Journal of Architectural Research and Development, 2024, Volume 8, Issue 2
http://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Analysis and Prediction Model Reinforced UHPC Shrinkage Property

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Abstract: This paper explores the shrinkage of reinforced UHPC under high-temperature steam curing and natural curing conditions. The results are compared with the existing shrinkage prediction models. The results show that the maximum shrinkage strain of reinforced UHPC after steam curing is 164 με and gradually becomes zero. As for natural curing, the maximum shrinkage strain is 173 με and the value stabilizes on the 10th day after pouring. This indicated that steam curing can significantly reduce shrinkage time. Compared with the plain UHPC tested in the previous literature, the structural reinforcement can significantly inhibit the UHPC shrinkage and greatly reduce the risk of cracking due to shrinkage. By comparing the results in this paper with the existing models for predicting the shrinkage strain development, it is found that the formula recommended in the French UHPC structural and technical specification is suitable for the shrinkage curve in the present paper.

Keywords: Ultra-high performance concrete (UHPC); UHPC shrinkage; Reinforced UHPC slab; Shrinkage prediction

1. Introduction

Ultra-high performance concrete (UHPC) is a new type of cement-based material that removes coarse aggregate and replaces it with quartz sand [1]. The added silica fume, blast furnace slag powder, active admixtures, high-efficiency water reducer, and steel fiber result in ultra-high strength, high toughness, high volume stability, and excellent durability [2,3]. Due to the microfilling and pozzolanic effect of active admixture, UHPC is denser than ordinary concrete and has improved compressive strength [4]. The addition of steel fiber improved the tensile strength, mechanical strength, and toughness of UHPC [5,6]. Compared with ordinary concrete structures, the ultra-high compressive and tensile strength of UHPC can significantly reduce the overall weight and size of the structure [7,8]. The excellent impermeability and corrosion resistance can significantly improve the service life of the structure [9]. With the extremely low water binder ratio (0.14–0.19), high content of cementitious materials, high content of active minerals, and low content of coarse aggregate, the shrinkage characteristics of UHPC are quite different from ordinary concrete and conventional high-performance concrete [10,11]. Compared with ordinary concrete and conventional high-performance concrete, UHPC has the characteristics of early and rapid development of shrinkage which has a more significant influence on curing conditions [12–16].

In the curing process of reinforced UHPC structures, the shrinkage is often constrained by reinforcement, stud, steel plate, or formwork with a high risk of early cracking unlike plain UHPC material [13]. The early cracking of UHPC will significantly affect the performance of components. In harsh climate conditions, the internal steel fibers will rust, reducing the durability of the structure and bringing potential safety hazards.

Currently, most of the existing studies explore the shrinkage performance of UHPC from the material level (plain UHPC). Xie investigated three different techniques to reduce the impact of shrinkage of UHPC, namely, reducing the binder content, incorporating high levels of shrinkage-reducing admixture, and using crushed ice to partially replace mixing water [17]. The effects of these techniques are experimentally investigated and the underlying mechanisms of the actions are identified. It is found that autogenous shrinkage predominates the overall shrinkage of UHPC and that the three techniques can effectively reduce shrinkage without significantly compromising its mechanical strength. The results also suggest that from the perspective of reducing shrinkage, the optimal binder-to-sand ratio is in the range of 1–1.1, the optimal dosage rate of shrinkage reducing admixture is 1%, and replacing of mixing water by crushed ice up to 50% by weight has also induced a significant reduction in shrinkage. Valipour evaluated the efficiency of various shrinkage mitigation approaches in reducing autogenous and drying shrinkage of UHPC [18]. Meng investigated the effects of hybrid micro-macro steel and micro steel blended with synthetic fibers on creating a cost-effective UHPC [19].

It is well known that plain UHPC is rarely used in practical projects, most of which need to be reinforced by steel bars or steel plates. As a result, its shrinkage will be restrained. Once the shrinkage stress exceeds its tensile strength, the UHPC matrix will crack. However, there are few studies on the shrinkage of UHPC under this constraint. A study by Yoo described the UHPC restrained shrinkage and cracking behaviors, in which the use of expanded polystyrene and Teflon sheets with two different slab thicknesses was considered to improve the shrinkage crack resistance [20]. Free shrinkage was simultaneously measured to evaluate the degree of restraint according to the above test parameters. Yoo also studied the combined effect of shrinkage-reducing admixture (SRA) and expansive admixture (EA) on the shrinkage and cracking behaviors of restrained UHPC slabs [21]. For this investigation, six full-scale UHPFRC slabs with three different thicknesses ($h = 40$, 60, and 80 mm) were fabricated using two different mixtures. Test results indicated that the combined use of 1% SRA and 7.5% EA is beneficial to improve the mechanical strengths and to reduce the free shrinkage strain of approximately 36%–42% at 7 days. Regardless of SRA and EA contents, the slabs with the lowest thickness of 40 mm showed shrinkage cracking at a very early age, while the slabs with higher thicknesses of 60 and 80 mm showed no cracking during testing. However, the UHPFRC slab including 1% SRA and 7.5% EA exhibited a shallow crack with a very small maximum crack width of below 0.04 mm, while the slab without SRA and EA showed through cracks with a large maximum crack width of 0.2 mm. Li studied the development of early shrinkage of UHPC during heat-curing treatment [22]. Results showed that after 48 hours of heat curing, approximately 450 $\mu\varepsilon$ of early-age shrinkage was found, and early-age shrinkage decreased more with the increase of the inside longitudinal reinforcement ratio.

This paper studies the shrinkage development of reinforced UHPC under high-temperature steam and natural curing. The test results in this paper are compared with the existing shrinkage strain prediction models, and the shrinkage prediction model suitable for reinforced UHPC structures was obtained.

2. Test introduction

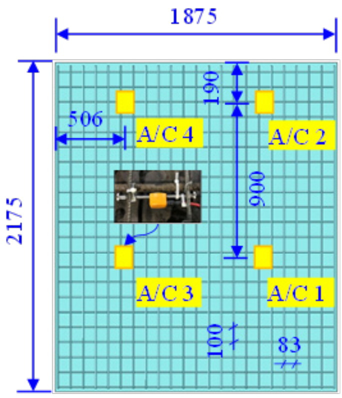

Figure 1. Schematic of test slab

A total of two test slabs of the same size were made, with a length of 2.175 m and a width of 1.875 m, as shown in **Figure 1**. HRB400 reinforcement (yield strength of 400 MPa) was configured inside, with a transverse spacing of 100 mm and a longitudinal spacing of 83 mm. The two test slabs were cured naturally or by steam in the laboratory respectively.

The shrinkage of the UHPC slab is measured by the strain gauge embedded at the four corners of the test slab. The test lasted 2112 hours (88 days, in southern China, from March to June), and the temperature range was 10.5–26.5°C. The curing time of the steam curing is 51 hours (including heating time) with a curing temperature of 98°C. After steam curing, the test slab was exposed to the environment until the temperature dropped to normal. Shrinkage measurement frequency was every 2 hours during steam curing, every 24 hours within one month after steam curing, and every 48 hours in the second month onwards.

The main materials of UHPC used in this test include cement, quartz powder, quartz sand, silica fume, superplasticizer, steel fiber, and so on. The material composition is listed in **Table 1**. Two types of hooked-end steel fiber with a volume content of 1% are used in UHPC, one has 0.2 mm diameter and 13 mm length while the other has 0.3 mm diameter and 25 mm length as shown in **Figure 2**.

Table 1. Composition of UHPC material for test

Material	Cement (PO42.5)	SiO_2	Fly ash	Quartz sand	Quartz flour	Slag powder	Superplasticizer	Water
Ratio	0.7	0.2	0.1	1.1	0.1	0.2	0.015	0.2

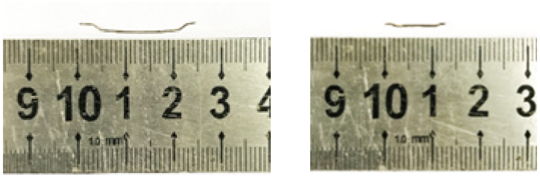

Figure 2. Schematic of steel fiber: long hooked end (left), short hooked end (right)

The properties of compressive strength, flexural strength, and elastic modulus of UHPC materials were tested according to the building technical code. Six test pieces were made for each group to ensure the accuracy of the test results. The compressive test specimen is 100 mm × 100 mm × 100 mm with a loading rate of 1.2–1.4 MPa/s. The bending test specimen is 100 mm × 100mm × 400 mm with a loading rate of 0.08–0.1 MPa/s. For the elastic modulus test, 100mm × 100mm × 300 mm with a loading rate of 1.2–1.4 MPa/s was applied. The mechanical properties of UHPC are shown in **Table 2**.

Table 2. UHPC mechanical properties

Curing condition	Fibre type (diameter×length, volume content)	Compressive strength (MPa)	Flexural strength (MPa)	Elastic modulus (GPa)
Steam	0.2 × 13mm, 1%	139.6	23.7	42.7
Natural	0.3 × 25mm, 1%	137.1	25.3	42.5

3. Test results and discussion

3.1. Reinforced UHPC shrinkage test results

The test results are shown in **Figures 4 and 5**. **Figure 4** shows the test results of natural curing specimens. It can be seen from the curve development in the figure that the shrinkage of UHPC during natural curing develops rapidly in the first 250 hours and then keeps fluctuating until the end of the test. The maximum shrinkage strains of A1–A4 are 141 με, 87 με, 173 με, and 119 με respectively, with an average of 121 με. Among them, the shrinkage strain of A1 and A3 located in the relative middle of the test slab is larger than that of A2 and A4 located in the relative edge, which indicates that the middle of the test slab has a more considerable constraint that produces an enormous shrinkage strain with a maximum difference of about 54 με.

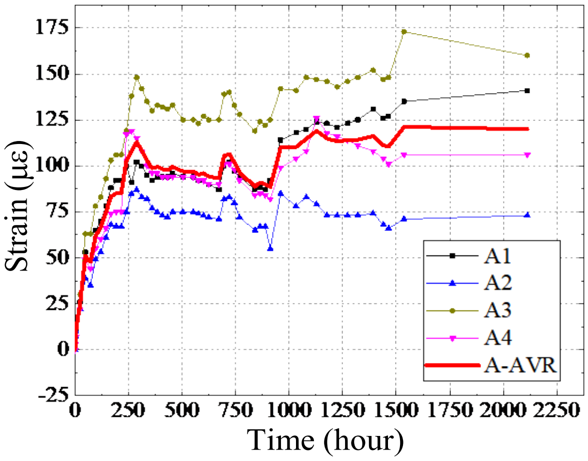

Figure 4. Shrinkage strain development of natural curing

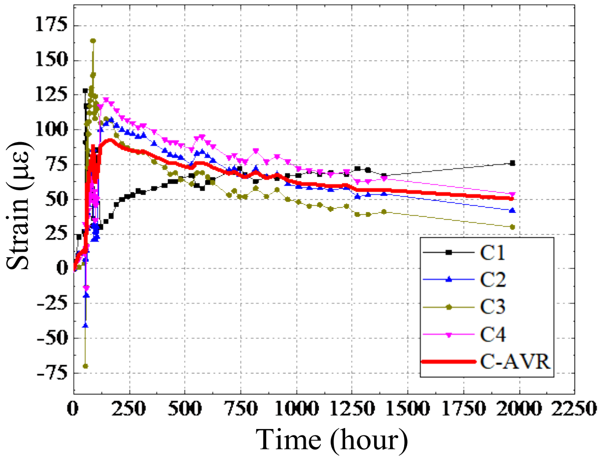

Figure 5. Shrinkage strain development of steam curing

Figure 5 shows the test results of steam curing samples. The shrinkage strain of the test slab cured by high-temperature steam developed rapidly within 48 hours and then decreased slowly until stable. The maximum test values of C1–C4 are 128 με, 107 με, 164 με, and 122 με respectively with an average value of 130 με. When the test time reaches 2,000 hours, the shrinkage strain of the structure is stable, which is 30–76 με. Moreover, the values of C2 and C4 are also slightly larger than those of C1 and C3, showing again the pattern that large shrinkage strain will occur when the middle of the test slab is subject to large constraints.

Zhang carried out several direct tensile tests on reinforced UHPC [23]. The results show that when the 2% reinforcement ratio of a UHPC structure with a steel fiber content of 2%, its visible initial crack strain is 1,777 με. When the reinforcement ratio reaches 3.5%, the visible initial crack strain can reach 2,088 με. It can be seen that the above shrinkage strain is far less than the visible initial crack strain of the structure in the test. Therefore, naturally cured UHPC will not have initial damage due to material shrinkage, indicating that naturally curing UHPC structure is feasible in engineering.

3.2. Plain UHPC shrinkage properties discussion

This paper collects the maximum shrinkage strain test results of some UHPC materials tests under different curing conditions as shown in **Table 3**. In the table, the shrinkage strain of the UHPC at different natural curing ages is 200–900 με. At different curing conditions or steam temperatures, the shrinkage of the UHPC is 622–900 με. After the steam curing, the shrinkage of the UHPC decreased to zero. Therefore, the recommended value of UHPC shrinkage strain for steam curing is 550 με and then decreased to zero. For natural curing, the shrinkage strain in the first 60 days is 700 με [24].

Table 3. Shrinkage of UHPC under different conditions

Curing condition	Test duration (day)	Autogenous contraction (με)	Total (με)	After steam (με)	Literature
90℃, 60℃ steam	4,21,28		622–766	0	[25]
Natural	28		555		[25]
90℃ steam	3.5	60/h	850	0	[25]
Natural	40	400	790		[25]
Natural	28	600–900			[26]
Natural	150	200–550			[27]
Natural	365	640			[28]
Sealed steam	7,28		700,900	0	[29]

Compared to the test results of the present paper (**Figures 4 and 5**), the maximum shrinkage strain of the UHPC slab is 173 με after 88 days of natural curing and 164 με after steam curing, while the shrinkage strain remains almost unchanged after steam curing. Compared with the values in the table above, it is shown that structural reinforcement has a tremendous inhibiting effect on UHPC shrinkage and the shrinkage strain of the material in the UHPC structure after steam curing will not change.

3.3. Effect of reinforcement on UHPC structure shrinkage

There are few studies on the shrinkage properties of reinforced UHPC. Yoo studied the influence of different reinforcement types on the shrinkage of UHPC materials [30]. The results showed that a lower reinforcement ratio and stiffness could reduce the self-shrinkage property, restraint degree, and cracking risk of the material. The study also indicated that the deformed steel bar has the highest shrinkage stress and cracking risk, while the plain round steel bar has the highest degree of restraint.

Oesterlee proposed the restrained shrinkage strain calculation formula for reinforced UHPC shown below [31].

$$\varepsilon_{c,shr}=\frac{\varepsilon_{cs}-\varepsilon_{c,creep}}{1+\alpha_E\rho_s} \qquad (1)$$

For **Equation 1**, ε_{cs} is the free shrinkage strain of UHPC, $\varepsilon_{c,creep}$ is the creep strain, α_E is the elastic modulus ratio of reinforcement, and UHPC, ρ_s is the reinforcement ratio.

It can be seen from the above calculation formula that the restrained shrinkage strain of the UHPC structure is related to the creep of material, elastic modulus ratio, and reinforcement ratio. The shrinkage strain of the structure decreases gradually with the increase of the reinforcement ratio.

Shao conducted shrinkage tests on two steel-UHPC lightweight composite deck models, and the results showed that no shrinkage cracking was found on the test model surface under the two curing conditions [32]. Furthermore, the UHPC slab shrinkage test value under natural curing conditions is 161 με. After steam curing, the maximum shrinkage strain of the UHPC slab on the 10th day is mostly stable at 82 με with the calculation method of shrinkage stress of the steel-UHPC lightweight composite bridge deck proposed.

3.4. Shrinkage prediction model of reinforced UHPC

The concrete shrinkage prediction model is obtained by regression of measured data. The regression formula applicable to this sample cannot be accurately obtained due to only eight measuring points of the structure are being tested in this paper. Therefore, the regression formula in the existing literature is used to find a suitable model for the shrinkage performance of reinforced UHPC slabs.

The existing standard shrinkage prediction models include the B3 model (**Equation 2**), ACI209 (92) (**Equation 3**), CEB1990 (**Equation 4**), CEB1990/99 (**Equation 5**), Mazloon model (**Equation 6**) as well as the prediction model proposed in Swiss UHPC structural design specification (**Equation 7**) and French UHPC structural technical specification (**Equation 8**) [33–39]. The meaning of the letters in the equations can be found in each of the papers.

$$\varepsilon_{sh}(t,t_0) =- \varepsilon_{sh\,\infty} k_h S(t) \tag{2}$$

$$\varepsilon_{sh}(t) = t/(35+t)\cdot \varepsilon_{sh}(u) \tag{3}$$

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cs0}\beta_s(t-t_s) \tag{4}$$

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cas}(t) + \varepsilon_{cds}(t,t_s) \tag{5}$$

$$\varepsilon(t,t_0) = \frac{(t-t_0)}{(t-t_0)+(0.3SF+12.6)} Y(516E-6) \tag{6}$$

$$\varepsilon_{Us} = \varepsilon_{Us\,\infty} e^{\frac{c}{\sqrt{t+d}}} \tag{7}$$

$$\varepsilon_{re}(t) = A\,exp\left[\frac{B}{\sqrt{t+C}}\right] \tag{8}$$

By comparing the above model with the natural curing shrinkage results in the present test, the results shown in **Figure 6** can be obtained. It can be seen from the figure that the formula proposed in the French UHPC structural design code can better predict the test results in this paper. The most significant deviation is the model proposed by Mazloon. ACI-209-92, CEP-FIP-1990, and the Swiss UHPC technical code which underestimate the test results of shrinkage strain to varying degrees.

According to the above test results, there is only a slight difference between the maximum shrinkage strain value obtained by steam and natural curing. When natural curing is utilized, the shrinkage strain gradually stabilizes on the 10th day whereas the steam curing accelerates this process. Therefore, when steam curing is applied, large time parameters can be used to predict the maximum shrinkage strain of UHPC materials.

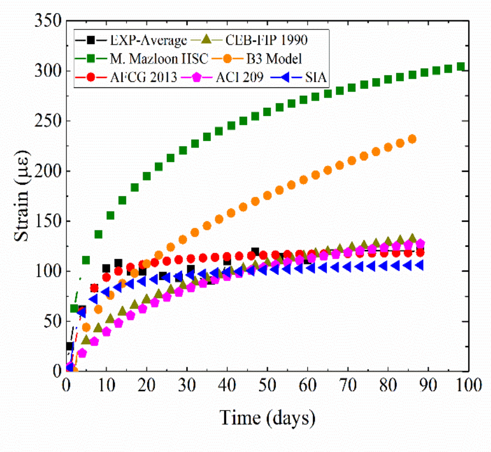

Figure 6. Shrinkage prediction results

4. Conclusion

In this paper, the shrinkage development law of reinforced UHPC under different conditions (high-temperature steam curing and natural curing) is studied and then the results are compared with the existing shrinkage prediction models with the following conclusions obtained.

The shrinkage tests show that the maximum shrinkage strain of reinforced UHPC after steam curing is 164 με and it gradually becomes zero. For natural curing, the maximum shrinkage strain is 173 με and this value stabilizes on the 10th day after pouring. This shows that steam curing can significantly reduce shrinkage time. Compared with the plain UHPC tested in the previous literature, structural reinforcement can significantly inhibit UHPC shrinkage and greatly reduce the risk of cracking due to shrinkage.

By comparing the results in this paper with the existing models for predicting the shrinkage strain development, it is found that the formula recommended in the French UHPC structural and technical specification is suitable for the shrinkage curve in the present paper.

Funding

The authors acknowledge the financial support received from the National Natural Science Foundation of China (No. 52108211), Hunan Provincial Department of Education (No. 21B0188), and Natural Science Foundation of Hunan Province (No. 2022JJ40186), Water Resources Science and Technology Program of Hunan Province (No. XSKJ2023059-44).

Disclosure statement

The author declares no conflict of interest.

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