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Importance of drying to control internal curing effects on field casting ultra-high performance concrete

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ABSTRACT

In this study, the interdependent relationships among hydration reaction, internal relative humidity (RH), and strength of internally cured ultra-high performance concrete (UHPC) were investigated, to emphasize the importance of drying on superabsorbent polymer-based internal curing (IC). Experiments showed that the self-desiccation of UHPC cannot be prevented by external curing, such as water curing, but can be prevented by IC. Although the desiccation and resulting shrinkage of UHPC were effectively mitigated by the IC, a slow strength development was found when maintaining a high internal RH. Under water-curing conditions, the internally cured UHPCs showed 12–17% lower strength at 28 days compared with the reference sample. However, the results were 0–1% when exposed to dry air (RH 60%) between 7 and 28 days, showing accelerated external drying. The results show that the early-age shrinkage-related problem of UHPC can be fundamentally resolved, without a negative effect on strength, by controlling the drying period.

1. Introduction

1.1. Field casting ultra-high performance concrete

Ultra-high performance concrete (UHPC) features outstanding strength, flowability, and ductility, and it also possesses very low permeability [1,2]. This type of material generally does not include coarse aggregates, to satisfy the requirements specified in the standard [3]. Because of the high material cost, UHPC should be used only where these superior properties are truly necessary [2,4]. For example, one of applications is a field-casting UHPC for retrofitting old concrete structures with a thin overlay layer (commonly 30–40 mm thick) [1,2,5–7]. This enables the structures to significantly improve the mechanical performance and durability without any notable increase in thickness, due to the superior watertightness and crack-resistance capacity of UHPC [2,8]. Owing to the rebars that are generally reinforced in the new layer, the tensile strength and ductility of the structurers can be further improved [5–9]. Bridge decks, floor slabs, and beams and columns of buildings have been considered as suitable structural members for reinforcement by field-casting UHPC [5,8,10].

When an old concrete substrate is overlaid with new repair concrete, the performance of the new material and also the compatibility between the two concretes are crucial factors to consider in advance [11]. Early-age shrinkage of the repair concrete can lead to interface stress and premature cracking between the substrate and the new layer, especially under the restrained conditions caused by the hardened concrete substrate or the embedded deformed bars [2,11]. The shrinkage-related problem is especially crucial in UHPC because severe autogenous shrinkage (AS) occurs at an early age [12,13]. Thus, the early-age shrinkage of UHPC is the primary problem to be surveyed and solved to use this overlay material successfully.

1.2. Contradictory effects of high internal relative humidity on field-casting UHPC

The driving force of AS is the self-desiccation that occurs in low water-to-cement ratio (w/c) cementitious materials such as high-performance concrete (HPC) and UHPC. The desiccation and resulting AS are directly related to the loss of internal relative humidity (RH) [14–18]. However, the very low permeability of HPC or UHPC makes it challenging to diffuse external water into such concretes by external curing methods [19,20]. In the case of HPC, internal curing (IC) by porous lightweight aggregate has been successfully used [21–26]. However, the average diameter of typical lightweight aggregates is larger than the maximum particle size of aggregates of UHPC (typically, smaller than 1 mm) [27]. To solve the shrinkage-related problems of

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UHPC, IC by superabsorbent polymer (SAP) has been considered as the most promising method [19,28–31]. The particle size of commercial SAP ranges mostly between 10^1 and 10^3 μm [32–34]. Thus, the compact composition and homogeneity of UHPC are not disturbed. The internal RH of UHPC can be maintained at a high level, because this polymer releases the absorbed water inside concrete [19,33]. While low-w/c (0.3) mortars showed low internal RH (75–80%) due to the self-desiccation, those with SAP maintained 95% or higher under sealed curing conditions [29,35]. Maintaining a high internal RH also coincides with the purpose of the traditional external curing, which is for ensuring the design strength of normal concrete [14,36,37]. Likewise, SAP-based IC can increase the degree of hydration of low-w/c concrete, which is one factor for increasing strength [19,38,39].

Under the sealed condition, maintaining a high internal RH using SAP is certainly an effective way to mitigate the early-age shrinkage of low-w/c concrete [19,28–30]. However, this condition is not always beneficial or practical for concrete structures. For instance, a high level of moisture content is a disadvantage in concrete slabs of building structures, because the slabs are commonly covered with adhesive finishing materials. To install this moisture-sensitive material, a sufficient drying period is required for preventing a detaching problem. This leads to a longer construction period [40]. Furthermore, in a repair or retrofitting project, it is impractical to maintain sealed or wetted curing conditions for a long period [1,8]. Thus, the field-casting UHPC should be exposed to dry air, and the internal moisture content inevitably decreases by evaporation on the wide and thin UHPC overlay [38,41]. The moisture content also crucially affects the mechanical properties of hardened cementitious materials [36,42,43]. Generally, the higher the moisture content on the test day leads the compressive strength of concrete lower [36,44,45]. For instance, the air-dried concrete showed a 20–25% higher compressive strength than the water-saturated concrete [29,46,47]. The surface energy and disjoining pressure of the cement paste are involved in this phenomenon [36,42,46,48].

1.3. Dependence of drying on strength of internally cured concrete by SAP

Theoretically, it is possible to use SAP-based IC without a strength loss [49]. This is because SAP addition and the resulting IC have complementary effects on the compressive strength [28,50]. The additional pores formed by the swollen SAP particles are large enough to be comparable to the entrained air void that can decrease the strength of concretes, including UHPC [28,51,52]. However, the IC can increase the degree of hydration, which is directly related to the strength [28,50]. Nevertheless, strength loss was reported [53] when a larger amount of water was added than the absorption capacity of SAP [49]. There are three fundamental concepts of w/c in the mix design of internally cured concrete with SAP, such as total (w_{tot}/c), extra (w_{ext}/c), and effective (w_{eff}/c) w/c ratios [54,55]. Among them, w_{eff}/c is especially important for the strength, because it is closely related to the microstructure [56]. Thus, in this case, w_{eff}/c of concrete should be increased, and, in turn, the compressive strength decreases [33,49].

Aside from excessive amounts of water added owing to the overestimation of the SAP's absorption capacity (i.e., increase of w_{eff}/c), another possible reason for strength loss is the high internal RH caused by water released from the SAP [28,50]. At room temperature (20 °C), in which drying is not allowed, strength losses have occurred in the low w/c (0.25–0.35) cementitious materials because of SAP-based IC, i.e., 2–13% in concrete [57,58] and 15–20% in mortar [29,59]. However, the mortar did not show strength loss when cured under the air-drying condition (RH 30–50%) [59]. The internal RH of low w/c mortar should be far lower (due to the self-desiccation) than that with SAP, which can positively affect the compressive strength [28,29]. If the strength of cementitious materials can be measured with a similar internal RH, the SAP would have no negative effect on the strength; therefore, the need for a strength test under similar moisture contents has been proposed for the accurate evaluation of strength [29,35].

Although the internal RH or moisture content is a decisive factor influencing the mechanical properties of the internally cured cementitious materials using an SAP, most studies have considered only its effect on the porosity and the hydration reaction. It is challenging to obtain a similar internal RH in the materials, and even to measure their internal RH. The internal RH of UHPC with or without SAP has been recently measured [19]. However, the information about the RH during the early (24–48 h) and long-term (> 7 days) ages is still lacking, even though these ages are the critical periods for self-desiccation and strength development, respectively. Therefore, the interdependent effect of the internal RH on the compressive strength and early-age shrinkage has not been fully understood yet. To use IC for field casting UHPC successfully, the internal RH should be rigorously investigated under the air-drying condition, because this has a decisive impact on the dimensional stability and mechanical properties. Accordingly, we investigated the effect of IC on UHPC considering air-drying and water-curing conditions. The internal RH of UHPC with or without SAP was measured for 28 days to understand clearly the effect of moisture content on the length change and compressive strength. The measured shrinkage and strength of internally cured UHPC (I-UHPC) were compared with those of ordinary UHPC (O-UHPC). Finally, the characteristics of the compressive strength of I-UHPC were interpreted from its interdependent relationship with the history of measured moisture contents.

2. Material and methods

2.1. Specimen preparation

Two commercially available SAPs, namely SAP_AA (acrylic-acid-type polymer) and SAP_AM (an acrylic acid-*co*-acrylamide type of polymer), were chosen to study the effect of the type and absorption capacity of SAPs on the IC. In the field of cement-based materials, the hydrogels based on acrylic acid and/or acrylamide have been used most [31,33]. The selected SAPs have different shapes and absorption capacities, depending on the manufacturing methods, but they have a similar particle size distribution of 100–700 μm [33,34]. SAP_AA was manufactured by the solution polymerization method, and its particle shape is irregular. However, SAP_AM was manufactured by the inverse suspension method and has a perfect globular shape.

To measure the strength, length change, and internal RH of UHPC, the specimens were prepared using the same raw materials, instruments (including a 5-L Hobart mixer), and methods employed in our previous studies [33,39,60–62]. The dry powders presented in Table 1 were blended with silica sand (SiO_2 content > 90 wt%) and dried SAP particles (only for I-UHPC) for 10 min, after which water, superplasticizer (polycarboxylate type), and steel fibers (Φ 0.2 mm × 13 mm, tensile strength > 2500 MPa) were added to the blended mixtures and mixed

Table 1
Chemical composition of raw materials (wt%).

Material	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	SO_3	Na_2O	K_2O	MnO	P_2O_5	ZnO	SrO	LOI	Total
Cement	20.80	4.82	0.29	3.33	3.30	61.74	1.86	–	0.90	0.09	–	0.08	0.07	2.50	99.78
Silica fume	96.90	0.29	0.01	0.15	0.18	1.54	–	0.16	0.64	0.03	0.05	–	–	0.02	99.97
Silica powder	97.70	0.49	0.08	0.05	0.21	1.37	–	0.02	0.02	0.01	–	–	–	0.02	99.99