Compressive Creep Behavior of Cellulose Fiber Reinforced Concrete

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Abstract: The effect of cellulose fiber on the long-term compressive creep performance of concrete was clarified. For this, the long-term compressive creep properties of four cellulose fiber reinforced concrete (CFRC) groups with contents of 0, 0.9 kg/m³, 1.1 kg/m³, and 1.3 kg/m³ were investigated using a spring creep tester. Loading ages of 7 days, 14 days, and 28 days, and a loading stress ratio of 0.40 were employed. Furthermore, the creep model of CFRC was established. The results revealed that the creep of concrete at three loading ages decreases by 16%, 12%, and 17%, respectively, after adding cellulose fiber to the concrete. With increasing loading age, the difference of creep degree of CFRC with different cellulose fiber content decreased gradually. Furthermore, the range of specific creep decreased from 8 × 10⁻⁶ / MPa for a 7 day loading age to 2 × 10⁻⁶ / MPa for a 28 day loading age. The change regulation of CFRC creep coefficient was similar to that of the specific creep. The influence of the cellulose fiber on the creep performance of the concrete was reflected in two aspects. On the one hand, the internal curing effect of cellulose fiber can optimize the microstructure of concrete and reduce the creep deformation. On the other hand, the fiber increases the water migration channel and defects of interface transition zone, which will increase the creep deformation. The power exponential function model for CFRC creep provided a good description of the relationship between creep and loading age and holding time. This model can be used to predict the long-term creep of CFRC under different loading ages.

1. Introduction

Cellulose fiber, which was developed after chemical synthetic fiber, is a new type of special fiber for concrete engineering. The raw material is taken from a special plant in the alpine region, and is processed through a series of chemical and mechanical methods, and then pressed into a sheet-like fiber sheet. Cellulose fiber has a very high strength/mass ratio. Billions of fiber monofilaments are contained in each kilogram of the fiber. Under the action of mechanical friction and the shear force of coarse aggregates, the thin cellulose fiber sheet is highly dispersible and plays a key role in concrete.

Cellulose fiber can yield significant improvement in the crack resistance and durability of concrete [1-2], especially regarding the early plastic shrinkage cracking of concrete [3]. This material can also lead to improvement in the flexural properties of concrete [4], but has negligible effect on the corresponding compressive strength [5]. Due to the remarkable effect of cellulose fiber on improving the durability of concrete, CFRC has been widely used in tunnel lining concrete [6], concrete face rockfill dams [7], aqueducts [8], underground structure engineering, prefabricated buildings, and other concrete structures.
As a new type of functional fiber, the application time of the fiber is still short, and hence research on the influence of such fibers on the long-term performance of CFRC and concrete structures is still rare. Studies on the creep behavior of CFRC are also quite rare [9]. This has a significant effect on the evaluation of the long-term deformation performance, stress redistribution, and stress relaxation of CFRC structures, especially prestressed CFRC structures, long-span CFRC structures, and large-volume CFRC structures. Therefore, the evaluation of the CFRC structure long-term safety is affected.

In order to clarify the influence of cellulose fiber on the long-term compressive creep performance of concrete, the creep performance of CFRC with different fiber contents at different loading ages is evaluated in this work. The long-term compressive creep behavior of four groups of CFRC with fiber contents of 0, 0.9 kg/m³, 1.1 kg/m³, and 1.3 kg/m³ was investigated for loading ages of 7 d, 14 d, and 28 d, and a loading stress ratio of 0.40. The creep model of CFRC was established to provide data support for the structural design and application of CFRC.

2. Experiment

2.1 Materials

P·II 42.5R Portland cement produced by Nanjing Conch Cement Co., Ltd. is used. The physical and mechanical properties of this cement (see Table 1) meet the requirements of Common Portland Cement (GB 175-2007). Grade I class F (low calcium) fly ash produced by Nanjing Thermal Power Plant is adopted. The density, loss on ignition, water demand ratio, activity index, and sieve residue of 45 µm are 2240 kg/m³, 3.1%, 92%, 73%, and 4.6%, respectively.

Table 1. Physical and mechanical properties of the cement

| Specific surface/(m²/kg) | Water requirement of normal consistency/% | Setting time/min | Soundness | Flexural strength /MPa | Compressive strength /MPa |
|------------------------|------------------------------------------|------------------|-----------|------------------------|--------------------------|
| 370                    | 27.0                                     | 150              | 205       | 3d 28d                 | 3d 28d                   |
| 27.0                   | 150                                      | 205              | qualified | 4.8 8.0                | 29.2 48.5                |

The fine aggregate is ordinary river sand with a maximum particle size of 2.36 mm, fineness modulus of 2.3, bulk density of 1300 kg/m³, and apparent density of 2650 kg/m³. Moreover, the coarse aggregate is limestone macadam, and the aggregates (5–16 mm and 16–20 mm) are mixed in a mass ratio of 2:3. The apparent density, bulk density, crushing value, mud content, and water absorption rate are 2720 kg/m³, 1500 kg/m³, 5%, 0.7%, and 0.2%, respectively. The mixing water is ordinary tap water. Furthermore, a Sika polycarboxylic acid type high performance water reducer with a solid content of 40% and water reduction rate of more than 40% was used as the superplasticizer.

UF500 cellulose fiber was selected for the test (see Table 2 for the corresponding physical and mechanical properties).

Table 2. Physical and mechanical properties of the cellulose fiber

| Ultimate tensile strength /MPa | Elastic modulus /GPa | Ultimate elongation /% | Equivalent diameter /µm | Length /mm | Density / (g/cm³) |
|--------------------------------|---------------------|------------------------|-------------------------|------------|-------------------|
| 600–900                        | 29.0–39.0           | 3.5                    | 15–20                   | 2.1–5.3    | 1.1               |

2.2 CFRC mix proportions

The water binder ratio of CFRC is 0.41, the sand ratio is 42%, and the workability of fresh concrete is controlled according to a slump of 200 mm ± 20 mm (see Table 3 for the concrete mix proportions). In addition, the cellulose fiber content levels of C1, C2, and C3 are 0.9 kg/m³, 1.1 kg/m³, and 1.3 kg/m³, respectively. In the mixing process, the dosage of water reducing agent is slightly adjusted, based on the workability of the fresh concrete.
Table 3. Concrete mix proportions

| Mix No. | Cement (kg/m³) | Fly ash (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) | Water (kg/m³) | Superplasticizer (kg/m³) | Cellulose fiber (kg/m³) | Slump (mm) |
|---------|----------------|-----------------|------------------------|--------------------------|---------------|--------------------------|------------------------|------------|
| C0      | 266            | 114             | 760                    | 1050                     | 155           | 3.04                     | 0                      | 216        |
| C1      | 266            | 114             | 760                    | 1050                     | 155           | 3.04                     | 0.9                    | 210        |
| C2      | 266            | 114             | 760                    | 1050                     | 155           | 3.04                     | 1.1                    | 195        |
| C3      | 266            | 114             | 760                    | 1050                     | 155           | 3.04                     | 1.3                    | 196        |

2.3 Compression creep test method

In accordance with the “Standard for test methods of long-term performance and durability of ordinary concrete” (GB/T 50082-2009), the compression creep test of CFRC was performed with a spring creep tester. The test was performed on 100 mm×100 mm×300 mm specimens. The size of the prism compression specimen and shrinkage specimen is the same as that of the creep specimen. Furthermore, curing was performed under the same environmental conditions as those employed for the creep specimen. Testing was performed under the following conditions: loading age: 7 d, 14 d, and 28 d, loading stress level: 0.4, creep laboratory temperature: (20±2)°C, and relative humidity: (60±5)%.

3. Results and Discussion

3.1 CFRC basic mechanical properties

The flexural and compressive strength tests of reference plain concrete C0 and CFRC (C1, C2, C3) with different cellulose fiber contents are performed in accordance with the “Standard for test methods of concrete physical and mechanical properties (GB / T 50081-2019).” The test results are shown in Fig 1.

Fig 1. 28 d mechanical property of the concrete specimens

When the fiber content increases from 0.9 kg/m³ to 1.3 kg/m³, the flexural strength of concrete specimens C1, C2, and C3 increases by 6%, 13%, and 14%, respectively. Cellulose fiber plays a key role in bridging and preventing crack propagation.

With increasing fiber content, initially, the compressive strength of the concrete decreases slightly and then increases slightly. The change range is 4%, 1%, 5%, and the fluctuation range is 1.6–2.1 MPa, and the difference is even less than the fluctuation value among three specimens comprising the same group of concrete.

When cellulose fiber is added to the concrete, a weak zone is introduced between the fiber and the matrix. This fiber affects the compressive strength of the fiber reinforced concrete (in general), but adding an appropriate amount of the fiber has no effect on the compressive strength. Therefore, over a certain range, the flexural strength of concrete increases slightly with increasing cellulose fiber content, but the influence of the fiber content on the compressive strength is negligible.

3.2 CFRC specific creep

Loading age (τ) values of 7 d, 14 d, and 28 d are employed for the concrete, and the loading stress level
is 40%. The specific creep refers to the creep deformation under unit stress. The test results of concrete specific creep under three loading ages are shown in Fig 2.

![Graph showing specific creep of concrete at different ages](image)

**Fig 2. Specific creep of CFRC associated with different loading ages**

After adding cellulose fiber to the concrete, the specific creep of the concrete decreases. The specific creep occurs rapidly in the early stage and slows down gradually in the subsequent stage. In addition, the specific creep value increases with decreasing loading age.

The specific creep values of C0, C1, C2, and C3 at a loading age (τ) and load holding duration (t−τ) of (i) 7 d and 150 d, (ii) 14 d and 170 d, and (iii) 28 d and 170 d are (i) 59 × 10^{-6} / MPa, 45 × 10^{-6} / MPa, 51 × 10^{-6} / MPa, and 53 × 10^{-6} / MPa, respectively, (ii) 44 × 10^{-6} / MPa, 36 × 10^{-6} / MPa, 41 × 10^{-6} / MPa, and 39 × 10^{-6} / MPa, respectively, and (iii) 35 × 10^{-6} / MPa, 30 × 10^{-6} / MPa, 30 × 10^{-6} / MPa, and 28 × 10^{-6} / MPa, respectively. Compared with the value obtained for C0, the values obtained for C1, C2, and C3 are respectively lower by (i) 25%, 14%, and 10% (average reduction: 16%), (ii) 18%, 7%, and 11% (average reduction: 12%), and (iii) 14%, 16%, and 20% (average reduction: 17%).

With increasing loading age, the specific creep difference of CFRC with different cellulose fiber content decreases gradually. When τ = 7 d, the specific creep range of C1, C2, and C3 is 8 × 10^{-6} / MPa; when τ = 14 d, the range is 5 × 10^{-6} / MPa; when τ = 28 d, the range is only 2 × 10^{-6} / MPa. The hydration moisture of the concrete is sufficient when the loading age is small, and the concrete specific creep increases with increasing content of the cellulose fiber. When the loading age increases, the free moisture of the concrete decreases. Furthermore, the difference of specific creep between CFRC with different cellulose fiber content decreases gradually, i.e., the specific creep of CFRC decreases (in general) with increasing fiber content.

The creep performance of concrete is affected by many factors, and the creep deformation mechanism of concrete is quite complex due to the incorporation of cellulose fiber. The influence of the fiber on the creep performance of concrete is mainly affected by the dispersion of the fiber in the concrete, interface transition zone defect between the fiber and the matrix, and internal curing effect of the fiber. During curing, internal water is released, thereby promoting hydration of the surrounding matrix. The curing effect is closely related to the fiber content and loading age.

The influence of cellulose fiber on the creep performance of concrete investigated in this work is summarized as follows:

1. Cellulose fiber has a unique hollow structure and good hydrophilicity, which plays the key role in internal curing. The fiber can provide water in the subsequent hydration of concrete, improve the hydration degree of cement, improve the microstructure of concrete hydration products, and reduce the internal porosity of concrete\textsuperscript{10}. These factors are effective in reducing the creep deformation of concrete.

2. The elastic modulus of the cellulose fiber (29.0–39.0 GPa) is basically equivalent to that of the concrete matrix. The three-dimensional random distribution of the fiber in the matrix improves the anisotropic properties of concrete and inhibits the propagation of micro cracks in the concrete, thereby reducing the creep deformation of the concrete.

3. A weak interface transition zone exists between the fiber and the matrix. Increasing the fiber content will increase the size of this zone, possibly increasing the creep deformation of the concrete. According to the creep seepage theory of concrete, the creep of concrete results mainly from water...
migration in the matrix. The hollow structure of the cellulose fiber can be used as the water migration channel, which will increase the creep deformation of concrete to a certain extent.

In conclusion, the cellulose fiber has both positive and negative effects on the creep performance of concrete. On the one hand, if fully saturated when the concrete is mixed and formed, the fiber can play a good role in internal curing and optimization of the microstructure comprising the concrete; the random distribution of cellulose fiber in the matrix improves the homogeneity of the concrete and the crack resistance effect of internal micro cracks, thereby reducing the creep deformation of the concrete. On the other hand, with the addition of the fiber, the number of interfacial defects and water migration channels increases, thus increasing the creep deformation of the concrete.

3.3 CFRC creep coefficient

The creep coefficient of CFRC at different loading ages is shown in Fig 3. When the loading age (τ) and the load holding duration (t-τ) are (i) 7 d and 150 d, (ii) 14 d and 170 d, and (iii) 28 d and 170 d, coefficients of (i) 2.31, 1.90, 2.16, and 2.28, (ii) 1.79, 1.33, 1.48, and 1.50, and (iii) 1.47, 1.19, 1.33, and 1.32 are obtained for C0, C1, C2, and C3, respectively. The creep coefficient of CFRC is similar to the creep degree. After cellulose fiber is added to the material, the creep coefficient of concrete decreases. The coefficient increases rapidly in the early stage and decreases gradually in the subsequent stage. Furthermore, the coefficient increases with decreasing loading age.

3.4 CFRC creep model

Based on the creep test data, the empirical relationship between specific creep and loading age and load holding duration can be established by means of a mathematical method. The common creep expressions include the power function, exponential function, hyperbolic function, logarithmic function, power exponential function, and polynomial function. Creep expressions can be divided into two categories. In the first category, the relationship between creep and load holding duration is expressed (only the creep occurring at a certain loading age is expressed). The expressions used vary with the loading age, and despite the simplicity of each expression, use of various expressions is tedious. In the second category, the relationship between creep and loading age and load holding duration is expressed. These expressions are complex in form and require difficult calculations. However, such expressions can be used to determine the creep value associated with different loading age and different holding time. The corresponding structural stress can be conveniently calculated via the finite element method.

Based on the power exponential function model proposed by Zhu\cite{11}(see Formula 1), the creep model of CFRC is established by determining the test constant of the model. This is achieved by combining the trial algorithm\cite{12} with the programming solution method of EXCEL.

\[
C(t, \tau) = \phi(\tau) \left[ 1 - e^{-r(\tau)(t-\tau)^p} \right]
\]

where:

\[
\phi(\tau) = \phi_0 + \phi_1 \tau^{-p}, \quad r(\tau) = r_0 + r_1 \tau^{-q}, \quad S = a + b \ln(\tau)
\]
Where: $C(t, \tau)$——specific creep, $10^{-6}/$MPa; $t$——age, d; $\tau$——loading age, d; $t-\tau$——load holding duration, d; $\phi_0, \phi_1, r_0, r_1, p, q, a, b$——constant.

The test constants of the CFRC creep model are shown in Table 4. The correlation coefficient between the measured value of CFRC specific creep and the fitting value of creep model (Fig 4) is $>0.995$. The specific creep of CFRC can be well described by using a power exponential function model, and the long-term creep of CFRC under different loading ages can be predicted with high precision.

Table 4. Experimental constants of creep model for CFRC

| Mix No. | $\phi_0$ | $\phi_1$ | $r_0$ | $r_1$ | $p$ | $q$ | $a$ | $b$ |
|---------|----------|----------|-------|-------|-----|-----|-----|-----|
| C0      | 5.00     | 128.22   | 0.09  | 0.01  | 0.42| 0.10| 0.60| 0.02|
| C1      | 2.31     | 120.00   | 0.09  | 0.03  | 0.42| 0.30| 0.35| 0.09|
| C2      | 1.00     | 149.83   | 0.06  | 0.07  | 0.48| 0.10| 0.41| 0.07|
| C3      | 2.08     | 133.36   | 0.05  | 0.06  | 0.47| 0.30| 0.67| 0.01|

Fig 4. Measured and fitted values obtained for CFRC specific creep

4. Conclusions

(1) After adding cellulose fiber to the concrete, the creep degree of the concrete decreases. The creep difference of CFRC with different cellulose fiber content gradually decreases with increasing loading age.

(2) The creep coefficient and creep degree of CFRC follow a similar development law.

(3) Cellulose fiber has both positive and negative effects on the creep performance of concrete. On the one hand, the internal curing effect of the fiber can optimize the microstructure of concrete and reduce the creep deformation. On the other hand, the fiber increases the defects of water migration channels and interface transition zone, which will increase the creep deformation.
(4) The power exponential function model of CFRC expresses the relationship between creep and loading age and load holding duration, which can be used to predict the long-term creep of CFRC under different loading ages.

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