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Experimental Investigations of the Dimensional Stability and Durability of Ultra-High-Performance Concrete

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Abstract-An experimental investigation was conducted to provide further insight into the material properties of UHPC. The aspects of UHPC performance investigated in this work included dimensional and chemical stability, sorption resistance, and freeze-thaw durability. UHPC was found to produce the desired balance of dimensional and chemical stability, and distinctly low sorptivity and water absorption capacity. The drying shrinkage of UHPC was 25% less than that of normal-strength Portland cement concrete. The moisture sorptivity of UHPC was an order of magnitude below that of normal-strength concrete. The heat of hydration of the UHPC paste was about one-third that of Portland cement paste used in a normal-strength concrete mix. The UHPC paste, unlike a normal Portland cement paste, exhibited autogenous shrinkage; the amount of this shrinkage was, however, relatively small. These test results were explained based on the distinctly low water content, the high pozzolan content of the cementitious binder in UHPC, and the high dosage of superplasticizer used in UHPC mixtures. The fact that water content of UHPC is not adequate for thorough hydration of cementitious particles seems to be a significant factor influencing those aspects of the UHPC behaviour evaluated in this investigation.

Keywords- Ultra-high Performance Concrete (UHPC); Volume Stability; Drying Shrinkage; Autogenous Shrinkage; Sorptivity; Freeze-Thaw Durability

I. INTRODUCTION

Ultra-high-performance Concrete(UHPC) refers to cement-based materials with compressive strengths exceeding 150 MPa, with also provide high ductility and excellent durability [1]. UHPC materials are also expected to provide the desired flowability for reliable construction at high speed [2]. UHPC was first introduced in the mid-1990s, with heat curing, extensive vibration and longer mixing times [3]. The high cementitious paste content, the fine pore system, and the potential for chemical/autogenous shrinkage tend to compromise the dimensional stability of UHPC, which would otherwise benefit from a low water/cement ratio [4-9].

The high resistance of UHPC against transport of moisture and dissolved chemicals is an important aspect of its behaviour. Restrained shrinkage cracking of UHPC can undermine this highly desired quality. As far as shrinkage cracking is prevented, UHPC is known to provide highly desirable durability characteristics under adverse exposure conditions [10, 11]. Hence, besides improvements in structural efficiency, UHPC applications can lead to a significant rise in the service life of the concrete-based infrastructure. For UHPC, sufficient curing is essential for concrete to provide its potential performance [12, 13]. The durability of concrete subjected to aggressive environments depends largely on transport properties, which are influenced by pore system [14-18]. Pozzolanic materials commonly used include fly ash, silica fume, and metakaolin; these materials are usually added to concrete as a constituent of blended cement or at the concrete batch plant as a partial replacement. The addition of these materials mostly can enhance various aspects of concrete durability [19-21].

Ultra-high-performance concrete provides a segmented capillary pore system which enhances its barrier and durability characteristics [22]. The surface layer of UHPC, however, could be compromised by a combination of drying and autogenous shrinkage considering that the surface water cannot be replenished due to its low bleeding [23, 24]. Given the emphasis on high strength, air-entrainment is not commonly practiced with UHPC. This approach assumes that the high barrier qualities of UHPC provide it with desired freeze-thaw durability [25].

The key contribution of this work relates to a quantitative investigation of the distinctions between the UHPC cementitious paste composition and that of a normal Portland cement paste used in conventional concrete. The UHPC paste is distinguished by relatively high concentrations of supplementary cementitious materials, distinctly low water content, and very high superplasticizer content. These features are shown here to significantly alter the heat of hydration and dimensional stability of the UHPC paste when compared with the Portland cement paste in conventional concrete.

II. MATERIALS AND METHODS

The granular raw materials used in the UHPC mix design considered in this investigation can be divided into two categories: (1) cementitious materials and fine filler (limestone powder); and (2) aggregates. The cementitious materials and the fine filler considered in this investigation were: (i) Type I Portland cement; (ii) undensified silica fume with ~200 nm mean particle size, ~15 m²/g specific area and >105% 7-day pozzolanic activity index; (iii) ground granulated blast furnace slag with specific gravity of 2.9 and bulk density of 1,200 kg/m³, ground to less than 45 micrometer particle size; and (iv) limestone powder with 2 micrometer mean particle size. The particle size distributions of cementitious materials and limestone powder, measured using a laser granulometer (Malvern Mastersizer 2000E), are presented in Fig. 1. The aggregates used in UHPC mixtures included (see Fig. 2 for particle size distributions evaluated via sieve analysis): (i) limestone coarse aggregate with 12 mm maximum size; (ii) coarse silica sand with mean particle size of 0.8 mm and specific gravity of 2.67; and (iii) fine silica sand with mean particle size of 0.4 mm and specific gravity of 2.65. A polycarboxylate-based superplasticizer (Chryso 150 supplied by Chryso, with 1.06 specific gravity and 1.8% solid content) and steel fiber of 0.2mm diameter and 15mm length with a brass coating (supplied by Bekaert) were also used in UHPC mixtures. The UHPC mix design considered in this investigation is presented in Table 1.

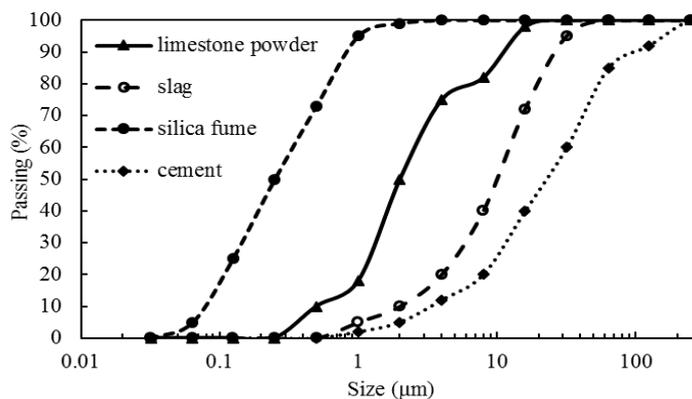


Fig. 1 Particle size distribution of the cementitious materials and limestone powder

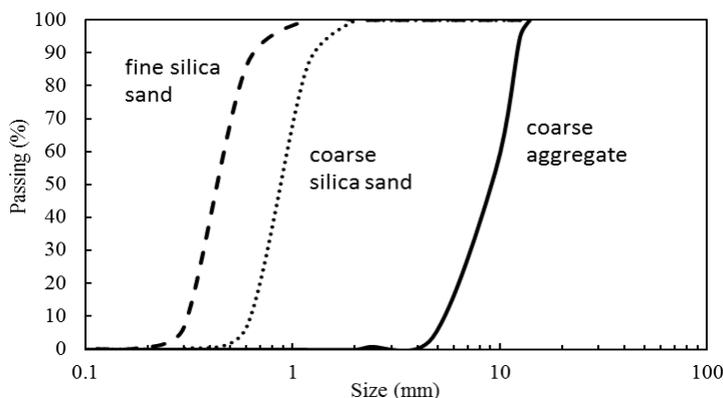


Fig. 2 Particle size distribution of coarse and fine aggregates

TABLE 1 UHPC MIX DESIGN

Material	Quantity, kg/m ³
Coarse aggregate	612
Coarser silica sand	500
Finer silica sand	500
Cement	604
Silica fume	268
Slag powder	120
Limestone powder	216
Water	144
Superplasticizer	57.6
Steel fiber	148

Ultra-high-performance concrete mixtures were prepared in the following steps using a rotary drum mixer:

1. Add all aggregates and powders to the mixer in the following sequence: coarse aggregate, fine aggregates, and powders (cement, silica fume, slag and limestone powder).

2. Dry-mix for two minutes.
3. Add water with half of the superplasticizer over two minutes, and mix for an additional half a minute.
4. Add the rest of the superplasticizer to the mix over one minute.
5. Continue mixing until wet paste forms (usually 4 to 9 minutes).
6. Add the steel fibers to the mix.
7. Mix until a total mixing duration of 15 minutes is reached.

The resulting fresh concrete mixtures were cast in molds and consolidated using a vibrating table. The molded specimens were stored under the sealed condition and demolded after 24 hours. Unless specified otherwise for specific tests in the following description, the specimens were subjected to steam curing at 90°C for 48 hours. The specimens were then stored at 50% relative humidity and room temperature for 3 days.

Drying shrinkage tests were performed following the ASTM C596 procedures. Mortar mixture was prepared using the same materials presented in Table 1 (without coarse aggregate). The mortar specimens were cast on 25mmx25mmx285mm steel moles. Following the ASTM C157 requirements, the specimens were moist-cured inside molds for 24 h ± 30 minutes. They were then cured in lime-saturated water for 72 h ± 30 minutes when the initial length was recorded (Fig. 3). The specimens were then stored at 50% relative humidity and room temperature, and their length change was up to 60 days.



Fig. 3 Drying shrinkage set up

Autogenous shrinkage experiments were performed per ASTM C 1698. A corrugated plastic tube of 30 mm diameter and 420 mm length was capped and sealed at one end and was filled with UHPC while held vertically. The open end was then capped and sealed. The filled corrugated tubes were kept in a length measurement instrument (Fig. 4) at 50% relative humidity and 22°C, with a (Linear Variable Displacement Transducer) LVDT contacting the specimen end (with the other end fixed) to measure length change as a function of time. While ASTM C1698 starts length measurements after final set, the length measurements in this study were initiated immediately after mixing and placement in corrugated tubes. For comparison purposes, similar tests were also performed with Portland cement. It is worth mentioning that the initiation of length measurement immediately after placement of fresh mix in the tube is not uncommon [26].

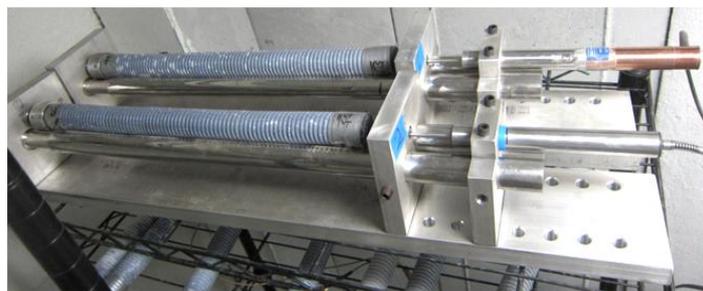


Fig. 4 The autogenous shrinkage test setup

Sorptivity tests were conducted per ASTM C1585, using 10 cm x 5 cm cylindrical specimen. This test measures the rate of capillary sorption of cured specimens after conditioning their moisture content to a standard level.

Autoclave expansion is an accelerated soundness test that was used to evaluate the chemical stability of UHPC. Autoclave expansion tests were performed per ASTM C151. This test was performed on the UHPC paste specimens prepared by mixing the (micro- and nano-scale) powder constituents of UHPC with water and superplasticizer to produce a paste of normal consistency. The heat of hydration for the UHPC paste was measured per ASTM C1679. This test was also performed on the UHPC paste prepared by mixing the powder constituents of UHPC with water and superplasticizer to produce a paste of normal consistency. The freeze-thaw experiments were performed per ASTM C666, with both freezing and thawing occurring

in water. The freeze-thaw test setup is shown in Fig. 5. The effects of freeze-thaw cycles on the dynamic modulus of elasticity and weight of UHPC specimens were investigated.



Fig. 5 Freeze-thaw test chamber

III. RESULTS AND DISCUSSION

A. Drying Shrinkage

The drying shrinkage test results are presented in Fig. 6 for UHPC, together with typical data for normal-strength concrete. UHPC is rich in cementitious paste content, with relatively high proportions of pozzolanic materials, which tend to increase its shrinkage movements. On the other hand, the very low water content of UHPC tends to lower its drying shrinkage. The comparison made with normal-strength concrete in Fig. 6 indicates that the drying shrinkage of UHPC is comparable to that of normal-strength concrete. The low water content of UHPC can be used to partly explain this finding. The distinctly low water content is below that required for hydration of the cementitious powder. Therefore, cores of cementitious powders remain non-hydrated; they act as well-bonded dense fillers within cement hydrates, which restrain their shrinkage movements. Another factor lowering the shrinkage movements of the UHPC binder is the dense packing of the particulate matter and the high concentration of pozzolans, which lower the capillary porosity of the resulting hydrates. Another factor is the dense packing of aggregates in UHPC, which improves their effectiveness in restraining the drying shrinkage movements of the binder.

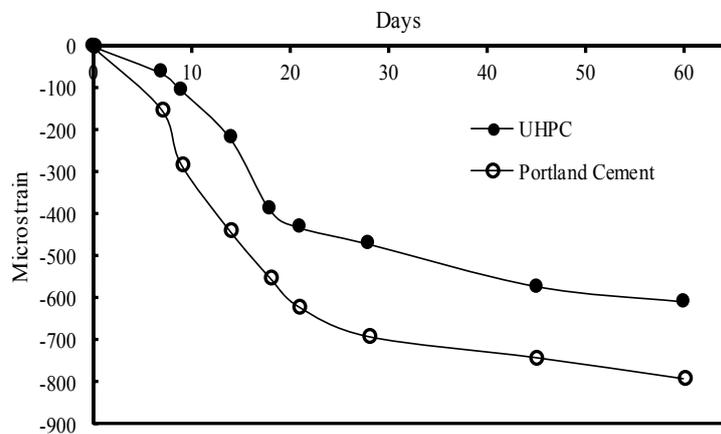


Fig. 6 Drying shrinkage test results

B. Autogenous Shrinkage

The autogenous shrinkage test results for the UHPC paste and a Type I Portland cement paste are presented in Fig. 7. Autogenous shrinkage is measured after final set time per ASTM C1698. Autogenous shrinkage results from loss of physically adsorbed water to hydration (instead of drying which is the case for drying shrinkage); it is prevalent for low ratios of water-to-cementitious ratios. In the case of Portland cement paste, autogenous shrinkage is marginal because bulk water is available for hydration reactions, and loss of bulk water does not cause shrinkage. In the case of UHPC, however, dense packing of the granular matter and the limited presence of water implies that most of the water is physically adsorbed. Its loss to hydration reaction would thus cause (autogenous) shrinkage. The autogenous shrinkage of the UHPC paste is still relatively small (though larger than that of a normal Portland cement paste) partly because of the dense packing of the granular matter and the limited extent of hydration which leaves the cores of reactive particles non-hydrated (acting as well-bonded fillers which restrain shrinkage movements) [27].

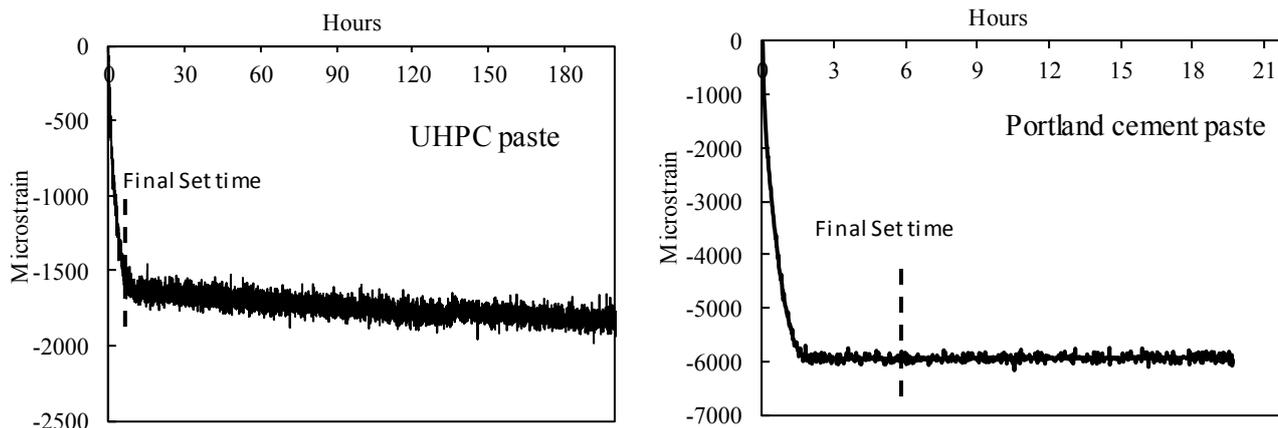


Fig. 7 Autogenous shrinkage test results

C. Heat of Hydration

The heat of hydration test results for UHPC and Portland cement are presented in Fig. 8. The rates of heat release of the UHPC cementitious paste are observed to be well below those of Portland cement. The dormant period with UHPC is also longer than that for Portland cement. These findings can be explained by: (i) the very low water content of the UHPC paste, enabled by the use of a high dosage of superplasticizer, which is not adequate to fully hydrate the cementitious materials; (ii) the relatively high dosage of pozzolans among the cementitious materials of the UHPC paste; and (iii) retarding effects of the superplasticizer. The total exothermic heat release of UHPC was 118 J/g compared with 327 J/g for Type I Portland cement. This comparison indicates that the cementitious materials in the UHPC paste remained partly unhydrated due to the low water content of this paste [28].

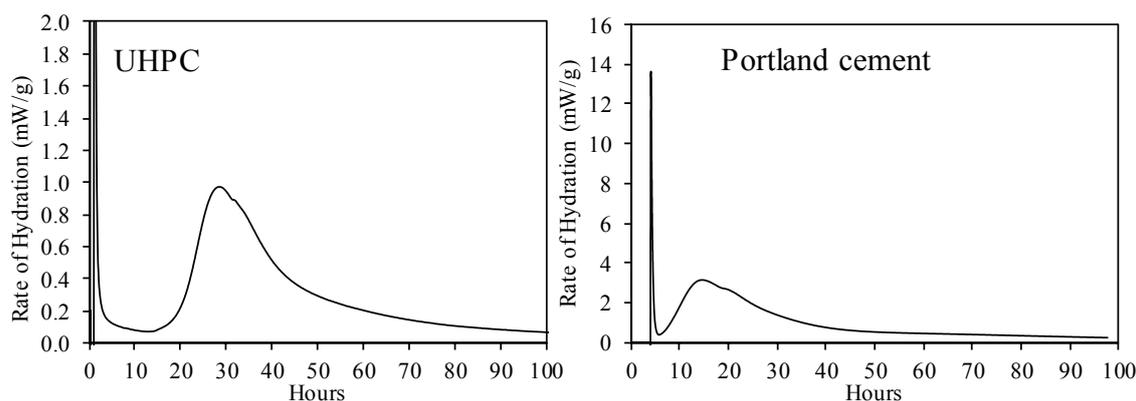


Fig. 8 Heat of hydration tests results for UHPC and Portland cement pastes

D. Sorptivity

The sorptivity test results for UHPC and normal-strength concrete are presented in Fig. 9. The initial and secondary sorption rates of UHPC are 0.20 and 0.10 $\mu\text{m/s}^{1/2}$, respectively, compared to 5.6 and 0.7 $\mu\text{m/s}^{1/2}$, respectively for normal-strength concrete (Table 2). The very low water content of UHPC and the high packing density of the granular matter significantly lower the capillary porosity and thus capillary sorption capacity of UHPC. This feature provides UHPC with distinct barrier qualities which significantly benefit its durability characteristics.

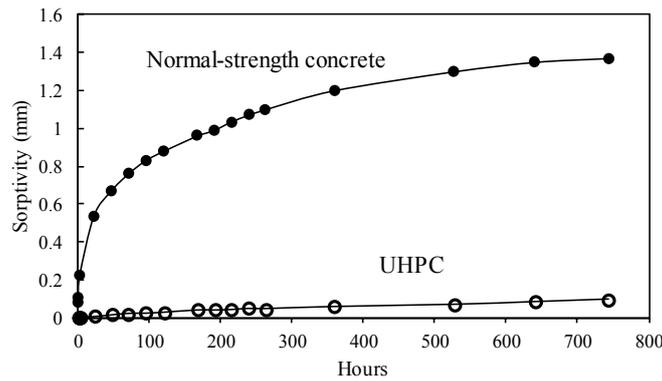


Fig. 9 Sorptivity test results

TABLE 2 INITIAL AND SECONDARY SORPTIVITY VALUES

	Initial Sorptivity, $\mu\text{m/s}^{1/2}$	Secondary, $\mu\text{m/s}^{1/2}$
Normal strength concrete	5.60	0.70
UHPC	0.20	0.10

E. Autoclave Expansion

The autoclave expansion tests result generated in this work for UHPC, and normal-strength concrete is presented in Table 3. The autoclave expansion of UHPC (0.162%) is less than that of normal-strength concrete (0.38%) and well below the maximum limit of 0.8% required by ASTM C1157. Given the hydration mechanisms of the UHPC paste, one expects that the elevated temperature of autoclave raises the extent (and rate) of hydration in the case of UHPC, thus benefiting the end product structure and properties.

TABLE 3 AUTOCLAVE EXPANSION RESULTS

	Autoclave length change, %
Normal strength concrete	0.38 ± 0.02
UHPC	0.162 ± 0.01

F. Freezing and Thawing

The measured values of dynamic modulus, expressed as a percentage of unaged values, are presented in Fig. 10 a versus the number of applied freeze-thaw cycles. The corresponding weight loss test data are presented in Fig. 10 b. Both these test results point at the high degree of freeze-thaw durability provided by UHPC. This is in spite of the fact that UHPC was subjected to freeze-thaw cycles without any air entrainment. The low moisture sorptivity and water absorption capacity of UHPC can be used to explain its high level of freeze-thaw durability. The relatively low moisture content of UHPC lowers the damaging effects of freeze-thaw cycles [29].

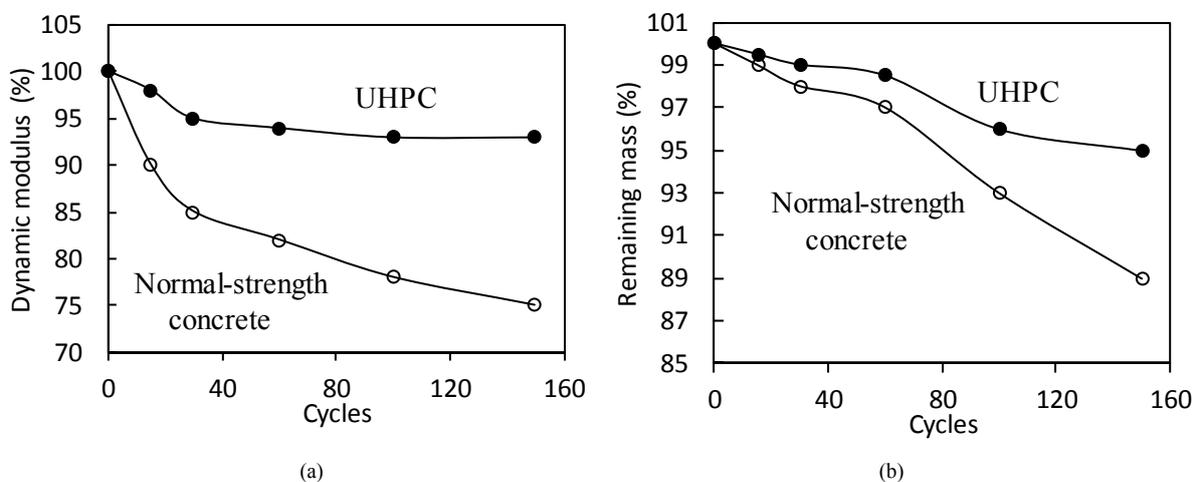


Fig. 10 Dynamic modulus (a), and the remaining mass after freeze thaw cycle (b)

IV. CONCLUSIONS

Investigations of the dimensional and chemical stability, the heat of hydration, barrier qualities and durability characteristics of UHPC in this project yielded the following conclusions:

- The very low water content of UHPC and the high packing density of granular matter significantly lowered the capillary porosity of the resultant hydrates, yielding distinctly low capillary sorptivity and water absorption capacity. This feature provides UHPC with superior barrier qualities which significantly benefit its durability characteristics.
- The heat of hydration of the UHPC paste was found to be relatively small in spite of its very high content of cementitious materials. This observation can be attributed to the low water content of the UHPC paste that limits the extent of hydration reactions, and the retarding effects of pozzolans and the superplasticizer used at relatively high concentrations in the UHPC paste.
- The presence of high superplasticizer contents and pozzolans in the UHPC paste delay its set time. The hydration process thus occurs over extended time periods. This observation together with the high moisture barrier qualities of UHPC can be used to explain the extended period during which the UHPC paste undergoes shrinkage movements. The drying shrinkage movements of UHPC were significantly below that of a Portland cement paste. This was in spite of the high cementitious materials content of the UHPC paste and can be attributed to the very low water content of UHPC which leaves a notable fraction of the cementitious particles non-hydrated at their cores. These non-hydrated cores could act as fillers that reduce the UHPC paste drying shrinkage movements. The high packing density of the granular matter in UHPC also enables effective restraint of shrinkage movements by aggregates and also the non-hydrated cores of reactive particles.
- UHPC exhibits autogenous shrinkage movements over extended time periods. This is expected because the limited water content of UHPC that is used for its hydration is physically adsorbed, and its loss to hydration reactions causes (autogenous) shrinkage movements. The amount of UHPC autogenous shrinkage, however, is relatively small when compared with those caused by other sources of dimensional movement (e.g., drying shrinkage).
- UHPC provides high levels of freeze-thaw durability without the need for air-entrainment. This was attributed to the low sorptivity and water absorption capacity of UHPC. The limited capillary porosity of UHPC significantly reduces the moisture content residing in these pores, thus reducing the damage caused by freeze-thaw cycles.

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