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Damage evolution and deformation behaviour of dry and saturated sandstones: Insights gleaned from optical measurements

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ABSTRACT

Microscopic properties have a marked influence on the macroscopic mechanical response of sandstones. Improved understanding of the mechanical behaviour of these rocks caused by their microscopic properties is imperative for the successful design of rock structures. Here we experimentally investigate the damage evolution and deformation behaviour of three types of sandstones from Australia with contrasting petrographic properties under dry and saturated conditions with the aid of an optical strain and deformation measurement system (ARAMIS camera). More accurate and representative strain measurements are obtained using ARAMIS camera images compared to conventional strain measurement techniques. The results revealed that the quartz content of sandstone alone is not indicative of its strength, as the sandstone with the highest quartz content showed the lowest strength and this was attributed to the superior influence of other microscopic properties, such as grain size and porosity. However, the quartz content displayed a significant influence on the water-weakening behaviour of the sandstones, where the sandstone with the greatest quartz content was least affected by saturation and the sandstones with considerable clay mineral content showed greater weakening due to water. It was also found that some clay minerals are susceptible to swelling in the presence of water, and this can increase the initial crack volume and affect deformation characteristics. ARAMIS camera images clearly illustrated a more brittle behaviour by the sandstone with the greatest quartz content and notable early deformation by the sandstones with greater clay mineral content. Moreover, it was found that the overall deformation of sandstones was influenced by the swelling capacity of the constituent clay minerals, in addition to their composition by percentage.

1. Introduction

The macroscopic mechanical behaviour of granular rocks is influenced by their microscopic properties, including their mineralogical composition, grain size, grain packing characteristics and porosity. Typical granular rocks such as sandstones are made up of three components – grains, pores and cement – and one or more of these constitutive elements undergo changes in shape and size during deformation [4]. The skeleton of granular rocks is formed of grains, while the pores act as flaws and concentrate stresses that may lead to macroscopic failure. Inter-granular movements are resisted by the cement, and cement also assists the distribution of contact forces. The petrographic properties of sandstones vary greatly depending on their geological history, and this has often led to an appreciable variation of their mechanical properties, in particular, their strength and deformation behaviour [7,46]. Previous studies, such as Hsieh et al. [22], Ulusay et al. [44], Shakoor and Bonelly [39] and Richards and Bell [38], have also highlighted the importance of the microscopic properties of sandstones for their macroscopic mechanical behaviour.

Rocks in engineering applications often encounter water and the presence of water in rocks is usually detrimental to their mechanical properties [47,27,22,36]. Understanding of the nature of water-rock interactions in saturated rocks and consequent modifications of the mechanical response are crucial for solving a range of problems related to many rock mechanics and rock engineering applications, including mining, tunneling, sub-surface fluid waste disposal, and radioactive waste storage [37,23]. The water-weakening behaviour (i.e. the weakening of mechanical properties in the presence of water) of sandstones is influenced by their microscopic properties in addition to the moisture level.

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The mechanical behaviour of different types of rocks under both dry and saturated conditions has been studied by many researchers using different techniques. In this paper, we experimentally investigate the damage evolution and deformation behaviour of three types of sandstones, obtained from three different locations in Australia and with different microscopic properties, under both dry and saturated states and under uniaxial compression. Understanding the behavior of rock under uniaxial compression has important direct implications to several rock mechanics and rock engineering applications as stated by many researchers in the literature (e.g. [40,29,28]). In particular, here we use an advanced optical strain and deformation measurement system to gain some critical insights in to the damage evolution and deformation behaviours of the selected sandstones. A comprehensive review of the results of the most relevant previous studies is presented next, followed by the experimental procedure and the results and discussion.

2. Previous studies

Microscopic properties and saturation play different roles on the mechanical behaviour of granular rocks and we review below some of the key findings related to both aspects. To keep the review concise and pertinent, here we focus mainly on sandstone.

2.1. Effect of microscopic properties on rock mechanical behaviour

Failure of granular rock under compression is progressive and initiated with the growth of grain-scale microcracks, which then coalesce to form fracture zones leading to macroscopic failure [52,49]). Therefore, the microstructural characteristics of rocks are of utmost importance for their macroscopic mechanical response. Microscopic properties, such as mineralogy, porosity and grain characteristics, have a great influence on the macroscopic mechanical behaviour of granular rocks among others.

From a minerological point of view, quartz-rich sandstones are abundant around the world. Other common minerals found in sandstones include feldspar, kaolinite, calcite and rutile. As the contents of minerals other than quartz, when present, are generally small, the relationship between mineralogy and mechanical properties has been mainly studied in relation to quartz content. Gunsallus and Kulhawy [19] and Shakoor and Bonelli [39] observed a definite relationship between quartz content and the uniaxial compressive strength (UCS) of the sandstones they studied. In contrast, Bell [6] did not observe a noteworthy relationship between the UCS of Fell sandstone and its quartz content. Bell and Culshaw [7] did not observe a statistically significant relationship between strength and quartz content for sandstones of the Sneinton Formation in supportive of the Bell [6] observations. In a contrasting study, Ulusay et al. [44] found that the influence of the textural characteristics is more important than the mineralogy for the prediction of the engineering properties of the Litharenite sandstone they tested. Richard and Bell [38], in support of Ulusay et al. [44], suggested that an increase in silica cement, in the form of quartz overgrowths, leads to an increase of the strength of sandstones of the Natal group. Contrasting observations such as those above suggest that the minerology may vary significantly across different sandstones and the nature of its influence on rock mechanical properties can be unpredictable.

For some sandstones, porosity dominates the petrographic parameters that influence their mechanical behaviour. For instances, Jeng et al. [25] reported that porosity has more influence on the UCS than the grain and matrix content of tertiary sandstone in Taiwan, and Palchik [32] found that the amount of textural characteristics of porosity is much more significant than the mean grain size of porous Donetsk sandstone. In general, lower porosities result in higher strength and modulus, as lower porosities means more space is occupied by grains and cement which stiffen the rock skeleton, and the vast majority of previous studies agree with this behaviour (e.g. [35,6,11],Yang et al. [53,7,39].

Different characteristics of grains and their distribution patterns have been used in the literature to correlate them with the mechanical properties of rock. However, the mean grain size (the mean diameter of grains) is the most common. While studies such as Shakoor and Bonelli [39] and Palchik [32] report no strong correlation between the grain size and the fracturing strength of rock, numerous other studies have shown that the compressive strength of rock correlates inversely with the square root of grain size (e.g. [8,30,24,15,52,21,26].

Griffith's crack theory [18] provides a theoretical basis for this experimentally- observed relationship between compressive strength and mean grain size. Griffith's theory for an elliptical crack loaded in compression is shown in Eq. (1):

$$\sigma_c \geqslant 8* \sqrt{\frac{2E\alpha}{\pi c}} \tag{1}$$

where, σ_c is the compressive stress required for fracture, E is the elastic or Young's modulus, α is the surface energy per unit area of the crack surfaces, and c is the crack half-length.

According to Hatzor and Palchik [21], it has been common to assume in rock mechanics applications that the grain boundaries can function as potential 'Griffith cracks'. Therefore, Eq. (1) depicts that the compressive strength is proportional to the inverse square root of grain size. However, Wong et al. [52] found that the crack length of Yuen Long marble is approximately equal to the grain size for grain diameters < 50 μm, but the crack length is only approximately 20% of the grain size for grain diameters greater than 300 μm. Nevertheless, they observed a general trend of increasing crack length with increasing grain size. Moreover, Hatzor and Palchik [21] tested Dolomite specimens and showed that the assumption that the initial flaw size is equal to the mean grain size is valid only in the very restricted case of low porosity-low grain size rocks. In such rocks, the mean grain size significantly influences the crack initiation stress as a result of the minimal voids in the rock texture and the available crystal faces may function as true initial flaws. Furthermore, Hatzor and Palchik [21] found that in high porosity rocks the crack initiation stress is much less sensitive to variations in mean grain size.

2.2. Water-weakening behaviour of rock

Water-weakening is a concern in many situations related to rock mechanics, such as a dry rock slope subjected to heavy rainfall and the crown settlement of an excavation tunnel due to the seepage of water inside the tunnel [27]. Weakening of rock properties due to water may be a result of either mechanical effects [33,34,5] or chemical effects [13,41,1,3]) or both. According to Atkinson [2], both these effects tend to reduce the strength of rock through the reduction in surface free energy or sub-critical cracking mechanisms such as stress corrosion, or a combination of both. In general, water-weakening is more pronounced in clay-rich rocks than in quartz-rich rocks [17]. Table 1 presents some of the data on the strength reduction of different sandstones due to water published in the literature.

It can be seen from Table 1 that the strength reduction of sandstones due to water can vary from zero to as high as *ca* 86%.

3. Experimental work

The experimental work reported here included petrographic analyses of test materials, in order to characterize their microscopic properties, and a series of UCS tests on test specimens under both dry and saturated conditions. In particular, an optical strain and deformation measuring system was employed during all tests to scrutinize the damage evolution and deformation characteristics of the specimens.