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Effect of water pressure on mechanical behavior of concrete under dynamic compression state

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HIGHLIGHTS

- Concrete exposed to water pressure are subjected to compression under different strain rates.
- Strength of concrete under water pressure increases nonlinearly with increasing strain rate.
- Strength and failure modes under fast loading are significantly affected by water content.
- Effect of water content on the strength and failure mode of concrete is described.

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ABSTRACT

This paper reports the experimental study of water pressure environment effects on the mechanical behavior of concrete under a dynamic compression state with strain rates ranging from 10^{-5}/s to 10^{-2}/s. The water content of concrete under different water pressure (0, 2, 5, and 10 MPa) was obtained, and the failure modes and the strength of concrete were proposed. Results show that strength and failure modes are remarkably affected by water content and strain rate. Under water pressure, the strength of concrete increases nonlinearly as strain rate rises, and the strain rate sensitivity of concrete increases with increasing water content. When the water content of concrete is higher than 1.27 times of w_s^{ac}, (w_s^{ac} is water content of concrete which becomes a fully saturated state in atmospheric condition), and concrete under the fast loading results in cone-type failure (CTF). Moreover, the area of crack surface and the volume of debris shedding also decrease as both water content and strain rate increases; however, when the water content of concrete is lower than w_s^{ac} or the concrete under slow loading, slant shear failure (SSF) occurs. As explained through a basic poromechanics analysis, this dissimilarity is mainly attributed to the excess pore water pressure and the viscous stress inside the saturated concrete during fast (quasi-static or dynamic) experiments.

1. Introduction

Numerous concrete structures such as dams, offshore platforms, bridge piers, and ports are often exposed to a hydraulic environment, such that, they often suffer from water pressure, which is unavoidable in deep water area. Over a long period, the shallow part of the structures will lead to pore pressure equal to water pressure [1]. These structures must withstand static loadings, as well as suffer from dynamic loadings, such as explosion, impact, earthquake, and hydrodynamic pressure. Under dynamic loading, the behavior of concrete is significantly different from that under static loading [2–4]; moreover, water environment influences the mechanical properties of concrete [5]. Therefore, the implementation of dynamic mechanical experiments for concrete in ambient water is greatly significant for its application in civil engineering.

A lot of efforts have been devoted to considering the effect of water on concrete. Most studies mainly used three ways to saturate specimens, including curing dried specimens in humidity rooms or immersing them in water in atmospheric condition for an intended period to achieve the predetermined water content [6–13], and fog- or water-curing specimens for a long time after demoulding [14–18]; After demoulding, specimens are protected from free water and atmosphere exchange by wrapping them in a thin sheet of plastic paper covered with two layers of adhesive

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aluminium foil [19–21], whose pore water pressure is 0.1 MPa, far less than that of concrete structures in deep water area. Although the effect of pore water pressure on the mechanical properties of concrete was considered by Li [22], Wegen [23], and Harris et al. [24], who saturated specimens at high pressure water or obtained them from the dam core, the tests were ultimately carried out under atmospheric environment. The test conditions of these researches differ from the real condition of hydraulic structures, such that utilizing these results for concrete structures in deep water area remains debatable.

Existing literature shows that mechanical tests are not par for concrete both saturated and loading under water pressure. Haynes [25] first began to study the effect of water pressure on the strength of concrete, and the static uniaxial compression strength of the concrete was reduced by 10% when water depth is 6100 m (equivalent to 61 MPa) compared to the fog-cured concrete. However, water pressure failed to depress the strength and elastic modulus of concrete when water depth is lower than 800 m, according to the study by Bjerkeli [26]. These test results [25,26] were further verified by Clayton [27]. In addition, the test of water pressure on cement paste was carried out by Clayton [27], and results showed that the strength was not weakened through submersion at 6000 m depth (60 MPa); moreover, it was considered that the reduced strength caused by the effect of confining pressure results in cracks around the concrete aggregate when water pressure is higher than the strength of concrete [27]. The dynamic mechanical experiment of concrete under water pressure was conducted first by Chen [17], and mechanical loading was applied on the specimen when water pressure was steady. However, it is not clear whether the specimen was saturated and dispersion of the test data was larger. Thus, more experimental studies on dynamic loadings, particularly test data, are necessary.

Concrete material is sensitive to the strain rate of loading. Under dynamic loading, the strength of normal concrete increases with increasing strain rate [2–4]; furthermore, the moisture content of concrete shows an important effect on strain rate sensitivity [8,18,28]. According to the principle of mercury intrusion porosimetry (MIP) [29], the water content of porous media increases as liquid pressure heightens, which can influence the mechanical behavior of concrete; however, the test [17] fails to consider the impact of water content on dynamic mechanical properties of concrete.

The strength of concrete is also influenced by the saturation method. When concrete specimens are constantly in a humid environment and never dehydrated, the uniaxial strength of concrete is higher than that of dry concrete under dynamic loading [14–16]. However, when concrete specimens are dried at high temperature or stored in natural condition over a long period, and then immersed in water to be saturated, the uniaxial strength of concrete is lower than that of dry concrete under dynamic loading [6,8]. In the studies by Bjerkeli [26] and Clayton [27], specimens were water-cured after demoulding for a long time, and then concrete specimens were saturated and tested under water pressure, which were not dehydrated. However, many concrete structures, such as dams, are in a dry state during construction period and under high water pressure during operation period [30,31], such that studying concrete in this kind of environment is still necessary. Based on the literature analysis, the focus on dynamic mechanical behavior of concrete in ambient water remains inadequate and requires further research.

This study aims to investigate the static and dynamic compressive mechanical properties of long-term dry concrete under water pressure. The strain rate ranges from 10^{-5}/s to 10^{-2}/s, such that, the strain rate of 10^{-5}/s is defined as the quasi-static strain rate and the strain rate of 10^{-4} to 10^{-2}/s as dynamic loading. Water pressures ranges from zero to 10 MPa. The water content of concrete under different water pressures are obtained for this study, and failure modes and strength of concrete are proposed. Moreover, the effect of water content and strain rate on the failure modes and strength of concrete are analyzed.

2. Experimental

2.1. Specimens

In this investigation, an ordinary Portland cement (P.O 42.5) produced in the Yichang Hualin cement plant in China was used, and all its properties were in accordance with the Chinese standard of Common Portland Cement [32]. Natural river fine sand was adopted as fine aggregate, with a fineness modulus of 1.8. Natural river pebble was used as coarse aggregate (diameter ranging from 5 to 30 mm). Water was tap-water. Water-cement ratio was 0.5, and the mix proportions by weight of the mixture are shown in Table 1. The properties of freshly mixed concrete were determined in respect of the slump [33], and the average slump of control mixes ranged from 3 to 5 cm.

The concrete was mixed using an ordinary forced action mixer. Subsequently, concrete mixtures were poured into a 400 mm deep pond, and cured in natural condition. After 90 days, concrete specimens were extracted by a concrete coring machine, and then stored in room condition. Concrete specimens were 150 mm in diameter and approximately 400 mm long. Before the test, double ends of a specimen were cut to 305 mm left and the end faces were ground with a grinding machine, until concrete length was 300 mm and double end faces were accurately plane and parallel. Specimens were undertaken at ages of over 1200 days. The age of the concrete was so long that the strength tended to be stable. Thus, the effect of ages on the strength was neglected in the tests.

2.2. Test apparatus

The test apparatus used in this study is an electro-hydraulic servo testing system controlled by a computer in the material laboratory of China Three Gorges University, as shown in Fig. 1. The axial load capacity is 10,000 kN and the accuracy is 0.1%; the pressure vessel capacity is 30 MPa and the accuracy is 0.1%. The axial load is transmitted to the specimen by a piston, which passes through the top of the pressure vessel. The axial load was measured by a load transducer attached at the top of steel frame of the test setup. Once the pressure vessel was filled with water and hydrostatic pressure was applied through a pump, which pushing water from a water tank into the pressure vessel controlled by the water pressure control system. The water pressure was monitored by a pressure transducer connected to the pressure vessel.

2.3. Mechanics experimental procedure

The mechanical tests were divided into two groups. One group was dry concrete specimens Tested in Atmospheric Environment (TAE) and the other group was dry concrete specimens Saturated and Tested under Water Pressure (STWP). The STWP group was initially saturated for 6 h under 2, 5, and 10 MPa of water pressure, respectively, and then the mechanical tests were carried out under the same water pressure. In addition, the 0 MPa of STWP group were conducted to compare with the TAE group. In this case, the

Table 1
Concrete mixture ratio by weight (kg/m^3).

Cement	Fine aggregate	Coarse aggregate	Water
370	646	1199	185