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Mechanical Behaviour of an Anisotropic Porous Sandstone Affected by Different Loading Histories and Rates

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Abstract. Results of an extensive experimental study on mechanical properties of an anisotropic sandstone subjected to different loading histories and loading rates during monotonic and cyclic loading are presented. Cyclic loading test were performed in uniaxial and triaxial condition and loading rate tests were undertaken under unconfined condition. The mechanical properties of the rock were altered by cyclic loading; dependent upon the applied stress level during cyclic loading the rock may become weaker or stronger as a result of cyclic loading. The strength and the stiffness of the sandstone were increased with an increase in loading rate. In addition, it was found that increase of loading rate will increase fatigue life during cyclic loading.

Introduction

Rock material in engineering projects is frequently exposed to different loading rates and cyclic loadings. The mechanical properties of the rock are altered by cyclic loading and loading rates and consequently rock may fail at stress levels lower than the monotonic failure stress.

Effects of cyclic loading on mechanical properties of geomaterials have been studied by several researchers. Some researchers have found that the decrease in peak strength by cyclic loading is insignificant [1-2]. Along with this, others [3-4] discusses, however, that in some cases the cyclic loading may increase rock strength. In contrast to the previous studies, the cyclic loading can often also cause rock to fail at a stress lower than its determined compressive strength [5-7].

Additionally, behaviour of rocks under different loading rates has been studied by many researchers. Several studies confirm increasing of peak strength with an increase in loading rate [8-9]. However, others couldn't find any conclusive trend between rock strength and loading rate [10]. Loading rate dependency of rock material heavily depends on material properties, testing condition and the adopted loading rate. The scatter between outcomes of previous studies in different rocks is even more significant when it comes to rock deformability properties [11-12].

Porous sandstones formed underneath the seabeds or lands contain a large amount of inter-granular pore spaces. Due to this granular property, sandstones create subsurface energy basins by trapping hydrocarbons in the form of petroleum and natural gas. In order to make use of these resources, sandstones will need to be drilled to allow for resource extraction. Therefore, it is important to understand the change in properties of this type of rock subjected to different loading conditions. However, there are very limited studies in this area. For this study the Hawkesbury sandstone which is a medium-strong sedimentary rock is selected to investigate the effect of cyclic loading and loading rate during monotonic loading and cyclic loading on mechanical behaviour.

Experimental set-up

The rock samples were cored from two similar blocks to a cylindrical shape. The rock samples were cored to have a diameter of 42 mm, with a length of 100mm, resulting in a constant aspect ratios (length: diameter) at 2.4. They were then ground smooth on all surfaces to ensure even contact with the platen of the machine compression arm with reduced chances for bedding error. A closed-loop servo-controlled testing machine with a loading capacity of 250 kN and a loading rate capability in the range 0.001–10mm/s were used. The load and strain data are acquired automatically by a data acquisition system. Cyclic loading tests were performed in triaxial condition, under 4 MPa confining pressure, whereas, effect of loading rate on properties were investigated by a series of uniaxial monotonic and cyclic loading testing.

Based on a study performed by [13], the Hawkesbury sandstone is not entirely a homogenous rock. To remove variations among samples they cored all the samples in a same direction using a rock block. However, the uniaxial compressive strength of the samples were varied up to 25%. To solve this problem, recently a method to predict rock peak strength, without failing the specimen has been developed [14]. In order to analyze the effect of cyclic loading and loading rate on rock mechanical properties, it is essential to eliminate the effect of sample variation. As a results the method developed by Taheri et al. [14] is implemented in this study.

Effect of Cyclic Loading on Behaviour

Fig. 1a shows results of several cyclic tests in 100% unloading amplitude where sample is failed during cyclic loading. The figure confirms that a higher value of q_{un}/q_f (unloading deviator stress normalized by the peak strength) at unloading will result in failure after fewer cycles.

Several samples, however, didn't fail during cyclic loading after at least 1300 cycles. Therefore a monotonic load was applied until failure. It was found that in all the tests which did not fail due to cyclic loading, the deviator stress at failure was higher than the monotonic peak strength. This indicates that the strength of the rock specimens increased as a result of cyclic loading. In other words, if the stress level at the beginning of cyclic loading is not high enough to generate a failure in sandstone due to progressive cyclic loading damage, the rock strength, as a result of cyclic loading for a long period of time, may be increased. Fig. 1b shows the results of tests in different unloading amplitudes (i.e. 50%, 75% and 100%). Based on these results it is hypothesised that there exists a value of q_{un}/q_f which lies between 93% and 94% that indicates the critical boundary of rock strength hardening and weakening under cyclic loading. This boundary is called herein the crack damage stress. Fig. 1b shows that an increase in fatigue strength is directly proportional to the normalised deviator stress, q_{un}/q_f in unloading. In this way, increase of peak strength with cyclic loading decreases with a decrease in q_{un}/q_f. In addition, peak strength increase reduces if unloading amplitude during cyclic loading decreases.

To quantify the effects of cyclic loading on deformability for both cyclic hardening and cyclic damage tests. Tangent Young's modulus (E_{tan}) and Poisson' ratio (v) values were determined at 50% of unloading strength (q_{un}) for each loading cycle and presented in Fig. 2. As can be seen in Fig. 2a for a cyclic damage test, there is a continuous degradation in E_{tan}, until beginning of large plastic deformation, after which there is a rapid decrease in stiffness until failure. Moreover, it may be seen that v, initially increases rapidly, followed by a stage of slower accumulation and then it begins to rapidly increase as the rock approaches failure. In general, the increase of Poisson's ratio and the degradation of stiffness indicate the progressive accumulation of damage in the rock sample over the loading cycles.

Fig. 2b gives an example of results for a cyclic hardening test. The stiffness and Poisson's ratio values resulted from cyclic hardening tests indicate that the behaviour of the sample is significantly different from those presented in Fig. 2a. E_{tan} and v values for the cyclic hardening test remained fairly constant with cycle loading. Even, E_{tan} slightly increased (from 0 to 2GPa) between the first and last loading cycle. This suggests that cyclic loading causes existing pores to be closed and therefore, the sample is experiencing compaction.

Effect of Loading Rate on Behaviour – Monotonic Loading

Fig. 3a shows normalized peak strength, q_f/q_{f1} (q_{f1} is equal to peak strength in the basic 0.05 mm/min loading rate), values versus different loading rates. As it may be seen in this figure, peak strength generally increases with an increase in loading rate. This demonstrated that the Hawkesbury sandstone can sustain more axial stress when subjected to higher loading rates. The sudden stress created by higher loading rate increase the rate of pores closure which allows the rock to sustain more stress before the development of critical lateral cracks dominating the failure.

Fig. 3b demonstrates relations between Tangent Young's modulus, E_{tan}, values and the shear stress ratio, q/q_{max}, at different loading rates. The figure clearly shows that rock stiffness increases with an increase in loading rate. This is mainly because, when the porous rock is under stress, the stiffness increases mainly due to the closure of existing voids and the collapse of weak elements. Higher loading rate exerts the stress on the rock with higher velocity which intensifies the crack closure, where under lower loading rate, more new micro-cracks have time to evolve along with the crack closure. Therefore the rock is less compacted at lower loading rate, which results in having lower stiffness.

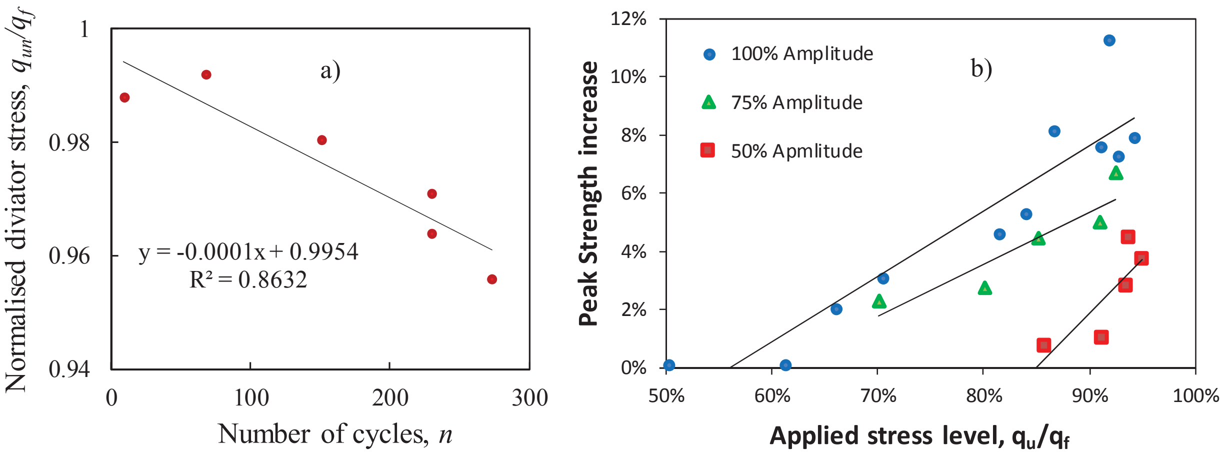

Figure 1: Effect of cyclic loading on peak strength; a) when unloading stress, q_u, is higher than the cyclic damage stress; b) when unloading stress, q_u, is smaller than the cyclic damage stress;

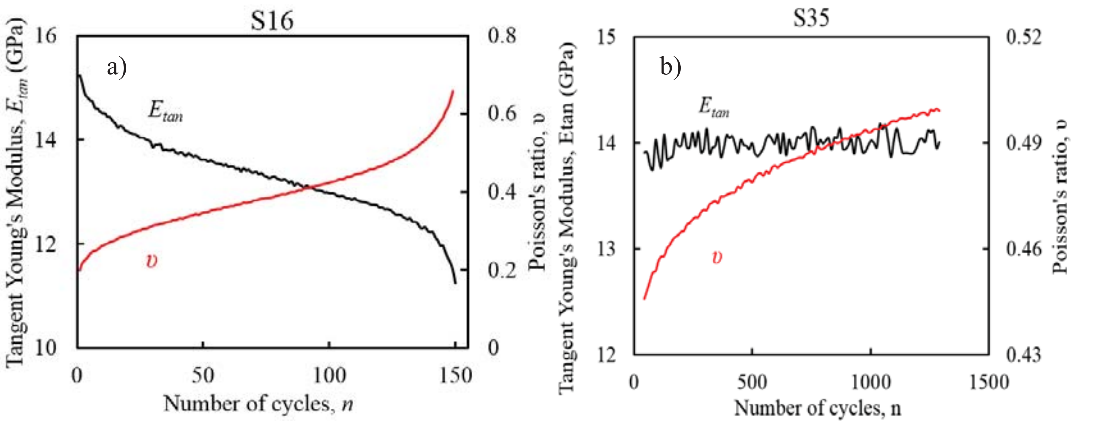

Figure 2: Rock deformability during cyclic loading; a) when unloading stress, q_u, is higher than the cyclic damage stress; b) when unloading stress, q_u, is smaller than the cyclic damage stress.

Effect of Loading Rate on Behaviour – Cyclic Loading

To study the effect of loading rate on progressive damage during cyclic loading, cyclic loading were carried out at q_{un}/q_f of 0.95 and loading rate was varied and it was set at 0.1, 0.5, 1, 5, 10 and 30 mm/min. Table 1 clearly shows that the number of cycles (damage increment) required to fail a sample increase with an increase in loading rate. This is mainly because higher loading rate exerts a sudden stress to the rock where the deformation cannot immediately transmit to every part of the body. As a result, part of the body remains undisturbed, which lead to more loading cycles prior to failure.

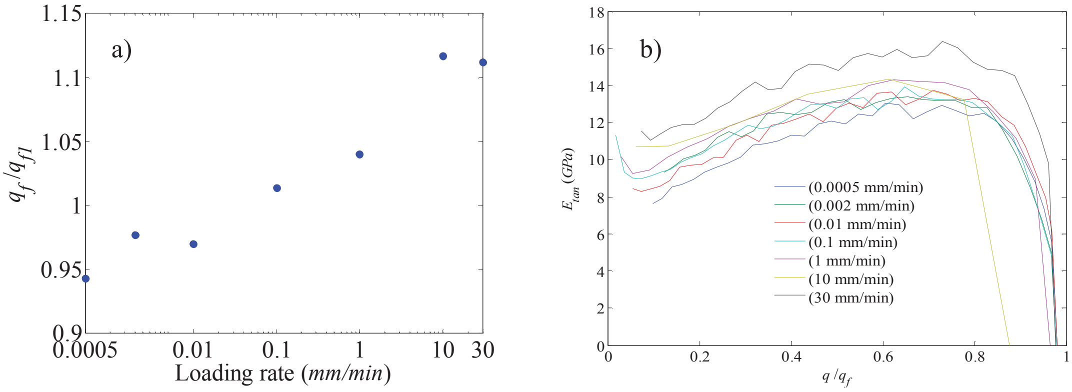

Figure 3: Effect of loading rate on mechanical properties in monotonic loading; a) on the peak strength; b) on the stiffness.

Table 1. Number of cycles obtained in cyclic loading tests with different loading rates

Loading rate (mm/min)	No. of cycles
0.1	2
0.5	8
1	9
5	15
10	43
30	27
30	33

Fig. 4 shows Young's modulus and Poisson's ratio values which were normalised using the value in the last cycle (i.e. the damaged sample) divided by the value in the first cycle (i.e. the intact sample) at 50% and 80% of unloading stress, q_u. As it may be seen in this figure, the normalised E_{tan} is found to decrease with an increase in loading rate. It indicates that more reduction in stiffness is resulted from the first cycle to the last cycle at higher loading rate. It is a reflection of longer fatigue life with an increase in loading rate. During longer fatigue life, progressive damage due to cyclic loading increases before the sample completely failure in an eruptive manner. In addition, the normalised v was found to increase with increase in loading rate. This indicates that more lateral deformation develops than axial deformation when the sample is subjected to higher loading rates. An increase in sample dilation during progressive damage also contributes to the increase in Poisson's ratio.

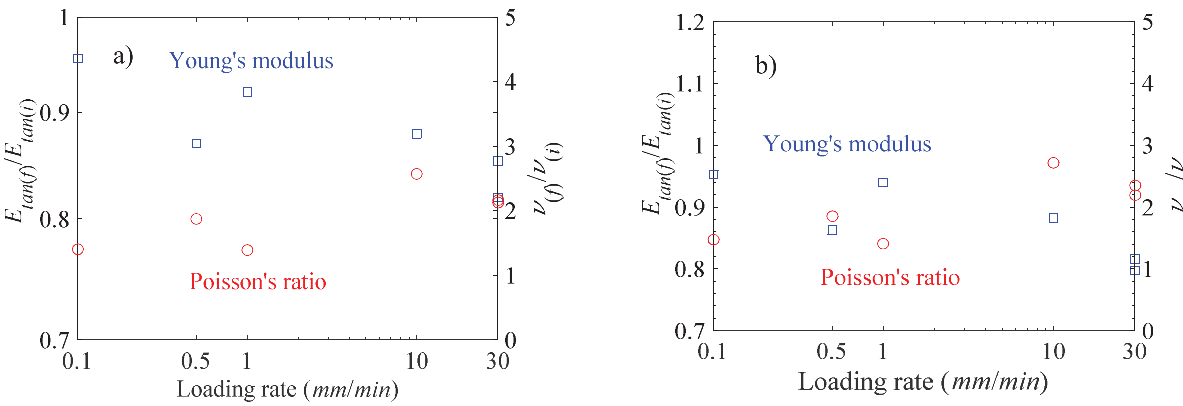

Figure 4: Young's modulus and Poisson's ratio variations during cyclic loadings; a) 50% stress level; b) 80% stress level.

Summary

Variation on the mechanical properties of an anisotropic sandstone were investigated through an extensive experimental study. Peak strength of the rock was altered by cyclic loading; dependent upon the applied stress level during cyclic loading the rock may become weaker or stronger as a result of cyclic loading. Variations of deformability properties during cyclic loading confirmed this argument. It was found that the amount of increase in peak strength decreases with a decrease in cyclic loading deviator stress. In addition, peak strength increase reduces if unloading amplitude during cyclic loading decreases. In monotonic uniaxial compressive loading, the peak strength and the stiffness sandstone were increased with an increase in loading rate. Fianlly, during cyclic loading it was found that the number of cycles (damage increment) required to fail a sample increase with an increase in loading rate. Due to this increase in fatigue life, degradation of stiffness and increase of Poisson's ratio during cyclic loading increased with an increase in loading rate.

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