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Investigation of the curing time on the mechanical behavior of normal concrete under triaxial compression

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HIGHLIGHTS

- Effect of curing time on the triaxial mechanical behavior of concrete was studied.
- Failure strength, plastic deformation is highly dependent on the confining pressure.
- Present curing time dependent model can describe the main behavior of the concrete.

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ABSTRACT

Due to its hydration process and applications under complex loadings, concrete is a live material and might be subjected to triaxial loadings in short time after pouring. The aim of this study is to investigate the main mechanical behavior of normal concrete at different curing time under different confining stress state. A series of triaxial compression tests of a concrete are conducted firstly. Four curing times of 3, 7, 14 and 28 days, as well as four confining pressures of 0, 5, 10 and 20 MPa, are considered at a C30 concrete type. The interesting observation is that the failure strength and plastic deformation of concrete is not only related to curing time, but also highly dependent on the confining pressure. With the increasing of confinement, curing time dependence on deformation and failure strength is increasing and decreasing respectively. Based on experimental investigations, a curing time dependent constitutive model is proposed. In this model, the effect of curing time is introduced to elastic characteristic, failure function and plastic hardening law. Finally, calibration of the proposed model shows good agreement with the test results.

1. Introduction

In the 21st century, concrete materials have been widely used in engineering constructions. As it is applied in civil engineering projects such as military defense shelter, nuclear containment, and deep sea drilling project, their mechanical behaviors of concrete under triaxial loading have become the focus in analyzing and stabilizing concrete structures. These multiaxial loadings are normally generated by hydrostatic pressure, thermal stress, soil pressure and boundary limitations individually or simultaneously. Through the relevant modeling and numerical calculation method, structure simulation and analysis at early age have become a hot topic for scientists and engineers. Meanwhile, concrete is a common and effective material especially for rush-repair work. Understanding the evolution of their mechanical behavior at early age is beneficial to accelerate the repair process. Furthermore, in the case of disasters, e.g. earthquake and wars, complex loadings may lead structures poured within few days to hazards. Thus, it is necessary to study the mechanical behaviors of concrete at the early stages as well as analyzing their characteristic under complex loadings.

The experimental researches under complex loadings have mainly been performed by compression tests with confining pressure. The Hoek triaxial cell or an analogous one with a larger dimension is often utilized [1]. The relevant researches show that with the increasing of the confining pressure, the failure stress of concrete would be increased obviously. Meanwhile, a transition from brittle to ductile fracture can be observed [2–4]. A large number of triaxial tests supported the experimental researches on different concrete, such as normal concrete, high strength concrete (HSC), high strength fibre reinforced concrete (HSFRC) [3–8], as well as the influence of environment conditions, e.g. freeze-thaw cycles [9], chemical corrosion [10].

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Based on the relevant experimental data, continuous researches have been concentrated on developing the constitutive models. The constitutive law is a general term and it may include yield criteria, failure criteria, hardening law and flow rule. After the well-known Mohr-Coulomb theory, many modelings have been established and modified by introducing the principal shear stresses, the principal normal stress and stress invariants. Tresca criterion [11], von Mises criterion [12], Drucker-Prager criterion [13], Ottosen criterion [14], Willam-Warnke criterion [15], and their modified formulations, as well as others' work [16–18], have been proposed to develop the modeling the mechanical behavior of concrete. Meanwhile, some damage criteria established by Mazars [19] and Kitsutaka [20] can be introduced to describe its softening behavior. More detailed contents can be found in relevant review articles and books [21,22]. As classical quasi-brittle material, e.g., rock and concrete, the mechanical behavior of concrete is similar to that of rock [23]. The further modeling research of concrete is analogue to that of rock [24,25].

As well-known, concrete is a live material and its strength development is a result of the hydration process or curing time [26]. Therefore, the concrete at early age might show time dependent elastoplastic behavior with respect to different curing time. However, it is found that the applied constitutive laws are generally established on uniaxial compression tests while the plastic evolution at early age under triaxial stress state is always neglected [27]. Meanwhile, a series of researches on elastic characteristic, uniaxial compressive strength, flexural strength, as well as shrinkage of concrete at early age have been conducted [28–31]. We can see clearly that there are few studies investigating the mechanical behavior of early age concrete under multiaxial loading. Considering the above mentioned applications related to both early age and complex loading, it is necessary to carry out the investigation of concrete at different curing time under triaxial loading.

In this paper, a C30 normal concrete is investigated systematically. A series of triaxial compression tests are performed firstly. Four curing times of 3, 7, 14 and 28 days, as well as four confining pressures (Pc) of 0, 5, 10 and 20 MPa, are considered. Then a curing time dependent constitutive law is proposed. Based on the experimental data and relevant calculation method, the model's parameters are determined and the numerical simulation is calibrated finally.

2. Experimental research

2.1. Experimental preparation

The Ordinary Portland cement (P.O. 42.5) produced by Anhui Conch Cement Company, China was in use and its strength characteristics was confirmed to GB/T 17671-1999 [32]. The fine aggregates with fineness modulus of 2.5 were used in this study. According to the dimension of the samples, the crushed limestones with a maximum particle size of 10 mm were selected as the coarse aggregates. Mixture proportions were designed to achieve a mean value compressive strength of 30 MPa at 28 days. Table 1 shows the mix proportions of the mixture by weight. Furthermore, the slump test of fresh concrete was performed according to GB/T 50080-2002 [33]. The slump of the concrete was 10 cm, which indicated that the concrete mixture had good workability. The fresh mixture was put into the Φ 50 mm × 100 mm cylindrical molds by three times, and compacted by a vibrating table for 2–3 min at a frequency of 50 Hz and vibration amplitude of 0.5 mm. After compacting, the samples were cured at 20 °C for 24 h. Then the demolding was done and the specimens were cured in water saturated with lime at 20 °C until the day of test in accordance with GB/T50081-2002 [34]. Three cylindrical samples were used for each compression test, and there were totally 84 cylinders were tested in this study. Meanwhile, 12 100 mm × 100 mm × 100 mm cubic samples were made in the same conditions. Three cubic samples were used in each splitting tensile test.

Table 1
Mix proportions of the concrete (kg/m^3).

Cement	Sand	Coarse aggregate	Water
350	736.5	1104.7	210

The compression tests and splitting tensile tests were performed at 3, 7, 14 and 28 days, respectively. After being cured in saturated lime water for 3, 7, 14 and 28 days, the concrete samples were taken out from lime water, the surface of each specimen was thoroughly washed and was wiped with soft cloth. The triaxial compressive tests of cylindrical samples were performed in the triaxial cell V5 system (Fig. 1) of TOP INDUSTRY, France. Meanwhile, the splitting tests with cubic samples were conducted in a 3000 kN electro-hydraulic servo universal test machine.

In the present triaxial system, the maximum of confining pressure and deviator stress can be up to 40 MPa and 150 MPa respectively. The axial displacement is measured by two LVDTs in the cell, and the lateral deformation is measured with a special strain ring located at the middle of the sample. In our study, the triaxial test was performed by two loading stages shown in Fig. 2. The axial and confining pressures were simultaneously applied to targeted values σ_3 in load control at first. Then the confining pressure was kept constant at the targeted level, the control load mode was transformed to axial displacement control with rate of 1 μm/s and the deviatoric stress (σ_1–σ_3) increased until the specimen reached fractured. In this study, four series of triaxial compression tests were carried out at 3, 7, 14 and 28 days. In each series, four triaxial compression tests with the confining pressures of 0, 5, 10 and 20 MPa were performed.

The tensile strength was obtained by the splitting test and would be used as a reference for hydrostatic tension strength. In the following section, hydrostatic tension strength will be introduced to establish the modeling. It is generally accepted that it is hard to measure the hydrostatic tension strength. Meanwhile, hydrostatic tension strength might be some smaller than the tensile strength. Thus, the value of the tensile strength can be used to limit the range of hydrostatic tension strength. In this study, four splitting tests were performed at 3, 7, 14 and 28 days.

2.2. Experimental results and analysis

Triaxial compression tests were carried out respectively to characterize basic mechanical behavior of concrete at different curing time. The stress-strain curves obtained from these triaxial compression tests are shown in Fig. 3(a–d).

The elastic characteristic is discussed firstly and Table 2 shows the elastic modulus of the concrete at different curing time. The elastic modulus is obtained at the initial linear elastic stage, and defined as the slope of stress versus axial strain. The elastic modulus of the concrete enhances gradually as the curing time increases due to the continuous hydration. Such early-age concrete stiffening has also been reported by other authors [30,29,35], and is often introduced as "aging elasticity". In our study, there is no evident evolution of the Poisson's ratio (ν) with respect to curing time. In literature, the evolution of the Poisson's ratio is neither not always taken into account. Truman and Oluokun conclude that ν remains constant during hydration [36,37], although some lower values at very early age are mentioned [37].

Under low confining pressure, the curing time causes a significant increase of failure strength. The hydration between 3 days and