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Influence of free water on dynamic behavior of dam concrete under biaxial compression

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HIGHLIGHTS

- Concrete is subjected to biaxial compression under different strain rates.
- The strength of dry and saturated concrete increases with increasing strain rate.
- The strengths and DIF of strengths of dam concretes under dynamic biaxial loading are described.
- The dynamic biaxial compression failure criterion of saturated dam concrete is established.

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ABSTRACT

The effect of saturation coupled with loading rate on the behavior of dam concrete was investigated under the biaxial compression. Dynamic biaxial compressive experiments on dam concrete cubes with an edge length of 250 mm (dry and saturated) were carried out using a large static and dynamic triaxial electro-hydraulic servo multiaxial testing system. The specimens were loaded in biaxial compressive stress states (with the stress ratios of 0:1, 0.25:1, 0.5:1, 0.75:1 and 1:1 respectively) under static and a series of dynamic loading velocities (with strain rates ranging from 10^{-5}/s to 10^{-2}/s). The ultimate strengths of dry and saturated concretes were found to increase with the increase of strain rate, while the damage pattern and ultimate strength are closely related to the magnitude of lateral pressure exerted on the specimen. In addition, the dynamic failure criterion is proposed to characterize both the effects of strain rate and water content on the ultimate strength of dam concrete under biaxial compressive stress states. By testing dry and saturated specimens, the effect of water content on concrete strength was also examined. The experimental results indicate that the static compressive strengths of saturated concrete are lower than those of concrete in dry state, but on the contrary the dynamic strengths of saturated concrete is higher than those of concrete in dry state. The strain rate effect on strength of saturated concrete is more significant than that of dry concrete in lateral confining pressure, indicating that the saturated concrete is more rate-sensitive than dry concrete. As explained through a basic mechanical analysis, this dissimilarity is mainly attributed to the inertia effect and the viscosity of pore-water inside the saturated concrete during fast (quasi-static or dynamic) loading.

1. Introduction

Concrete is one of the most commonly used building materials. It is applied to build house, dam, port, bridge, nuclear safety shell, etc. And concrete structures suffer not only static loads but also dynamic loads such as wave stroke, earthquake, impact, explosion etc. Under such dynamic conditions, the strain-rate causes the material behavior to be significantly different from what is observed under quasi-static conditions. As well known, strength of concrete depends on the rate of loading, and the values of strength increase as the stress or strain rate increases.

Much research has been conducted since Abrams [1] observed the rate-sensitive behavior of concrete when he carried out compressive tests in 1917. There are many research achievements [2–9] about the rate features of concrete. Bischoff and Perry [10] reviewed the test results of concrete in dynamic compressive loading. Malvar and Ross [11] summarized the test results of concrete in dynamic tensile loading. Bicanic and Zienkiewicz [12] general-

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ized the dynamic behavior of concrete based on the experimental results in uniaxial stress state and established dynamic constitutive model.

In recent years, a lot of efforts have been dedicated in the dynamic behavior, only in uniaxial tension and compression. Partly because of the difficulty in conducting multiaxial dynamic experiments, few tests have been reported in the literature concerning the strength and deformation of concrete subjected to varying strain rates and confining pressures. At present, a great deal of experimental research on the deformation and strength of the common small-aggregate concrete has been carried out [13–16], but multiaxial experiments on large-aggregate concrete commonly used in hydraulic engineering are seldom done, except for a few biaxial experiments on large-aggregate concrete carried out by Song et al. [17].

In practical engineering, large-aggregate concrete is often used in hydraulic engineering such as various gravity dams and arch dams, etc. Concrete structures, such as dams, bridge piers, offshore structures, and marine petroleum platforms, often serve in ambient water, and the water content of concrete will have a certain influence on the mechanical behavior. Therefore the concrete could be in saturated or unsaturated states due to water pressure and different types of original defects in the concrete. In the past few decades, many works about the effect of water content on the static properties of concrete have been performed [18–27]. The dynamic mechanical properties of concrete are supposed to be affected by free water in the concrete defects, however very few references about the influence of water content on dynamic properties of concrete could be found. It is very important to conduct special experiments to investigate the mechanical properties of concrete with respect to saturation effect and loading rates in order to facilitate the dynamic performance analysis of hydraulic structures accurately.

As is well known, concrete material is sensitive to the rate of loading. Many studies have been undertaken on the behavior of concrete under uniaxial dynamic loading, as reviewed by Bischoff and Perry [10] for uniaxial compression and by Malvar and Ross [11] for uniaxial tension. However, the dynamic characteristics of concrete under multiaxial stress state are still not well understood due to the lack of experimental data. Only limited dynamic multiaxial experimental studies of concrete under high loading rates have been carried out because of the difficulty for such type of test. From the available literature [28–33], it can be found that the dynamic strength of concrete under multiaxial compressive stress state is also higher that in static state, but the enhancing magnitude is less than that of concrete under uniaxial compressive loading. Consistent conclusions need more experimental and theoretical support. Up to now, researches about the effect of water content on the dynamic behavior of concrete have been focused on the uniaxial state with different moisture content at high strain rates [34,35]. It is shown that the strain rate effect of saturated concrete is more significant than that of normal concrete.

The effect of water content on the behavior of concrete is not taken into account in today's design code. For this reason, it is necessary to carry out experimental investigation into the mechanical behavior of saturated concrete, especially the quasi-static and dynamic characteristics under multiaxial stress state. In this paper, through large numbers of experiments, the strength of dam concrete under the condition of saturation has been studied in the stress state of biaxial compression under different strain rates (10^{-5}–10^{-2}/s). The experimental results of dry and saturated concrete have been analyzed. By fitting the dam concrete experimental data, the dynamic failure criterion is established in the stress state of biaxial compression.

2. Materials and experimental program

2.1. Materials and mix proportions

The three-graded concrete is commonly used in the upstream face of arch dam. To well match with the real mix proportion of dam concrete in the current study, the size grading of the three-graded coarse aggregate is determined as: large size stone (40–80 mm): mid size stone (20–40 mm): small size stone (5–20 mm) = 4:3:3. This composition of coarse aggregate is a traditional mixture in Chinese code for mix design of hydraulic concrete (DL/T5330-2005), in which the maximum size of the coarse aggregate is set as 80 mm. Meanwhile, the minimum length size of the specimen should not be less than three times of the maximum aggregate size according to the test code for hydraulic concrete (SL352-2006). As a result, the specimens in this paper were all designed as cubes with dimensions 250 × 250 × 250 mm. The cement was ordinary Portland cement, which was produced by Dalian Onoda Cement Plant and one-level fly ash. The mixtures contained fly ash to save cement and to reduce the heat of hydration for practical application. The sand was natural river sand with fineness modulus of 2.6. Table 1 shows the mix proportions by weight of the mixture dam concrete.

2.2. Casting and curing of specimens

The cement, sand, aggregate and fly ash were mixed for about 3 min, then water and water reducer were added, and mixed for two additional minutes. The specimens were vibrated to be dense and solid using a high frequency resistance vibrator. Specimens of 250 mm^3 cube were cast in steel moulds. After 24 h, the specimens were removed from the steel moulds and placed in a condition of 20 ± 3 °C and 95% RH (relative humidity) for 28 days. The six sides of the specimen were ground to ensure that the specimen had flat edges and right-angled corners. The specimens were divided into two batches: one was stored in fresh water till tested, and the other was naturally cured at room condition.

2.3. Apparatus and testing methods

Triaxial testing system used in this project is shown in Fig. 1. The multiaxial experiments were conducted on the servo-hydraulic multiaxial testing system designed by Dalian University of Technology, which made great contributions to the studies of concrete multiaxial constitutive and failure criterion [36–40]. This testing machine is capable of developing three independent compressive or tensile forces. The tensile and compressive loads can reach 1000 kN and 2500 kN, respectively. The loads are applied by means of six loading jacks that were equipped with spherical, self-aligning heads to obtain uniform distribution of stress on the specimens. Forces were measured by the calibrated loading cells with the accuracy of 0.1%. Meanwhile, the deformation was measured by linear variable differential transformer (LVDT) with the accuracy of 0.001 mm.

The regulation circuit for a constant stress-ratio experiment with a constant displacement rate in the major loaded direction was used in the tests. In order to obtain the stable failure modes in the descending stage, the displacement from the output of two LVDTs was employed in computation of strain of the specimens and also used as the feed-back signal to each specimen. The specimens were loaded in biaxial stress states. The lateral pressure was maintained at a fixed proportion to the axial load, with the stress ratios of 0:1, 0.25:1, 0.5:1, 0.75:1, 1:1 respectively. The displacement rates for dam concrete were set as 0.005 mm/s, 0.05 mm/s, 0.5 mm/s and 5 mm/s, which corresponding to the strain rates of 2×10^{-5}/s, 2×10^{-4}/s, 2×10^{-3}/s and 2×10^{-2}/s, respectively. In order to eliminate the restraint induced by the loading platens on the specimen surfaces, the friction-reducing pads [19] were placed between the platens and the specimen for all compressive loading platens. The pads consist of three plastic membranes with two layers of butter between them. For each specific stress ratio, at least three specimens were tested and their average values were used as the presented test results, if it is discrete largely, the numbers of the specimens should be increased and tested.

Table 1
Mix proportion of dam concrete (unit:kg/m^3).

Water	Cement	Fly ash	Sand	Aggregate size (mm)			Water reducer
				5–20	20–40	40–80	
120	214	53	549	442.5	442.5	590	0.214