EARLY-AGE SHRINKAGE DEVELOPMENT OF ULTRA-HIGH-PERFORMANCE CONCRETE UNDER HEAT CURING TREATMENT

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Abstract

The effects of a novel heat curing regime and longitudinal reinforcement ratio on early-age shrinkage of ultra-high performance concrete (UHPC) were experimentally investigated in this study. The microstructure, porosity and calcium hydroxide (CH) content of UHPC after different heat curing durations were characterized with scanning electron microscopy, mercury intrusion porosimetry and thermal analysis. The results indicate that slight shrinkage was observed when the heat curing duration was less than 60 min and curing temperature reached 48°C. However, when the heat curing duration approached 70 min and curing temperature was around 55°C, the early-age shrinkage increased dramatically. It was found that the early-age shrinkage is approximately 450 με after 48 h of heat curing. The results also show that the early-age shrinkage of UHPC significantly decreased by percentage of 33 to 60 % with the increase of longitudinal steel reinforcement ratio from 2.0 to 4.52 %.

Résumé

L'effet d'un nouveau programme de traitement thermique et celui du pourcentage d'acier longitudinal sur le retrait au jeune âge d'un béton à ultra-hautes performances (BUHP) ont été étudiés expérimentalement. La microstructure, la porosité et la teneur en hydroxyde de calcium du matériau ont été caractérisées après différentes durées de traitement thermique par microscopie électronique à balayage, porosimétrie au mercure et analyse thermique. Les résultats indiquent qu'un léger retrait est observé pour une durée de traitement thermique inférieure à 60 mn à une température de 48°C. Au contraire pour une durée de traitement thermique approchant 70 mn à une température d'environ 55°C, le retrait au jeune âge augmente de façon très importante. On a obtenu un retrait au jeune âge d'environ 450 με au bout de 48 heures de traitement thermique. Les résultats montrent également que le retrait au jeune âge du BUHP diminue nettement, de 33 à 60 %, avec l'augmentation du pourcentage d'acier longitudinal, de 2,0 à 4,52 %.

1. INTRODUCTION

Ultra-high-performance-concrete (UHPC) is a kind of cement-based composite materials designed to have increased strength, enhanced toughness, volume stability and improved durability [1,2]. As for the raw materials of UHPC, quartz sand is usually used instead of coarse aggregate, and silica fume, ground granulated blast-furnace slag, superplasticizer and steel fibers are added with a relative lower water to binder ratio (w/b less than 0.18) [3, 4]. Because of the physical filling and pozzolanic effects of reactive powder composites, the UHPC usually has denser microstructures and greater mechanical properties compared to normal strength concrete [5]. Additionally, when incorporating steel and polymer fibers into UHPC, the tensile strength and ductility, and the blast resistant capacity under impact loading can be significantly improved. Previous studies have mentioned that early-age shrinkage can cause early-age cracking, thus having a considerable effect on the structural performance of reinforced concrete structures under service load conditions [6, 7]. As the water to binder ratio of UHPC is extremely low, the cement hydration and secondary hydration of reactive additions consume a large amount of water. Therefore, menisci are formed in the fluid capillaries which result in greater negative capillary pressure and eventually high shrinkage at early-age in UHPC leading to cracking and damage [8, 9]. Compared to standard curing methods at 20°C, the compressive and flexural strengths of UHPC cured at 90°C of heat curing are 20 and 10% higher, respectively [10]. High temperature curing may result from hot weather, accumulated heat of hydration or applied heat. Compared to the standard curing, the heat curing is usually used in the production of precast concrete products primarily in order to increase the early-age strength [11, 12]. It is found that heat curing treatment can be also designated to reduce shrinkage and cracking initiation in reinforced UHPC structures [2, 13, 14]. After heat curing, the volume change of UHPC usually results in autogenous shrinkage [15, 16]. Because the UHPC specimen is fully immersed into heated water during heat curing, there is no water evaporation from the specimen's surface. Thus, the early-age shrinkage of UHPC seems to be reduced by the heat curing. Up to now, the early-age strength of UHPC in various curing conditions was extensively studies [2, 17, 18]. The results show that adequate curing is essential for reducing shrinkage in UHPC when different shrinkage mitigation methods are applied. Adding partially hydrated cementitious material can reduce early-age autogenous shrinkage of UHPC [19]. The preparing UHPC using 20 to 30% of the porous ceramic coarse aggregate by volume as a partial replacement of the total coarse aggregate content can significantly reduce the magnitude of autogenous shrinkage and the induced self-stress of UHPC [20]. Many experiments on controlling the early-age shrinkage of UHPC have been carried out comprehensively from the material level [2, 7]. The studies revealed that expansive additive, shrinkage-reducing chemical agent, as well as Portland cement containing higher C2S content and lower contents of C3A or C4AF were effective for reducing the early-age shrinkage of UHPC.

While substantial research has focused on evaluating the early-age shrinkage of different UHPC mixtures under standard curing conditions, limited researches have explored on the early-age shrinkage of UHPC during heat curing process. Although few studies have been conducted on the early-age shrinkage of UHPC after heat curing treatment, it is necessary to understand the early-age shrinkage development rate of UHPC during heat curing process with different heat curing durations. In this study, a fundamental approach based on the progress of hydration is adopted in an attempt to evaluate the effects of heat curing regime

and longitudinal reinforcement ratios on the development rate of early-age shrinkage of UHPC. The early-age shrinkage of UHPC during an ascending-stable-descending temperature ramp is first experimentally investigated. The results will exhibit important implications in better understanding the evolution of early-age deformation of UHPC for the precast and cast-in-place concrete structure application.

2. EXPERIMENTAL PROGRAM

2.1 Materials and sample preparation

Ordinary Portland cement (P.O 42.5), fly ash, silica flour and silica fume were used as binders for the UHPC mix design. The chemical composition of the various binders is listed in Table 1. Quartz sand having particle sizes in the range of 0.9 to 2.0 mm was used instead of coarse aggregates [11, 21]. Silica flour with a density of 2.626 g/cm^3 and average particle size of 50.1 μm was used. The average particle size and specific surface of silica fume (Shanxi Xinzhou Ferro Alloy Co., Ltd., China) are 88 nm and 1850 m^2/kg, respectively. The gray fly ash has chemical composition which include SiO_2 (42.52 %) and Al_2O_3 (32.62 %). The steel fiber coated with copper has a length of 8 mm and diameter of 0.2 mm (slenderness ratio of 40) and the volume fraction of steel fiber is 3.5% of UHPC mix proportion. A poly carboxylate-based high-range water-reducing admixture (HRWRA) was used at a ratio by 2 % of the binder mass. The mix design proportions of the UHPC are shown in Table 2.

Table 1 Chemical composition of binder materials

Composites	Cement (P.O 42.5)	Fly ash	Silica flour	Silica fume
SiO_2 (%)	23.3	42.52	99.3	93.90
Al_2O_3 (%)	7.2	32.62	—	—
Fe_2O_3 (%)	3.1	9.35	—	0.59
SO_3 (%)	3.0	1.21	—	—
CaO (%)	59.6	8.63	—	1.85
MgO (%)	1.7	0.73	—	0.27
K_2O (%)	—	2.16	—	0.86
Na_2O (%)	—	0.59	—	0.17
Total (%)	97.90	97.81	99.3	97.64

Table 2 Mix proportion design of UHPC (mass/cement mass ratio)

Cement	Quartz sand	Silica flour	Silica fume	Fly ash	Water/binder ratio
1.0	1.1	0.25	0.25	0.1	0.18

Steel fiber is 3.5% by volume fraction. Superplasticizer is 2% of binder by mass.

UHPC mixing procedure was carried out in a rotary mixer according to the method presented in previous work [3, 4]. First, the cement, silica flour, quartz sand, silica fume and fly ash were added to the mixer and mixed at medium speed (80 rpm) for 5 min. After that, water containing the super plasticizer was added and mixed at a high speed for additional 5 min. Then steel fiber was added gradually to mix for another 6 min. The UHPC specimens for 10 thermal groups with total 30 specimens were cast into steel moulds with sizes of 25 mm ×25 mm ×280 mm for thermal expansion coefficient measurement. Another total 12 UHPC specimens of 100 mm ×100 mm ×515 mm for 4 groups with different longitudinal reinforcement ratios ranging from 0 (B0), 2.00 (B1) to 3.14 (B2) and to 4.52% (B3) [22], as shown in Table 3. The diameters of longitudinal steel bars are 8, 10 and 12 mm and the concrete cover thickness is 20 mm. After the prismatic specimens were cast, they were immediately covered with plastic watertight foil and wet burlap to avoid water evaporation and ensure a continuous moist-curing during the early-age. All the UHPC specimens were stored in standard curing conditions at 20 ±2 °C and relative humidity of 90 ±5% for 48 h, then were demoulded and prepared for the heat curing treatment later.

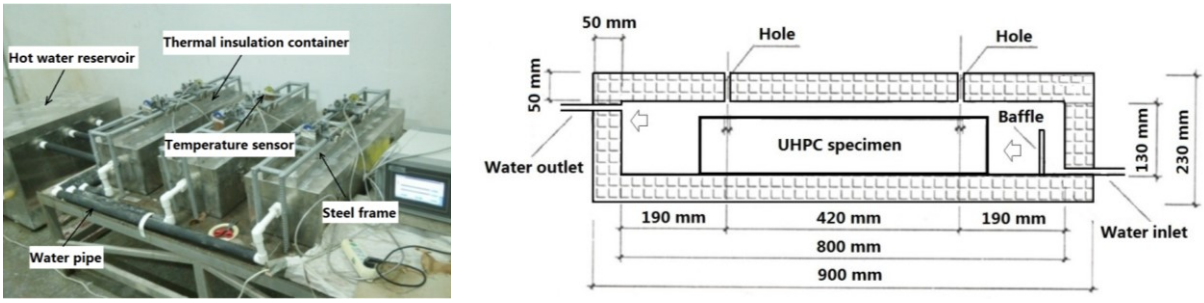
Table 3 Longitudinal reinforcement ratios of UHPC

Specimen	Cross section (b×h)	Reinforcing bar (Q235) [16]	Reinforcement ratio
B0	100 mm ×100 mm	—	—
B1	100 mm ×100 mm	4 ϕ8 mm	2.00 %
B2	100 mm ×100 mm	4 ϕ10 mm	3.14 %
B3	100 mm ×100 mm	4 ϕ12 mm	4.52 %

Steel rebar length and cover thickness are 525 mm and 20 mm, respectively.

2.2 Experimental program

A novel apparatus was designated in this study to effectively measure the early-age shrinkage of UHPC during heat curing as shown in Fig. 1. The enclosed or sealed condition was realized by tightly wrapping the specimen with polyethylene sheet to ensure that the internal moisture does not evaporate. This apparatus consists of thermal control system, hot water reservoir, thermal insulation container and temperature sensor. The thermal insulation container was typically made of a 50 mm thick polystyrene panel, wrapped with 1.0 mm thick stainless steel plate as protective cover. There was a small hole through the cover-board of the thermal insulation container, from which the water height marker was configured and could move freely in the vertical direction. The temperature sensors were fastened on the steel frame to detach from the thermal insulation container with the aim to avoid ambient disturbances. During both the temperature raising and cooling periods of the thermal insulation container, a certain target curing temperature in range of 20 to 90°C can be attained using the temperature control system. After the preset period, the sealed UHPC specimens were transferred to curing thermal insulation container and submerged in circulating water which was gradually heated. The temperature was measured by the temperature sensor. In hot water reservoir, the water temperature was elevated by heating pipes. Furthermore, a control valve of water level was used to make sure that heat water could be automatically added to heat reservoir water when the hot water level becomes lower than the defined value because of the water evaporation during heating.



(a) Thermostatic apparatus (b) Cross-section view

Figure 1: The overview of thermostatic apparatus for heat curing of UHPC

The early-age shrinkage development rate of UHPC during heat curing was measured using a non-contact shrinkage measurement according to the standard of test methods of long-term performance and durability of ordinary concrete. For more related details about this measurement, the readers can refer to GB/T 50082-2009 [23, 24]. As for the measurement of thermal expansion coefficient induced due to the heat curing, UHPC specimen of 25 mm × 25 mm × 280 mm was used to calibrate the thermal expansion coefficient. Each group had three duplicate UHPC specimens. The UHPC specimens with embedded steel pins at the ends were cured in standard condition at 20 ±2 °C and relative humidity (RH) of 90 ±5% for 48 h and then were demoulded. Then the specimens were completely immersed in hot water at different temperatures for 5 h to make sure the internal parts reach the same temperature with the ambient hot water. The temperature for UHPC increased gradually from 5 to 50°C at a step of 5°C by the temperature control system, as shown in Table 4. After 5 h full immersion, the specimens were removed from the hot water, and saturated surface dry condition without free moisture was obtained with a wet cloth. After the steel pins were cleaned, length comparator was quickly used to measure the length of specimen according to the standard test method for drying shrinkage of cement mortar [25]. Although the thermal expansion coefficient of UHPC is likely influenced by many factors such as curing temperature and curing duration since the microstructure of UHPC changes with the hydration, the measured lengths of UHPC specimen at different temperatures were still well fitted to a linear line by the least square method. Consequently, the thermal expansion coefficient was obtained by dividing the slope of the linear fitting by the distance between two pins of the UHPC specimen.

Table 4 Thermal expansion coefficient measurement of UHPC

Specimens	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
Temperature (°C)	5	10	15	20	25	30	35	40	45	50

3. RESULTS AND DISCUSSIONS

3.1 Thermal expansion during heat curing

Based on measurement results, the thermal expansion coefficient of UHPC was estimated be approximately 11.76 $\times 10^{-6}/^{\circ}$C, which is very close to the value of 11.0 $\times 10^{-6}/^{\circ}$C proposed by the French Society of Civil Engineering and previous results [5, 26]. So the thermal

expansion coefficient of UHPC was set as 11.76 $\times 10^{-6}/^{\circ}C$, including when the heat curing temperature reached 90°C. In spite of the thermal expansion coefficient of UHPC changes during heat curing, it is still reasonable to use this constant value to calculate early-age shrinkage. The curing temperature of hot water in insulation container was measured by ambient temperature sensor, and the temperature was recorded as a function of time as shown in Fig. 2. The total duration of heat curing treatment was 48 h, and each temperature ascending and descending periods lasted 2.5 h, respectively. The period of constant temperature of 90°C lasted a total of 43 h. For the thermal expansion coefficient, the thermal expansions of UHPC were calculated at different curing temperatures. For instance, the thermal expansion strain of UHPC was calculated to be 823.2×10^{-6} when the curing temperature reached 90°C.

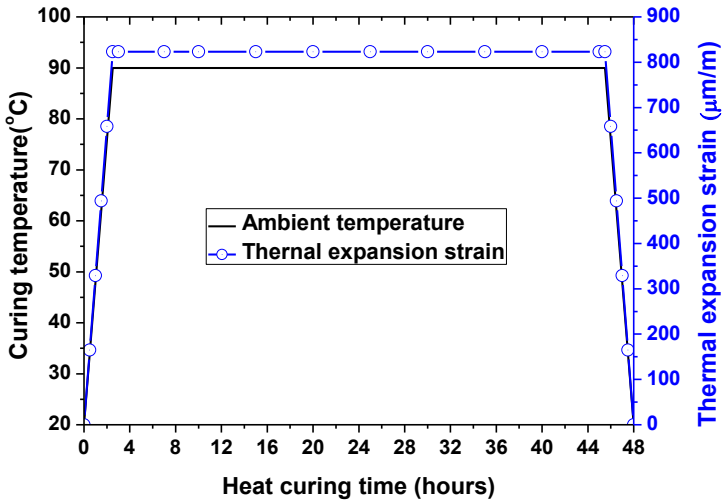


Figure 2: Ambient temperature and thermal expansion strain of UHPC during heat curing

3.2 Early-age shrinkage development

The observed early-age shrinkage (Am) of UHPC in the temperature insulation container during heat curing was determined by the non-contact length comparator. So the real shrinkage (Aa) of UHPC during heat curing from room temperature of 20 to 90°C can be calculated using the observed shrinkage minus the thermal expansion (At), which is defined as in the equation of Aa=Am-At, as shown in Fig. 3. In fact, the real shrinkage (Aa) exclusive of thermal expansion indicates early-age shrinkage deformation due to the autogenous and drying shrinkages of UHPC under heat curing [16, 27].

Figure 4 shows the early-age shrinkage development of UHPC as a function of curing temperature during the ascending period. It is observed that at the first 60 min curing period when the curing temperature reached 48°C and there was just slight shrinkage occurred, which was attributed to the low cement hydration degree during the beginning of heat curing with short curing period and moderate temperature. Also, as the UHPC specimen was fully immersed in the hot water, so it was reasonable to assume that there was not dry shrinkage resulting from the gel water evaporation. However, when the heat curing duration was more than 60 min, the early-age shrinkage became much more pronounced. This implied that the

chemical hydration of the internal cement matrix obviously accelerates, consequently resulting in larger volume shrinkage. Moreover, when the curing duration reached 70 min and the curing temperature approached 62°C, the early-age shrinkage increased significantly. It maintains that the high curing temperature can effectively promote the secondary hydration of the reactive addition powder in UHPC [28, 29]. From Fig. 3, the ultimate early-age shrinkage after 48 h heat curing treatment was around 450 με, which is relatively lower compared to other studies, and shrinkage development rate is obviously much faster [2, 20]. After 2.5 h heat curing during temperature ascending period, the early-age shrinkage was 260 με, which approximately accounts for 58 % of the ultimate shrinkage. It shows that after 3 h heat curing, the shrinkage increment gradually decreased and stabilized. This indicates that the internal chemical hydration progressively decreased, and simultaneously the early-age shrinkage development caused by hydration also slowed down. For instance, when UHPC specimen was heat cured for more than 10 h, the shrinkage development almost kept constant. It is concluded that that the cement hydration and secondary hydration tend to finish, and there is no evidence for further early-age shrinkage after 10 h heat curing. In other words, the heat curing accelerates the cement hydration and secondary hydration in UHPC, and enables early-age shrinkage to finish after 10 h of heat curing [30].

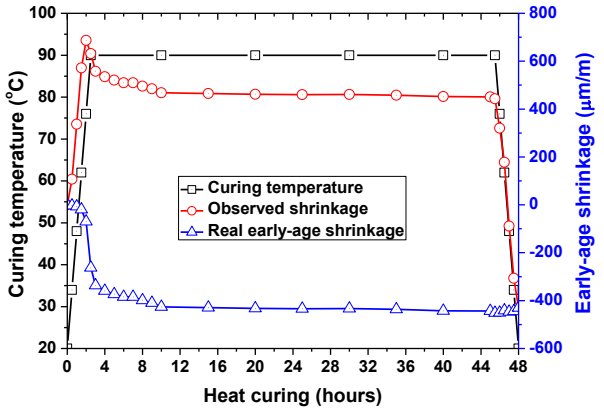


Figure 3: Early-age shrinkage of UHPC as a function of heat curing duration

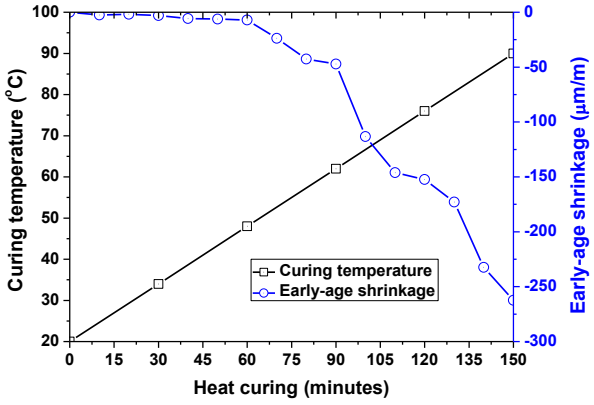


Figure 4: Early-age shrinkage of UHPC during temperature ascending related to Fig. 3

3.3 Effect of reinforcement ratio on shrinkage development

The early-age shrinkage development of UHPC with different longitudinal steel reinforcement ratios ranging from 0, 2.00, 3.14, to 4.52% were measured after heat curing treatment. Figure 5 shows that for all of the UHPC specimens with different reinforcement ratios, the early-age shrinkage tends to stabilize after 10 h of heat curing. As for the specimens with reinforcement ratios of 0, 2.00, 3.14 and 4.52%, the ultimate early-age shrinkages after 48 h of heat curing were 450, 300, 250 and 180 με, respectively. The results illustrate that the longitudinal reinforcements of UHPC can effectively reduce the early-age shrinkage by restraint effect, which agrees well with the other researcher's results [31, 32]. Moreover, it should be noted that this restraint effect become much more pronounced with the increase of steel reinforcement ratio.

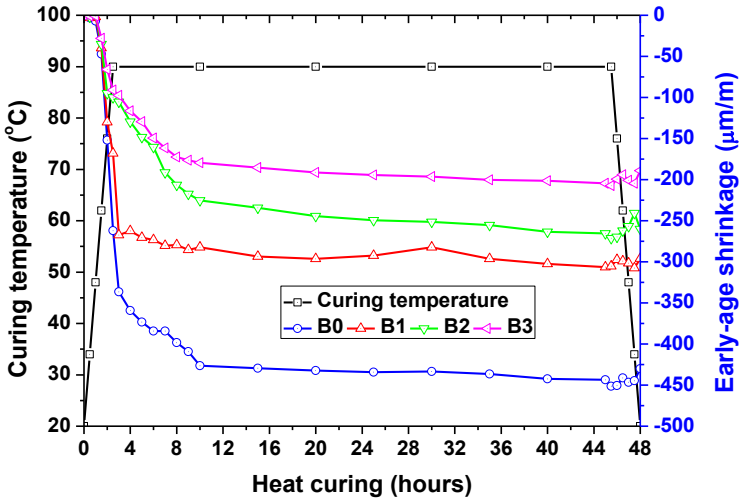


Figure 5: Early-age shrinkage for different longitudinal reinforcement ratio under heat curing

4. CONCLUSIONS

The effects of heat curing and longitudinal steel reinforcement on the early-age shrinkage of UHPC were experimentally investigated. When curing temperature was below 48°C, little early-age shrinkage of UHPC cured for 60 min was found. But after 90 min of heat curing when curing temperature approached 62°C, the shrinkage development rate became much faster. However, after 10 h of heat curing at 90°C, the shrinkage tended to stabilize, which indicates that chemical hydrations seem to finish in UHPC. The ultimate shrinkage of UHPC after 48 h of heat curing was approximately 450 με. The early-age shrinkage development during curing temperature ascending for UHPC with different longitudinal steel reinforcement ratio is basically similar to each other, which accounts for around 50 % of the ultimate shrinkage. However, during the heat curing period between 90 min and 10 h heat curing, the early-age shrinkage dramatically decreased with the increase of reinforcement ratio. Thus the higher reinforcement ratio is more likely to restrain shrinkage development.

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