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Shrinkage characteristics of heat-treated ultra-high performance concrete and its mitigation using superabsorbent polymer based internal curing method

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ABSTRACT

The shrinkage and cracking risk of heat-treated ultra-high performance concrete (UHPC) can be mitigated by using the superabsorbent polymer (SAP)-based internal curing method. The heat treatment (HT) accelerates the hydration reaction and resulting self-desiccation of UHPC; consequently, the UHPC experiences severe shrinkage during the HT. This study experimentally demonstrates that the shrinkage is effectively resolved by adopting the SAP-based internal curing method during the HT period as well as early-ages. This method also reduces the strain rate resulting from dimensional change, without showing an increase in drying shrinkage. The accurately conducted experiments herein can help to better understand the shrinkage characteristics of heat-treated UHPC and broaden the application of various internal curing agents.

1. Introduction

Ultra-high-performance concrete (UHPC) exhibits outstanding compressive strength (over 150 MPa), durability, and ductile behavior in tension, with the incorporation of metallic fibers [1–4]. In view of its various applications, including in architectural components, the latest standard classified UHPC more widely as concrete with a strength of over 130 MPa that contains specific types of fibers such as synthetic fibers [4,5]. This concrete is typically subjected to heat treatment (HT) (90 °C and relative humidity (RH) > 90%) for 48 h [1–3,6–10], which ensures its outstanding performance [11,12]. UHPC for architectural precast elements is subjected to HT at a lower temperature (60 °C and RH of 95%) for 72 h [13]. This also satisfies a condition for normal precast concrete, which requires the maximum temperature to be lower than 70 °C to avoid delayed ettringite formation (DEF) [14,15].

In UHPC, autogenous shrinkage (AS) accounts for a large proportion of total shrinkage (TS) which is the shrinkage measured under air-drying conditions [2,16,17]. An extremely low water-to-cement (w/c) ratio and high silica fume-to-cement ratio accelerate self-desiccation and the resultant AS [18,19]. The addition of silica fume accelerates the pozzolanic reaction, and also leads to a finer pore structure [20]. Furthermore, HT accelerates the reaction between the silica fume and portlandite [6] while changing the microstructure due to the additionally formed calcium-silicate-hydrate (C-S-H) gel [10]. Although the HT improves mechanical performance of UHPC in the early stages, it can also increase the magnitude and rate of AS due to the accelerated pozzolanic reaction and finer pore structure [2,21–24]. The reduction in the pore size causes an increase in capillary forces by self-desiccation [25,26], suggesting that the HT is a definite factor contributing to increased AS of UHPC. Heat-treated UHPC has exhibited higher volumetric reduction than ambient-cured UHPC at 40 d; especially, the shrinkage rate was up to 10 times higher due to the HT [27].

Regarding the risk of early-age cracking, the rate of shrinkage is known to be more critical than its magnitude [24,25,28]. A higher curing temperature can increase the risk of cracking due to increased shrinkage rate [24,25]. Previous studies have shown that

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high-performance concrete cured at over 30 °C exhibited more early-age cracks than that cured below 20 °C [25]. If practical curing temperature is not accurately reflected in the test, the cracking risk and deformation by shrinkage can be underestimated [21]. Hence the actual curing condition should be considered to evaluate the risks properly, especially when deformed bars are used to reinforce concrete [2]. However, most studies on the shrinkage of UHPC have considered room temperature conditions [29–32]. Only few studies have focused on AS under HT [33], perhaps because of the complexities and challenges associated with experiments, such as measurement of hydration heat and shrinkage, under HT conditions. Therefore, the impact of HT on the magnitude and rate of shrinkage has not been fully elucidated. More importantly, suitable methods to overcome the cracking problem of heat-treated UHPC have not been established.

Given the composition characteristics of UHPC, such as densely compacted fine particles (<1 mm) and low w/c ratio [10,13], one of the potential methods to mitigate its shrinkage (mostly AS) is the internal curing method using a superabsorbent polymer (SAP). Previous studies have confirmed that this method effectively reduces AS and the risk of early-age cracking under ambient-curing conditions [26,31,34,35]. The SAP releases the absorbed water gradually within the concrete, which maintains a high internal RH after self-desiccation commences. This mechanism can be similarly applied to mitigate the accelerated shrinkage or cracking risk of UHPC due to HT. Therefore, the objectives of this study are to elucidate the shrinkage behavior of heat-treated UHPC and to evaluate the effectiveness of internal curing using SAP in shrinkage reduction. By using this method, cracking risk of UHPC can be fundamentally resolved during the HT period as well as early-ages. For the verification, the shrinkage of the sealed UHPC, TS, and internal temperature (IT) were measured under HT condition of 60 °C. The complex phenomena related to the shrinkage, strain rates, and hydration kinetics were discussed to examine the effectiveness of the SAP as an internal curing agent.

2. Materials and methods

2.1. Preparation of UHPC with or without SAP

The prepared UHPC samples are composed of ordinary Portland cement-type I (Hanil Cement Co., Ltd., Korea), silica fume (Grade 940U, Elkem, Norway), silica powder, silica sand, steel fiber, water and superplasticizer (polycarboxylate-ether type). By the mix proportions shown in Table 1, the samples were prepared using 5 L Hobart mixer as in our previous studies [36–40]. The chemical compositions (by X-ray fluorescence using XRF-1700, Shimadzu) and particle size distributions (by laser diffraction method using Mastersizer 3000, Malvern Instruments) of the dry materials are presented in Table 2 and Fig. 1, respectively. The silica sand used is primarily composed of SiO_2 components (>90%). The internal curing of low w/c ratio concrete with SAP is dependent on its type, especially on its anionic group density [41]. Therefore, two chemically different SAPs (SAP_AA and SAP_AM) having similar particle sizes (100–700 μm) were used to investigate their effect on the shrinkage and hydration reaction. The (poly)acrylic acid (e.g., SAP_AA) and the (poly)acrylic acid-*co*-acrylamide types (e.g., SAP_AM) are the most commonly used types in cement-based materials [42]. Despite the similarity in size, the particle shapes of SAP_AA (irregular) and SAP_AM (spherical) are completely different due to differences in their manufacturing methods. The physical and chemical characteristics of the SAPs used have been previously reported in detail [36,37].

As presented in Table 1, two ordinary UHPCs (O-UHPCs), named Ref_0.215 and Ref_0.255, and two internally cured UHPCs (I-UHPCs), named AA_0.255 and AM_0.275, were prepared. These have varying w/c ratios, with the exception of Ref_0.255 and AA_0.255. The w/c ratios of the three samples (Ref_0.215, AA_0.255, and AM_0.275) were determined to satisfy the target slump-flow diameter, 750 ± 50 mm (see Table 1) [39,40]. It is common practice to increase the w/c ratio of I-UHPC to compensate for the reduction in flowability due to the absorption capacity of SAP [31,35,36,41]. Therefore, the w/c ratios of AA_0.255 and AM_0.275 are 0.04 and 0.06 higher than that of Ref_0.215, respectively. This increased amount of water is defined as extra water [36,37,41]. Based on the slump flow method, it is determined that the absorption capacity of SAP_AM (20 g/g) in UHPC is twice that of SAP_AA (10 g/g) at the time of the slump-flow test (10–15 min) [36]. The other O-UHPC, Ref_0.255, was additionally prepared to investigate the internal curing effect by SAP itself at a given w/c ratio (0.255).

2.2. Experimental methods

2.2.1. Heat of hydration test

The hydration heat was measured using an isothermal conduction calorimeter (TAM Air, TA Instruments) to investigate the effect of HT on the hydration reaction of UHPC. For this measurement, 15 g of each paste was prepared, excluding non-reactive materials such as silica sand and steel fibers. Heat curves were initially obtained under isothermal conditions of 20 °C for 48 h. Subsequently, the newly prepared pastes that had been subjected to curing at 20 °C for 48 h were tested under two different HT conditions, at 60 °C for 72 h and at 90 °C for 48 h. All the pastes were inserted after the calorimeter had attained its target temperature (20 °C, 60 °C, or 90 °C) so that the tests were conducted under isothermal conditions. Each curve that was measured under the HT condition was plotted from the previously measured early-age curve (48 h of curing at 20 °C). The measurements were taken thrice at different temperatures to yield two sets of hydration histories (20–60 °C and 20–90 °C) for each sample.

2.2.2. Shrinkage measurement

Prismatic steel molds (40 mm × 40 mm × 160 mm) were prepared to measure the shrinkage of the heat-treated UHPC. Each mold was lined with Teflon sheets to avoid friction with the specimen. An embedded-type strain gauge (PMF series, Tokyo Sokki Kenkyujo Co., Ltd.) was longitudinally positioned in the center of the mold using flexible steel wires. This method has been successfully used to measure early-age shrinkage of concrete with low

Table 1
Mix proportion of prepared ultra-high-performance concrete (weight ratio).

Sample	Cement	Silica fume	Silica powder	Silica sand	Water/Cement	Super-plasticizer[a]	SAP	Steel fiber (vol% of UHPC)	Slump flow [mm]	Time zero [h]
Ref_0.215	1	0.25	0.35	1.1	0.215	0.04	0	2	750	12
Ref_0.255					0.255		0		850	15
AA_0.255					0.255		0.004		800	13
AM_0.275					0.275		0.003		700	13

[a] Polycarboxylate type.