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Experimental studies and modeling of creep of UHPC

Yi Xu [a,b], Jiaping Liu [a,c,*], Jianzhong Liu [c], Ping Zhang [a], Qianqian Zhang [c], Linhua Jiang [b]

[a] School of Materials Science and Engineering, Southeast University, Nanjing 211189, China
[b] College of Mechanics and Materials, Hohai University, Nanjing 211100, China
[c] State Key Laboratory of High Performance Civil Engineering Materials, Jiangsu Research Institute of Building Science, Nanjing 210008, China

HIGHLIGHTS

- The creep of ultra-high performance concrete is studied.
- A modified creep prediction model applicable for UHPC is proposed.
- The creep mechanism of UHPC is discussed based on CT and SEM analysis.

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ABSTRACT

The ultra-high performance concrete (UHPC) mixed with normal coarse aggregate is a promising material due to its excellent mechanics, durability performance and relatively lower cost. To verify the applicability of the current creep prediction models on this concrete with ultra-high strength grade, the creep behaviors of the specimens with different steel fiber contents of 0%, 1% and 2% and two water-to-binder ratios of 0.16 and 0.22 were examined. The results show that the creep coefficient with 1% and 2% ultra-fine steel fibers exhibits remarkably decline of 25.4% and 13.4% after 180 days of loading in comparison to that without steel fibers. The rise of W/B has a negative effect on creep behavior of UHPC. While the specimens with similar compressive strength have different creep coefficients. The test results are compared with the values simulated by the common prediction models (fib MC2010, ACI 209-08, B4 and simplified B4, GB 50010-2010 and JTG D62-2004 models). By substituting the experimental compressive strength with the calculated compressive strength derived from the elastic modulus of UHPC, the modified creep prediction model based on fib MC2010 functions is applicable for the concrete with higher strength grade and more complicated components. In the meanwhile, the creep mechanism of UHPC was discussed based on the mesoscopic and microscopic analyses determined by X-ray computer tomography (CT) and scanning electron microscope (SEM) techniques.

1. Introduction

The creep phenomenon is an intrinsic time-varying characteristic of concrete materials which shows the continuously increasing deformation of concrete under the action of long-term loading. It significantly affects the service life of engineering structures. In current design codes of various countries, many models such as Fédération international du béton – International Federation for Structural Concrete (fib) MC2010 model [1,2], American Concrete Institute (ACI) 209-08 model [3,4], RILEM recommendation B4 model [5,6], Chinese specifications GB 50010-2010 model [7] and JTG D62-2004 model [8] are proposed to predict the creep deformation of traditional concrete. Compared to previous models, these latest models are developing to be more suitable for modern high strength concrete, while they are not applied to creep evaluation of ultra-high performance concrete (UHPC) with ultra-high strength based on very low water-to-binder ratio (W/B). For example, the mean cylinder strengths of concrete for ACI 209.2R-08 guide and B4 model are 20–70 MPa and 15–70 MPa, respectively, and the application ranges of GB 50010-2010 and JTG D62-2004 codes are under the strength grade of C80. Although the concrete grade of fib Model Code 2010 is higher, it is not well known that the creep model of MC2010 is capable to predict the creep behavior of UHPC.

UHPC is a promising material in the fields of buildings, bridges, defenses and others, owing to its excellent mechanical performance and improved durability [9–11]. In order to having the superior mechanical properties, UHPC is usually fabricated using

* Corresponding author at: School of Materials Science and Engineering, Southeast University, Nanjing 211189, China.
E-mail address: ljp@cnjsjk.cn (J. Liu).

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high cementitious materials, very low water/binder ratio, ultra-fine steel fiber, and high-range water reducing admixture [12,13]. These characteristics obviously make the creep performance of UHPC different from the traditional concrete. For example, the creep decreased with lower W/B ratio. But the abundant cementitious materials would lead to creep increase either. In the past few years, some experimental investigations of creep behavior of UHPC have been done, which were listed in Table 1. On the one side, most of these concretes were produced by eliminating normal coarse aggregates to increase the compaction degree and achieve higher strength, while it would lead to relative high produce cost. On the other side, the current prediction models were not validated to the creep of UHPC. To promote the development of UHPC and establish the standards for its structural design, it is necessary to study the creep performance of UHPC mixing with normal coarse aggregate and proposed a prediction model applicable for UHPC.

In this article, the concretes with very low water-to-binder ratios, ultra fine steel fibers and normal coarse and normal fine aggregates were produced. The creep coefficients were tested and the experimental results were compared with the values evaluated by the current prediction models (fib MC2010, ACI 209-08, B4 and simplified B4, GB 50010-2010 and JTG D62-2004 models). A modified model was proposed to consider the higher compressive strength of concrete. Also, the creep mechanism of UHPC with very low W/B ratios and ultra fine steel fibers was discussed based on the mesoscopic and microscopic structures determined by CT and SEM scanning techniques.

2. Experimental study

2.1. Materials

In the present study, the UHPC was fabricated entirely with natural aggregates. Crushed basalt with nominal maximum grain size of 20 mm and apparent density of 2800 kg/m^3 was used as the normal coarse aggregate. Natural sand with fineness modulus of 2.5 and apparent density of 2640 kg/m^3 was used as the fine aggregate. The Portland cement (P•II 52.5) was used in the experiments. The ultra-fine mineral admixture was commercially available SBT®-HDC (V̲) admixture which composed of ultra-fine slag, silica fume and microsphere, and so on. It had a density of 2.45 g/cm^3, a specific surface area of 8500 m^2/kg, and a 28-day activity index of 115%. The chemical admixture was also commercially available gather carboxylate water-reducing agent produced by SBT®. To improve the brittle behavior of the concrete with very low water-to-binder ratio, ultra-fine steel fibers (SF) with a diameter of 0.2 mm, a length of 13 mm and a strength of 2900 MPa were also added in the mixture.

2.2. Mix proportions

It is intended to investigate the most important ingredient parameters on creep performance of UHPC. Two influence factors — steel fiber content and water-to-binder ratio — were taken into consideration, which have significant effect on mechanical properties of UHPC. Four different UHPC mixes were designed. All of them were made by using normal coarse aggregates and normal fine aggregates. The detailed mixture proportions are given in Table 2 and the tested mechanical properties are summarized in Table 3. In series of water/binder ratio of 0.16, the ultra fine steel fibers were added to the concrete with volume content of 0%, 1% and 2%, respectively. The steam-curing compressive strengths of the three groups C16SF0, C16SF1, and C16SF2 were 139.7 MPa, 152.5 MPa, and 170.6 MPa, respectively. The results indicate that the micro steel fiber exhibits good toughening and reinforcing effect on ultra-high strength concrete. By comparison, the concrete with a water/binder ratio of 0.22 was produced. Its volume content of steel fibers was 2%. It is worth noting that the measured compressive strength of this group C22SF2 is close to that of C16SF1, while the elastic modulus tends to be very different.

2.3. Experimental procedure

Materials were mixed in the following order: Firstly, the dry constituents including cement, ultra-fine mineral admixture, sand and gravel were mixed initially for about 30 s. Secondly, the high-range water reducing admixture and water were added and mixed for more than 3 min. Then, ultra-fine steel fibers were added to the mixture and mixed for another 2–3 min until a uniform concrete had been obtained. This mixing process seemed to improve the workability and homogeneity of the fresh concrete. The concrete specimens were cast in molds after mixing and covered with plastic films to avoid water evaporation (see Fig. 1), followed immediately by curing at room temperature for 24 h before being demolded.

The compressive strength specimens were cast in 100 mm × 100 mm × 100 mm and 100 mm × 100 mm × 300 mm molds respectively. The cubic specimens were conducted to obtain the mechanical information about UHPC under the steam curing condition for 3 days, and under the standard curing condition for 28 days with the temperature of 20 ± 1 °C and the relative humidity (RH) of approximately 95%. The prism compressive strength was measured at the age of 28 days. The cross-section of UHPC specimens is shown in Fig. 2.

At least three specimens were examined for each case and the average strength was calculated. The creep tests were investigated on 100 mm × 100 mm × 300 mm prisms. The specimens were cured in the standard conditions until the days of test according to Chinese Standard GB/T 50082-2009, and then were loading under compression at the age of 28 days and stored in a control room maintained at 20 ± 2 °C and 60 ± 5% RH throughout the entire days of creep tests. The loading level is equal to 40% of the compressive strength of prismatic specimens. The large measuring range hydraulic creep apparatus with a capacity of 1000 kN were selected for load applying due to the ultra-high compressive strength of UHPC. This hydraulic loading frames automatically controlled by computer could adjusts the axial pressure timely and quickly, in order to maintain the load on the constant level. It increases the measurement accuracy due to the supplementary of loss pressure induced by the release of frames and the deformation of specimens. Three replicate specimens produced from one mix group were loaded simultaneously. The creep

Table 1
Creep investigations of UHPC.

Ref.	W/B	Strength	Creep type	Creep geometry	Testing conditions	Loading age
Rossi [14]	0.20	120.8 MPa	Compression, tensile	φ100 mm × 200 mm φ160 mm × 1000 mm	23 ± 3 °C, 50 ± 5% (sealing)	7 d
Garas [15]	–	–	Compression, tensile (heat treatment)	φ100 mm×380 mm 75 mm × 75 mm × 483 mm	23 ± 2 °C, 50 ± 3%	7 d
Mertol [16]	–	124 MPa	Compression	φ100 mm × 300 mm 75 mm × 75 mm × 290 mm	22 °C, 50%	1 d, 7 d, 4 d/28 d
Garas [17]	–	–	Tensile (heat treatment)	φ100 mm × 380 mm	23 ± 3 °C, 50 ± 5%	7 d
Kamen [18]	0.13	–	Tensile	50 mm × 100 mm × 1000 mm	20 °C, 65%	35 h, 46 h, 72 h

Table 2
Mixture proportions of UHPC.

Mixture	W/B	Cement (kg/m^3)	Ultra-fine mineral admixture (kg/m^3)	Nature sand (kg/m^3)	Crushed basalt stone (kg/m^3)	Ultra-fine Steel fiber (%)
C16SF0	0.16	619	206	743	782	0
C16SF1	0.16	619	206	743	782	1
C16SF2	0.16	619	206	743	782	2
C22SF2	0.22	589	196	743	782	2