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Water-weakening behavior of Hawkesbury sandstone in brittle regime

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ABSTRACT

This paper investigates the effect of water on the mechanical behavior of intact Hawkesbury sandstone, a massive rock formation in Sydney, Australia. Two sets of cylindrical samples — air-dried and water-saturated — were tested under the confining pressures of 4, 10, 18 and 25 MPa. Water-saturated samples were tested under undrained conditions with initial pore-water pressures of 1, 4, 7.2 and 10 MPa, respectively.

Initial pore-water pressure was observed to increase with increasing deviatoric stress during undrained tests and the maximum induced pore-water pressure was observed to increase with increasing effective confining pressure. Peak effective strength showed an increasing trend with increasing confining pressure for both sample sets and the strengths of dry samples were always greater. Peak strength drops of 13.36%, 25.27%, 34.70% and 38.12% were observed due to water at the confining pressures of 4, 10, 18 and 25 MPa, respectively. Results for the residual strength of tested samples displayed that it increased with increasing confining pressure for both sample sets. The volumetric strain response revealed that the volume reduction due to compaction increases with increasing confining pressure, and dilatancy-related volume increase close to sample failure was not significant at higher confining pressures for both sample sets. The samples tested under dry conditions showed a considerably higher volume reduction by compaction than that for the samples tested under undrained conditions. Analysis of failure mechanisms indicated that all samples failed mainly by shear localization, where the angle of the failure plane, measured from the minor principal stress direction, was varied from c.55° to c.45° for dry samples and from c.50° to c.40° for the samples tested under undrained conditions, at 4 and 25 MPa confining pressures, respectively. Fracture propagation behavior was studied using an acoustic emission detection system and the results demonstrated that the micro-crack initiation occurred very close to the failure stress under low confining pressures, leading to a more brittle sudden failure, w\hereas under higher confining pressures it occurred relatively earlier, compared to the failure stress, showing more quasi-brittle characteristics.

1. Introduction

Crustal rocks contain a considerable amount of various interstitial fluids and in most cases that fluid is water (Price, 1975). Water in porous rock can influence its deformation properties such that a significant difference in mechanical behavior can be expected for a rock under water-saturated and dry conditions. Knowledge of the influence of water–rock interactions on the mechanical behavior of rock is important for solving a range of problems relevant to many rock mechanics applications such as mining, tunneling, sub-surface fluid waste disposal and radioactive waste storage (Hubbert and Rubey, 1959; Griggs and Handin, 1960; Reviron et al., 2009).

In saturated rocks, deformation can take place under drained or undrained hydrogeological conditions. Deformation under drained conditions allows the pore water to be expelled from the rock volume such that the change in pore-water pressure is negligible, whereas under undrained conditions the total volume of pore water is a constant, and the pore-water pressure therefore fluctuates during deformation. In low permeable rocks, fluid flow is dominant through discontinuities. If the discontinuities are sealed or clogged, undrained conditions are more likely to prevail during their deformation. Conversely, permeable rocks, in which a considerable fluid flow occurs through the rock matrix, usually undergo drained deformation under slow/medium deformation rates. However, undrained deformations can be expected even in permeable rocks if the boundaries of the rock volume are sealed in a global sense (for example, a permeable rock mass surrounded by an impermeable rock layer). In addition, rapid deformation of rock (occurs in cases such as seismic events), where the pore water does not have sufficient time to be expelled from the rock volume, also causes undrained deformation of rock. Moreover, man-made alterations to rock masses, such as shotcreting a rock surface without adequate drainage, can create local undrained conditions within rock masses. As Aldrich (1969) stated, in *in-situ* rock masses pore-water pressure is more likely to fluctuate such that undrained conditions better describe

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real-world rock behavior. Therefore, it is clear that while the understanding of the mechanical behavior of rock under drained conditions is important, considerable effort should also be made to understand the mechanical behavior of rock under undrained conditions.

Rocks experience different stress conditions (i.e. different confining pressures and pore-water pressures) at different depths, and the degree of influence of water on the mechanical behavior of rock is different at different depths. Laboratory tests are very often used to study the behavior of rock under different confining and pore-water pressures and it is very important to use realistic stress conditions (confining and pore-water pressure) relevant to different depths in laboratory experiments such that the results are more representative of real-world rock behavior.

This paper experimentally investigates the water-weakening behavior of Hawkesbury sandstone in brittle regime, where we compare the mechanical behavior of Hawkesbury sandstone under dry conditions and undrained conditions. For testing, we used approximated field stress conditions relevant to different depths (i.e. confining pressure and equivalent pore-water pressure). A brief review of the important outcomes of related previous studies is presented in the next section, followed by the Experimental method and Results and discussion sections of the present study.

2. Previous studies

A considerable number of research studies have been carried out to investigate the effect of water on the mechanical behavior of different types of rock, and Hawkesbury sandstone has been used by several researchers for different types of studies. Outcomes of the most pertinent previous research studies relevant to the effect of water on rock mechanical behavior and mechanical behavior of Hawkesbury sandstone are discussed in the next two sub-sections.

2.1. Effect of water on rock strength

In general, water tends to reduce rock strength and this is known as water-weakening. The water-weakening behavior of rock is the result of one or a combination of two possible effects; (1) mechanical effects, which arise when pressurized pore water weakens the rock skeleton (pore-water pressure decreases the effective strength of the rock mass, meaning that fracture strength decreases, resulting in lower strength) (Paterson, 1978; Baud et al., 2000; Paterson and Wong, 2005) and (2) chemical effects, which basically account for the modifications of the cohesive strength of the constituent grains of rock when they are in contact with water (Swolfs, 1972; Martin and Durham, 1975; Dunning et al., 1984; Atkinson and Meredith, 1987; Althaus et al., 1994). Both these effects tend to reduce the strength of rock through a reduction in surface free energy or sub-critical cracking mechanisms such as stress corrosion, or a combination of both (Michalske and Freiman, 1982; Atkinson, 1984).

Previous studies have shown that the effect of water on the strength of rock is highly variable across different types of rocks. This is understandable, as the physico-chemical interactions between water and the constituent of rock grains are largely influenced by mineralogical composition, pore volume and shape, grain size and other microstructural properties, which vary greatly between different rock types. However, the effect of water is more pronounced in clay-rich rocks than in quartz-rich rocks (Goodman, 1989). Clay minerals in water-saturated rock weaken its strength by two mechanisms; chemical reactions with water (Cook, 1999; Demarco et al., 2007) and reducing the frictional coefficient of rock (Byerlee, 1978; Morrow et al., 2000). Uniaxial compressive strength (UCS) testing performed on quartzitic sandstone by Colback and Wiid (1965) showed a UCS reduction of 50% upon the presence of water, which is a significant strength reduction for sandstone. They postulated that the strength reduction is due to lowering the tensile strength, which is a function of the molecular cohesive strength of the material. Duperret et al. (2005) also observed an appreciable UCS loss of 41% due to water in their experiments on Chalk. However, Alm (1982) found only 5% of UCS difference between dry and saturated Aplite specimens, which is a very different result to those of Colback and Wiid (1965) and Alm (1982). Catane et al. (2007) reported a significant strength loss due to water, which was as high as 89% for Diliman Tuff. Vasarhelyi (2005) revealed an average UCS reduction of 44% for Miocene limestone. Triaxial testing on Berea, Boise, Darley Dale and Gosford sandstones was conducted by Baud et al. (2000) in both brittle faulting and cataclastic flow regimes (testing on Gosford sandstone in brittle faulting regime was however not performed). Within the brittle faulting regime, they observed a strength loss ranging from 5% to 17%, whereas in the cataclastic flow regime it varied between 20% and 70%. Hadizadeh and Law (1991) reported a strength reduction of 55% due to water for Pennant sandstone. In contrast, Reviron et al. (2009) did not observe any notable effect of water on the critical stress levels of Bentheim sandstone under drained triaxial conditions and they postulated that the absence of clay minerals and the quasi-excusive presence of quartz grains bonded together by a quartzose cement are responsible for that. In a more recent study, Duda and Renner (2012) reported a strength reduction of 23%, 13% and 16% for Ruhr sandstone, Wilkeson sandstone and Fontainebleau sandstone, respectively, after carrying out testing under triaxial conditions. Studies on the water-weakening behavior of crystalline rocks are relatively rare in the literature. Peschel (1974) stated that the weakening of the compressive strength due to water saturation in igneous and metamorphic rocks is around 3–15%.

The highly variable nature of water-weakening characteristics across different types of rock has precluded the development of a single general criterion to describe the water-weakening behavior of rock subjected to different stress conditions. Even for the same rock type, depending on the mineralogical and geomechanical properties at different locations, water-weakening behavior may differ. Therefore, different important rocks need independent investigations in order to understand their respective water-weakening characteristics.

2.2. Research on Hawkesbury sandstone

Hawkesbury sandstone dominates the landscape in a radius of 100 km in Sydney, Australia, covering an area of approximately 12,500 km^2. Fig. 1 shows the location of the Sydney basin where the Hawkesbury sandstone is found.

This sandstone is of the Triassic period and according to Spry (2000), there are six prominent classifications, drawn primarily from the color and color change of the sandstone. Herbert and Helby (1980) divided Hawkesbury sandstone in to three facies; sheet facies, massive facies and mudstone facies, of which the first two facies encompass 95% of the formation. Petrographic analyses by Standard (1969) revealed the average mineralogical compositions of Hawkesbury sandstone and according to him the main minerals include 68% of detrital quartz grains, 20% of clay matrix, 6% of secondary quartz, 4% of siderite, 2% lithic fragments and feldspar and mica of 1% each. Standard (1969) further reported that the sandstone is medium- to coarse-grained and moderately to well graded.

Some engineering properties of this sandstone have been reported in Pells (2004) in which the dry UCS varies from 23.2 MPa to 99.8 MPa and saturated UCS varies from 9.4 MPa to 39.7 MPa, showing water-weakening in the range of 33% to 70%. Triaxial tests performed by Pells (1977) revealed that the effective cohesion and effective friction angle of this sandstone varies between 2.4 and 6 MPa and 41°–53°, respectively. Cohesion and friction angle were found to be 2.3 MPa and 50° by Gu et al. (2005), and they further found a sliding friction angle of 32° for Hawkesbury sandstone. According to Ord et al. (1991), Hawkesbury sandstone has a poorly-connected porosity of c.5% and bulk density of c.2230 kg/m^3.

Apart from the testing performed to determine its fundamental mechanical properties, Hawkesbury sandstone has been used for some