the failure strength was determined by the peak of the differential stress-strain curve for the samples which had a stress drop, or by the stress level at the knee of the curve, which determines the transition from elastic to non-elastic (permanent) deformation in the rock.

Examples of images taken from the failed samples after the tests are shown in Figure 3. Macroscopic through-going fractures striking in σ_2 direction have developed in all of them, except for sample 1-7, which has not fractured along such macroscopic slip planes with the definite direction. Considering these fracture planes and also the stress-strain curves (Figure 2), these sandstones have deformed in a brittle manner.

In order to determine how σ_2 affects the rock strength, the laboratory results can be plotted in different domains. For many rock types (e.g. dolomite, shale, sandstone, granite) the experimental data of failure strength for any constant σ_3 fit a downward concave curve in σ_1-σ_2 domain (Haimson, 2006), which can be predicted by some failure criteria, such as the effective strain energy criterion proposed by Wiebols & Cook (1968). Figure 4 displays the obtained strength data for both levels of σ_3 and different magnitudes of σ_2 in the σ_1-σ_2 domain. Studies of Takahashi and Koide (1989) have shown that strength in sandstones increases by increasing σ_2. The results obtained from our experiments also indicate an overall increase in strength with σ_2, however not enough data points have been gathered to formulate the effect of the intermediate stress on rock strength.

Mogi (1971) developed an empirical criterion for brittle rocks in the $\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$ versus $\sigma_{m,2} = \frac{1}{2}(\sigma_1 + \sigma_3)$ domain. Based on his studies for brittle rocks, which undergo failure in form of fracturing along slip planes parallel to σ_2 direction, plotting the failure data in a τ_{oct} versus $\sigma_{m,2}$ domain, instead of $\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$, can better determine the failure criteria of the rock. τ_{oct} is the octahedral shear stress and σ_{oct} and $\sigma_{m,2}$ are the mean normal stress and the normal stress acting on the slip planes striking parallel to σ_2, respectively. The rationale is that since fracturing happens due to shearing along the slip planes, it is more realistic to assume that the failure occurs because the distortional strain energy reaches a critical value that is a monotonically increasing function of the mean stress on these planes. In Figure 4, our lab data has been plotted in Mogi's domain (τ_{oct} - $\sigma_{m,2}$). Although the data tend to fall along a single curve, tests under other levels of minimum and intermediate stress are still required to determine an empirical failure criterion for this type of rock.

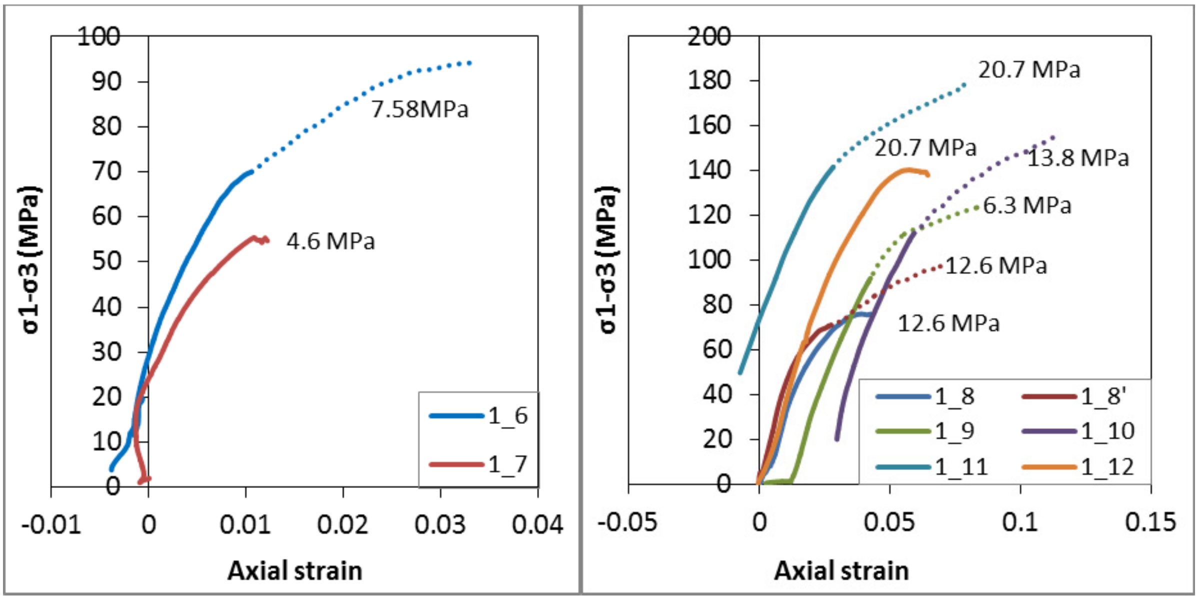

Figure 2 *Differential stress vs. axial strain curves of the sandstone samples tested at* σ_3*=2.3 MPa (left) and* σ_3*=6.3 MPa (right). The numbers on the plot show the values of* σ_2 *for each curve.*

Conclusions

The data presented in this paper, suggest that strength of the rock samples could be affected not only by the minimum stress but also by the intermediate stress. Although the sandstone specimens examined here are few, they have obviously shown this impact. The laboratory results reported in this paper are a part of an on-going project and thus conducting more experiments in wider ranges of σ_2 and σ_3 in future can better indicate the effects of stress magnitudes and anisotropy on rock deformation behaviour and assist in finding a proper failure criterion for the specific rock type being examined.

Figure 3 *Typical failure planes in the sandstone cubes after true triaxial tests, showing the growth of failure planes parallel to* σ_2*. Here* σ_1 *in acting axially and* σ_3 *acts in lateral direction.*

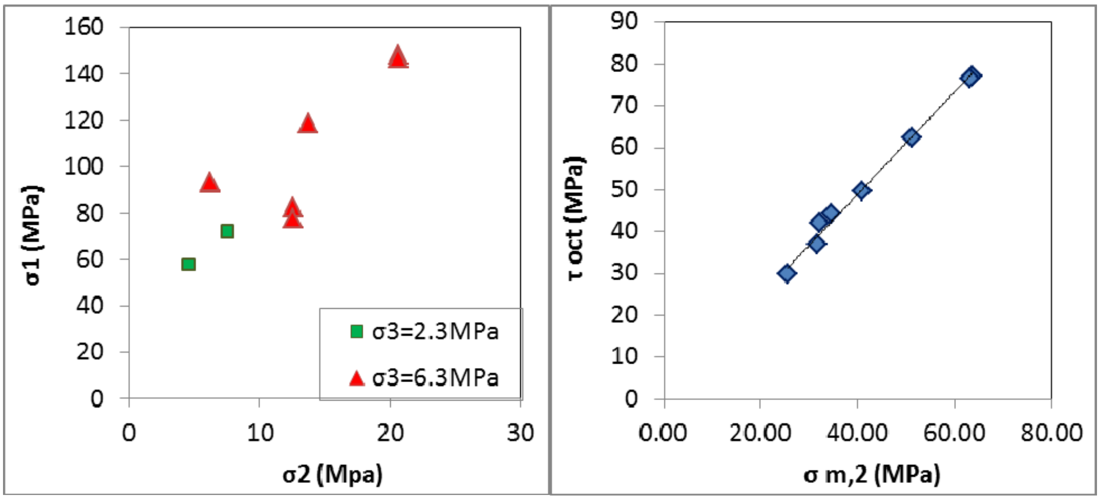

Figure 4 *Strength data in* σ_1*-*σ_2 *domain (left) and* τ_{oct} *vs.* $\sigma_{m,2}$ *domain (right).*

References

Haimson, B. [2006] True triaxial stresses and the brittle fracture of rock. *Rock Damage and Fluid Transport, Part I*, 1101-1130.

Haimson, B. and Chang, C. [2000] A new true triaxial cell for testing mechanical properties of rock, and its use to determine rock strength and deformability of Westerly granite. *Int. J. Rock Mech. Min Sci*., **37**, 285-296.

Kwaśniewski, M., Takahashi, M. and Li, X. [2003] Volume changes in sandstone under true triaxial compression conditions. *Proc. 10th Int. Congr. Rock Mech.*, 8–12 September, Sandton, 683-688.

Mogi, K. [1971] Fracture and flow of rocks under high triaxial compression. *Journal of Geophysical Research*, **76**, 1255-1269.

Popp, T. and Salzer, K. [2007] Anisotropy of seismic and mechanical properties of Opalinus clay during triaxial deformation in a multi-anvil apparatus. *Physics and Chemistry of the Earth*, **32**, 879-888.

Takahashi, M. and Koide, H. [1989] Effect of the intermediate principal stress on strength and deformation behavior of sedimentary rocks at the depth shallower than 2000 m. *ISRM International Symposium*, Pau, France.

Wiebols, G.A. and Cook, N.G.W. [1968] An energy criterion for the strength of rock in polyaxial compression. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **5**, 529-549.