Cement and Concrete Research 100 (2017) 140–152

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Experimental study of concrete damage under high hydrostatic pressure

Jian Cui[a,b], Hong Hao[a,b,*], Yanchao Shi[a,b], Xibing Li[c], Kun Du[c]

[a] Tianjin University and Curtin University Joint Research Centre of Structural Monitoring and Protection, School of Civil Engineering, Tianjin University, China
[b] Tianjin University and Curtin University Joint Research Centre of Structural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Australia
[c] School of resources and safety engineering, Central South University, China

ARTICLE INFO

Keywords:
Concrete
Hydrostatic pressure
Damage
True tri-axial test
Stress path

ABSTRACT

The objective of this study is to characterize the damage evolution behavior of concrete under hydrostatic pressures varying from 30 MPa to 500 MPa for better understanding the concrete material properties at complex stress states. A series of uniaxial tests were carried out to evaluate the damage degree of concrete after hydrostatic tests and a number of microscopic observations were also provided to allow visualizing the changes of microstructures of the specimen after and before hydrostatic tests. The effect of stress path on compressive meridian and tensile meridian of concrete was also studied. Experimental results indicate that concrete suffers obvious damage if the applied hydrostatic pressure is higher than the uniaxial compressive strength of concrete specimen. The strength and Young's modulus of concrete decrease significantly after hydrostatic tests and the aggregate-mortar interfacial transition zone (ITZ) is the most obvious damage region. The stress path has insignificant effects on ultimate strength envelopes. But if the stress path involves a high hydrostatic pressure that damages the concrete specimens upon unloading, the strength envelope "shrinks" because of the damage to concrete due to high hydrostatic pressure.

1. Introduction

Concrete is a composite material consisting of different sized aggregates which are embedded in a cement paste matrix, and this composition makes it a heterogeneous material. The cement paste has a high porosity, and these pores are filled with air and water. A large number of bond micro-cracks exist at the interfaces between coarse aggregates and cement matrix. These properties strongly affect the behaviors of concrete under complex stress states.

Concrete is the most commonly used construction material. Under extreme loading conditions such as near-field explosions and projectile penetrations, the material subjects to complex stress states. For example, when a projectile impacts a concrete structure, the stress state induced in the structure is very complex owing to wave propagation, reflection and refraction. The damage to concrete in complex stress states, e.g. in high hydrostatic pressure, is still not clear. Most experimental results available in the literature only address the damage and destruction of concrete material under deviatoric stress [1–7], usually obtained with a cylindrical specimen subjected to a confining pressure and an axial loading. The study of concrete under hydrostatic pressure is limited owing to the difficulty in applying the very high true tri-axial loads in tests. As it is well known that in theory the homogeneous materials will not suffer any damage in whatever high hydrostatic pressure. The commonly used concrete material models in hydrocodes such as K & C model [8] and RHT model [9] in LS-DYNA [10] therefore do not consider the damage of concrete material in hydrostatic pressure although concrete is not exactly a homogeneous material. However, the damage of concrete under high hydrostatic pressure influences the failure surface, damage evolution algorithm and equation of state (EOS) of the concrete constitutive model under complex stress states [11]. Gebbeken and Ruppert [12] also suggested considering this damage in dynamic concrete model as concrete is a highly inhomogeneous porous material. In the experimental study by Poinard et al. [13], it was observed that the bulk modulus of the concrete with a 29 MPa uniaxial compressive strength decreased substantially after the specimen having been subjected to a hydrostatic pressure higher than 60 MPa. The authors attributed this drop to cement matrix damage. Pham et al. [14] found that in their FRP-confined concrete tests, the core concrete has already suffered serious damage although the strength of FRP-confined concrete still could significantly increase a lot. The study on the effect of stress path on the ultimate strength envelopes of concrete is also very limited. Kotsovos [15] designed three different stress paths to get the ultimate strength envelopes and found the ultimate strength envelopes were independent of the stress paths. Gerstle et al. [16] reported a

* Corresponding author.
E-mail address: hong.hao@curtin.edu.au (H. Hao).

http://dx.doi.org/10.1016/j.cemconres.2017.06.005
Received 24 January 2017; Received in revised form 15 May 2017; Accepted 29 June 2017

similar observation. Gabet et al. [17] designed a pseudo tri-axial test by varying the confining pressure proportionally with the applied axial stress during the loading process. The latter study also revealed that the strength envelopes of concrete were independent of the loading paths. These studies all revealed that concrete material behaves differently under complex stress state as compared to the uniaxial stress state, and may be subjected to damage even under hydrostatic stress condition. Unfortunately the relevant studies, especially the true tri-axial tests, are limited in literature owing to the constraints of available testing equipment.

In the present study, more comprehensive experimental tests are carried out to further evaluate the performance and damage of concrete material after experiencing hydrostatic pressures. The uniaxial compressive strength and the uniaxial tensile strength of concrete specimens after experiencing certain level of hydrostatic pressure are compared with the ones without experiencing hydrostatic pressure. Electron microscope observations and ultrasonic examinations are also made to study the damage mechanism and damage degree of concrete subjected to high hydrostatic pressure. The influence of stress paths on ultimate strength envelopes is also examined. Compressive meridian and tensile meridian are determined by loading and unloading methods respectively. Based on the testing data the modified material model is put forward to consider the damage to concrete material under high hydrostatic pressure. The results obtained in this study lead to better understanding of the micro-damages to concrete material by hydrostatic pressure and its influences on strength degradation, and hence development of more accurate strength envelope and equation of state of concrete materials.

2. Experimental setup and specimens

2.1. Equipment

The experiments were conducted by a true tri-axial hydraulic servo-controlled test system in Central South University in China [18,19]. The system consists of the main machine, servo-controller, data acquisition system and measurement sensors, as shown in Fig. 1. It is a digital closed-loop control system, which can control load and displacement automatically.

This apparatus applies quasi-static loads along the three principal stress directions through hydraulically driven pistons independently. The maximum load capacities of the X, Y, and Z actuator are 2000, 2000 and 3000 kN respectively. High-strength steel (20CrNiMo), which has a yield strength of 785 MPa and an elastic modulus of 210 GPa, is used to transfer the applied loads from the actuators to the specimen as shown in Figs. 1 and 2. The side length of the steel load transfer block is 47 mm, 3 mm shorter than the side length of the cubic specimen (50 mm) to avoid collision of the load transfer bars in different directions when the specimen experiences a large strain during the loading process, as illustrated in Fig. 2. The axial loads were recorded by the load cells, and the deformation of the specimen was measured by LVDT sensors. The elastic deformation of the load transfer bar was removed from the measured deformation in the subsequent data analyses to obtain the strain of the tested specimen, as shown in Fig. 2.

2.2. Specimens

Two concrete mixes, i.e., LSC (low strength concrete) and HSC (High strength concrete) were considered in the study. The concrete mix properties are given in Table 1. Natural river sand with a fineness modulus of 2.9 was used as fine aggregate. Cleaned gravels with a maximum size of 10 mm were used as course aggregate. The specimens were cast in a 50 mm cubic metal molds and removed from the mold 24 h after casting. The specimens were moist-cured at 20 ± 2 °C and 100% relative humidity for 28 days. Before the test, the surfaces of specimen were smoothed by a polisher and coated with grease to reduce the friction between the specimen and the rigid loading platens. For the uniaxial compressive test, a 500 kN computer-controlled electromechanical servo hydraulic pressure testing machine was used to conduct the test. The loading rate was 0.03 mm/min and the deformation was recorded from LVDTs. The 28-day uniaxial compressive strength of LSC and HSC were 33.6 and 61.6 MPa, respectively. However, at the time of testing concrete was approximately half year old, and the corresponding uniaxial compressive strengths were increased to 35.2 and 63.8 MPa. The test set-up for the uniaxial tensile test is detailed in Section 3.2.2. It must be noted that the end friction inevitably existed and might affect the testing results although methods have taken to reduce it. To investigate the possible friction constraint, the static friction coefficients were measured between the greased specimen and steel surface. The average friction coefficient was found to be 0.105, which is relatively small. As is discussed later end friction only had minimum influences on the tri-axial testing results, and its influence was limited to a small layer near the specimen surface.

3. Concrete damage in high hydrostatic pressure

3.1. Hydrostatic test procedure

A hydrostatic load with one loading-unloading cycle was conducted during the test, as is shown in Fig. 3. To ensure $\sigma_1 = \sigma_2 = \sigma_3$ (σ_1, σ_2, and σ_3 are major, intermediate, and minor principal stresses, respectively) during the loading-unloading process, the forces of X, Y and Z axes were applied by the force control mode at a rate of 1 kN/s (0.4 MPa/s) until reaching the desired stress level. Before unloading,

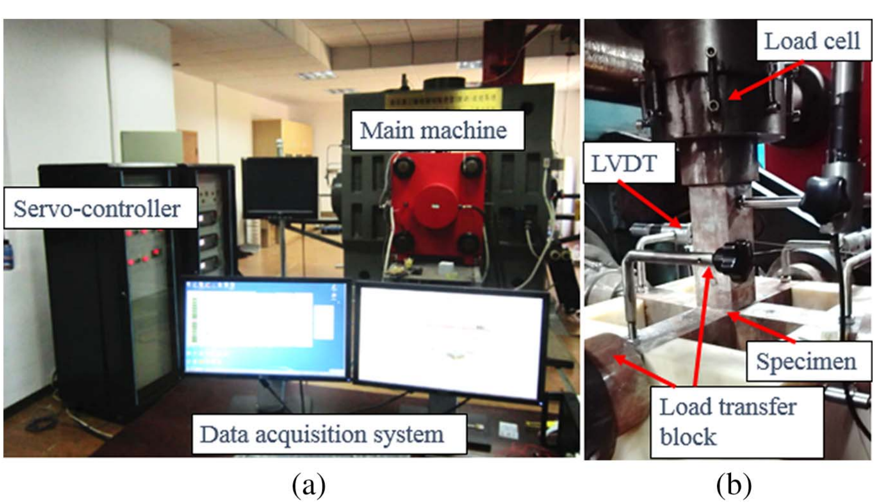

Fig. 1. True tri-axial testing equipment: (a) overview; (b) three direction loading actuators.