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Strength characteristics of dry and saturated rock at different strain rates

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Abstract: The strength of rock materials is largely affected by water and loading conditions, but there are few studies on mechanical properties of saturated rocks at high strain rates. Through compressive tests on dry and saturated sandstone specimens, it was found that the dynamic compressive strength of both dry and saturated sandstone specimens increased with the increase of strain rates. The saturated rock specimens showed stronger rate dependence than the dry ones. The water affecting factor (WAF), as the ratio of the strength under dry state to that under saturated state, was introduced to describe the influence of water on the compressive strength at different strain rates. The WAF under static load was close to 1.38, and decreased with the increase of strain rate. When the strain rate reached 190 s^{-1}, the WAF reduced to 0.98. It indicates that the compressive strength of saturated specimens can be higher than that of dry ones when the strain rate is high enough. Furthermore, the dual effects of water and strain rate on the strength of rock were discussed based on sliding crack model, which provided a good explanation for the experimental results.

Key words: rock; strength; strain rate; saturated rock

1 Introduction

Water plays an important role in controlling the strength of rocks. In order to investigate the influences of water on the strength of rock material, the static compressive strength of saturated rock materials has been widely studied. COLBACK and WIID [1] showed that the uniaxial compressive strength of well-saturated quartzitic sandstone could reduce up to 50%. BROCH [2] reported the unconfined compressive strength reductions of 33%−53% for phaneritic igneous and metamorphic rocks of low porosity (0.3%−1.2%) from dry to saturated state. HAWKINS and MCCONNELL [3] investigated the influence of water content on the strength and deformability of 35 different British sandstone rocks and proposed an empirical relationship between water content and uniaxial compressive strength. VÁSÁRHELYI [4] also conducted a lot of experiments to investigate the effect of water saturation on the static properties of rocks and obtained the relationship between different perto-physical parameters. LI et al [5] accomplished a large amount of tests on two kinds of meta-sedimentary rock specimens (meta-siltstone and meta-sandstone) under triaxial compression, and found that when the state of rock specimen changed to wet from dry, the peak cohesion increased by about 3% while the friction angle decreased by 26% for meta-siltstone; and the peak cohesion increased by about 14% while the friction angle decreased by 10% for meta-sandstone. From the above, it is commonly understood that the static compressive strength of fully saturated rock materials is usually smaller than that of dry ones.

However, all the researches mentioned above were based on static tests, limited studies can be found on the dynamic properties of saturated rocks. In fact, the rock and rock mass are usually broken and failed dynamically in rock engineering applications, such as impact, explosion, rock burst and seismic events, thus the investigation on the dynamic compressive strength weakened by water is greatly meaningful to assess the stability of rock structure and control the hazard of rock engineering. To examine the effect of water on dynamic tensile strength, OGATA et al [6] conducted a series of SHPB experiments at high porosity sandstone in both dry and saturated state and claimed that water reduced dynamic tensile strength as in the dry state. HUANG et al [7] investigated the water-weakening effect on the

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tensile strength of Longyou sandstone with a wide range of loading rates, their experimental results demonstrated that the tensile strength of sandstone is water softening and the softening factor decreases with the increase of loading rate. ZHOU et al [8] carried out lots of impact tests on sandstone with different water contents, and found that when the strain rate is 100 s^{-1}, both of dynamic compressive and tensile strengths of rock decrease with the increase of water content. By now, the properties and the water-weakening mechanisms of rock under dynamic compression are not acceptable universally. Thus, more information about the effect of water on the dynamic properties of rocks at different strain rates should be investigated.

In this study, tests have been conducted on both dry and saturated sandstone specimens in a wide range of strain rates by means of the INSTRON and Split Hopkinson Pressure Bar (SHPB) setup, the strength with the same strain rate but different saturation states was compared, and the strain rate sensitivity of the compressive strength was also examined. In addition, different rate sensitivity and variation of strength of both dry and saturated sandstone specimens were explained based on the sliding crack model.

2 Experimental

2.1 Specimen preparation

The rock material was a fine-grained sandstone. The mineral composition of this sandstone was determined by X-ray diffraction (XRD). It consists of 55% quartz, 23% feldspar, 9% mica, 6% calcite, 3% chlorite and a few clay minerals (1%−4%). Some essential physical properties of the sandstone were measured as density 2337.5 kg/m^3, porosity 6.2%, and P-wave velocity 2640.9 m/s.

All specimens were extracted from a single sandstone block which had high geometrical integrity and petro-graphic uniformity. They were manufactured in accordance with the standards in the ISRM (International Society for Rock Mechanics) suggested specification [9]. The ends of specimens were polished to ensure the surface roughness less than 0.02 mm and the end surface perpendicularity to its axis less than 0.001 rad. After the measurement of the dimensions of all specimens, the P-wave velocities of all specimens were also measured to pick out specimens with similar velocity for the tests.

The static compressive tests were conducted on INSTRON system. The average static compressive strength of the dry specimens was 34.8 MPa, and that of the saturated ones was 25.5 MPa.

2.2 SHPB technique and its principle

SHPB is a very popular and promising experimental technique for the study of material behaviors at different strain rates for its easy operation and accurate results [9]. As shown in Fig. 1, the SHPB system, modified by LI et al [10,11], consists of a cone-shaped striker bar, an input bar, an output bar and an absorption bar, which are made of high strength 40Cr steel with a density of 7800 kg/m^3, an elastic modulus of 250 GPa and a yield strength of 800 MPa.

During a test, the cone-shaped striker bar was shot out from the gas gun at a high velocity and impacted the front end of the input bar. Then, a half-sine wave (input wave) was generated and propagated along the input bar towards the specimen. Once the wave reached the bar/specimen interface, a part of it was reflected, whilst the remaining part went through the specimen and transmitted into the output bar. By collecting signals on the input and output bars (Fig. 1), the dynamic parameters of the specimen can be obtained.

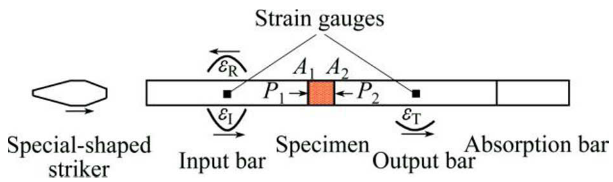

Fig. 1 Schematic of SHPB technique

In Fig. 1, A_1 denotes the input bar/specimen interface and A_2 represents the specimen/output bar interface. ε represents the measured signals on the bars, where the subscripts I, R and T represent incident, reflected and transmitted pulses, respectively. The arrowheads show the direction of wave propagation. According to SHPB principles, the relationship of the stress, strain and strain rate of the specimen can be derived as follows:

$$\sigma(t)=\frac{A_e E_e}{2A_s}[\varepsilon_I(t)+\varepsilon_R(t)+\varepsilon_T(t)] \quad (1)$$

$$\varepsilon(t)=\frac{C_e}{L_s}\int_0^t[\varepsilon_I(t)-\varepsilon_R(t)-\varepsilon_T(t)]dt \quad (2)$$

$$\dot{\varepsilon}(t)=\frac{C_e}{L_s}[\varepsilon_I(t)-\varepsilon_R(t)-\varepsilon_T(t)] \quad (3)$$

where A_e, C_e and E_e are the cross sectional area (mm^2), wave velocity (km/s) and elastic modulus of elastic bars (GPa), and A_s and L_s are the cross-sectional area (mm^2) and length of the specimen (mm), respectively.

2.3 Experimental program

A total of 60 specimens were prepared in dynamic compressive tests. Firstly, specimens were placed in a 105 °C oven long enough to reach the completely dry state, then the dry masses of the specimens were measured after they had cooled down to room