Review Article

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Internal curing of ultra-high-performance concrete: A comprehensive overview

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Abstract: This article presents an overview of the research on the effects of internal curing (IC) on ultra-high-performance concrete (UHPC). The process of adding a curing ingredient to the concrete mixture to serve as a water reservoir is known as internal curing. IC is a viable technique for supplying additional water for curing cement-based material with lower water-to-binder concrete. It is distinct from externally applied curing. The water meant for internal water curing is dispersed within the concrete after it hardened and facilitated the hydration process. It was used to minimize self-desiccation and shrinkage in UHPC. Based on the reviewed literature, an exchange was used to minimize self-saturation and shrinkage in UHPC. An exchange between mechanical characteristics and autogenous shrinkage for concrete was observed for internally cured UHPC. Even though IC affects the mechanical characteristics, after 28 days, it was possible to achieve a compressive strength of over 150 MPa. Thermal curing was found to exhibit a remarkable effect on the development of UHPC strength. Experimental findings revealed that using pre-saturated aggregates for IC improves the tensile strength of UHPC. The scanning electron microscope images revealed that the bulk of the voids within the super-absorbent polymer cavities are filled with portlandite.

Keywords: ultra-high-performance concrete, internal curing, super-absorbent polymers, mechanical behavior

1 Introduction

Because of its potential to contribute to the longer lifespan and more efficient performance of structures, ultra-high-performance concrete (UHPC) has recently evolved as one of concrete’s most interesting research areas [1]. Due to its densely packed matrix, UHPC has remarkable mechanical characteristics, including a high compressive strength of more than 150 MPa and a high tensile strength greater than 8 MPa [2]. The UHPC is known as an engineered cement-based composite with a low water-to-binder (w/b) ratio, a well-distributed material size (in micro- and frequently nano-scales), a higher quantity of steel fibers, and the elimination of coarse aggregate from the mixture [2]. The UHPC is primarily aimed at enhancing performance-oriented infrastructures by reducing the depth of concrete structural components with the added benefit of using an optimized mix design, resulting in high cost and material savings.

Due to the extraordinarily lower permeability of the dense matrix, ultra-high-performance fiber-reinforced concrete (UHFFRC) can be used as a water-proof layer on bridge decks [3]. The production of UHPC consists of a mixture of micro-/nano-cementitious fillers and densely packed aggregate with lower w/b ratios [4]. At any time, the dry particles are mixed with the small quantity of water, and the electric charges on the solid particles result in aggregation, thus preventing a good distribution of the water between the solid particles and, ultimately, preventing an optimal re-partition of the hydrates formed between the particles [5]. Yu et al. [6] explored the feasibility of producing a dense skeleton of UHPC with fairly low binder content. The authors have achieved a compressive strength of 150 MPa with a cement content of 650 kg/m³. The degree of hydration is low due to the low w/b ratio and relatively high cement content. As a result, it is justifiable to substitute inert cement with some less-expensive filler materials to improve the effective utilization of cement.

Many researchers have studied different curing conditions to improve the qualities of UHPC [7,8]. To achieve high strength, UHPC is often heated (by autoclave curing...
or steam) at an early age [6]. Yazici et al. [9] and Yoo and Banthia [10] used autoclave pressure and temperature conditions in curing UHPC. They have obtained enhanced strength by curing in an autoclave chamber. An enhancement in compressive strength of about 35% was obtained in an autoclave and of about 26% in a steam curing. They also studied the effect of autoclaving on the mechanical performance of UHPC with respect to preset time, target temperature, and holding duration. The authors concluded that the flexural strength of UHPC was decreased by steam and autoclave when compared to the conventional period of 28 days of curing. This may be attributed to the decrease in the bond strength between the matrix and the fibers. Therefore, it is vital to determine the influence of curing conditions on the UHPC's properties. It is commonly accepted that the UHPC's characteristics are significantly influenced by the curing regime [10].

Furthermore, the effect of the heat treatment technique on UHPC was examined by Heinz et al. [11]. The authors reported that the pyrolysis of UHPC tends to produce extraordinarily higher strength in a comparatively limited time duration. The initial strength advancement of UHPC was also studied under different curing conditions, and the results revealed that curing temperature has a large effect on the development of UHPC strength [12]. The authors achieved a higher compressive strength of 112 MPa under hot water curing for the period of 12 h. Shen et al. [13] reported that thermal curing had remarkable effects on the development of UHPC strength. The production of C–S–H gels resulted in a dense microstructure, which contributes significantly to the improvement in strength. The evolution of hydrates and microstructure as a result of curing regimes, as well as the appearance of quartz, plays a major role in influencing the unusual strength ratio behavior and enhancing mechanical properties [13]. Similarly, as reported by Yang et al. [7], the strength improvement and endurance of UHPC could be improved by the heat treatment process.

UHPFRC is considered a potential material that resists high impact or blast loads due to its significantly increased strength, energy-absorbing capacity, and distinctive strain-hardening behavior with numerous micro-cracks, as shown in Figure 1 [14]. The brittleness of normal concrete frequently resulted in a limited energy-absorbing capacity when subjected to impact and blast loading.

The majority of UHPCs are produced with a low water-to-cement (w/c ratio), which results in a lack of mixing water necessary to preserve the ability of the water-filled granular capillaries to sustain the hydration of cement or reaction of pozzolanic. Therefore, it is generally agreed that techniques relying on re-hydrating (internal water supply) are much more efficient for this kind of concrete. Concrete autogenous contraction can be effectively managed with internal curing (IC) [15]. IC is a type of concrete curing that is distinct from externally applied curing. It refers to adding a component that acts as a curing agent to the concrete mixture. Internal water curing is desirable because sealing cannot preclude self-desiccation [16]. The water intended for internal water curing was distributed inside the concrete after it hardened and aided the hydration process [16].

Although extra porosity in internally cured high-performance concrete (HPC) may result in compressive strength reductions in some cases when compared with reference concrete specimen, the advantages in terms of autogenous shrinkage reduction and cracking control are enormous [17,18]. Because it is challenging to resolve the increased porosity caused by the IC agents, there are few findings in

Figure 1: Tensile stress and stress characteristics of UHPFRC [14].
the literature about the characteristics of UHPC with IC. The aim of this study is to examine the existing state of knowledge regarding the IC treatment of UHPC and to suggest some prospective directions for further investigation. Moreover, the idea of strength properties and the effect of curing conditions, aggregate types, admixtures, fiber qualities, specimen size, and loading rate on the mechanical properties of UHPC are of particular interest for further investigation.

2 Fresh properties of UHPC

The placement and consolidation of new concrete depend significantly on the concrete’s workability. For a flowable UHPC, cement is required to have the right combination of alkali (K₂O and Na₂O) content, a C₃A specific surface, and SO₃ content recommended [19]. The effect of silica fume (SF) on the UHPC’s workability is fairly complicated. Previous studies revealed that SF improves UHPC’s workability [20,21]. However, some studies found that SF reduces the UHPC’s workability [22]. The substitution of limestone filler for cement was reported to reduce the incompatibility between the cement and the super-plasticizer, which is frequently the most difficult issue for UHPC with a very low w/b content [23]. The addition of nano-silica reduced the amount of lubricating water available within the inter-particle voids while increasing concrete yield stress and plastic viscosity. Therefore, the addition of nano-silica has been reported to have linearly reduced the slump flow of fresh UHPC [24]. Similar to shotcrete, super-absorbent polymer (SAP) can be used to change the rheology and viscosity of the mixture before placement [25]. Mechtcherine et al. [26] stated that when using SAP in a dry condition, additional water content is required to overcompensate for the water that the SAP will need to absorb throughout the blending process without affecting workability.

3 Effect of supplementary material in IC of UHPC

According to reports, the flowability of UHPC gradually improved when fly ash concentration and ground granulated blast furnace slag (GGBS) rose [27]. The workability of the UHPC combined with fly ash was higher compared to the UHPC mixture containing GGBS in the same proportion. Under standard curing conditions, the incorporation of fly ash or GGBS had a small effect on the compressive strength of UHPC. The compressive strength decreased with increasing GGBS or fly ash content during hot water and steam curing. The use of rice husk ash (RHA) at longer age of curing tends to enhance the degree of cement hydration, which was observed to be better than specimens made with SF. This is due to the fact that RHA filler impact and pozzolanic activity were less pronounced than those of SF. However, the use of SF exhibits a significant effect than that of RHA at later ages [20]. The process of water absorption using distilled water into SAP is described by Liu et al. [28], as shown in Figure 2.

Furthermore, metakaolin powder can be used to improve concrete’s early strength and durability, reduce internal shrinkage, and improve pore configuration. In the study by Tafraoui et al. [29], replacing SF with metakaolin results in a marginal gain for flexural strength with a little reduction in compressive strength. However, due to its accessibility and affordability, it would be a viable choice for use in producing UHPC. Another study by Van Tuan et al. [20] reported that UHPC with a combination of 10% RHA and 10% SF exhibited a greater compressive strength than the reference UHPC specimen or with other variations. Similar findings have credited this to RHA’s porous structure.

4 Methods of IC of UHPC

4.1 Water curing internally

The process of adding a curing ingredient to the concrete mixture to serve as a water reservoir is known as internal
curing. It is a viable technique for supplying additional water to cure cement-based composites with a low w/b ratio [30]. An internal water cure can stop shrinkage and self-desiccation. For this reason, some concrete may need 50 kg/m$^3$ of IC water. The cost of IC water ranges from 0.1 to 1 €/kg [31]. Because of the internal free water minimization mechanism, combined curing has significantly increased UHPC’s resistance to catastrophic spalling under elevated temperatures [32]. Due to the internal free water-minimizing mechanism, an innovative strategy to prevent UHPC spalling, this is distinct from the widely used addition of polypropylene fiber. Coupled curing technique is another approach to curing UHPC. It involves the use of steam dry air to cure UHPC; during this process, a high-temperature steam condition is formed in the dense structure of UHPC formed in the earlier hot water curing [1,2]. Yang et al. [7] examined the impact of coupled curing at 20 and 90°C on the mechanical properties of UHPC. They have compared the mechanical properties of UHPFRC cured at 90 and 20°C. Their comparison revealed that the 20°C cured UHPFRC has a 20% lesser compressive strength, 10% lesser flexural strength, and 15% lesser fracture energy than the 90°C cured UHPFRC, although, when compared to conventional concrete, the 20°C cured UHPFRC has superior mechanical properties.

### 4.2 Internal water curing using pre-saturated aggregates (PSAs)

IC of UHPC with pre-saturated lightweight aggregates is the established technique for avoiding self-desiccation and autogenous shrinkage. Zhutovsky and Kovler [33] studied the IC effect on the durability-related performance of UHPC. They have reported that reducing the w/c ratio in internally cured UHPC specimens does not result in a discernible enhancement in durability. They suggest that further study is needed to determine the influence of IC on UHPC’s durability containing microfiller. PSAs also act as an internal water reservoir, supplying IC water to prevent self-desiccation. The use of pre-saturated lightweight aggregate to provide IC was investigated by De la Varga and Graybeal [34], and their findings revealed that a substantial reduction in autogenous shrinkage could be achieved with PSA. However, previous research on UHPC IC indicates an exchange between mechanical properties and shrinkage of concrete using the SAP. IC using a saturated lightweight aggregate produces UHPC with compressive strengths ranging between 80 and 120 MPa, as stated by Bentur et al. [35]. In the study by Lura et al. [36], SAP does not offer as effective an internal cure as pre-saturated lightweight aggregates in the structure of cement-based composite with a low w/b ratio. The hardened properties of UHPC may be adversely affected by the lightweight sand (LWS) of large particle size, which is a serious concern.

Meng and Khayat [37] studied the effect of saturated LWS content on key properties of UHPC. They have reported that using LWS promoted the degree of cement hydration degree beyond 28 days and successfully slowed down and minimized UHPC autogenous shrinkage and internal relative humidity (IRH) drop. At 91 days, they obtained a maximum compressive strength of 168 MPa. Suzuki et al. [38] suggested that porous ceramic aggregate (PCA) can be vital for IC UHPC. Their findings revealed that the porous aggregate effectively reduces the drying shrinkage of the UHPC and subsequently mitigates the possibility of early-age cracking. An extra advantage of using PCA for IC is an enhancement in cement hydration reaction, leading to the improvement of compressive strength. An improvement of 10–20% of compressive strength was obtained with the aid of PCA, as shown in Figure 3. The improvement in compressive strength is primarily due to the improved hydration processes provided by the addition of the PCA. Indeed, the water entrapped by the PCA aids in the formation and development of supplementary C–S–H into the capillary pores [38].

The tensile strength is important in assessing the concrete ability to resist tensile strength development for concrete mixtures. A tensile strength of about 6 MPa was obtained by Suzuki et al. [38]. The presence of PCA aggregates tends to decrease the tensile strength of the internally cured concrete at early and later ages of curing. The reduction might be attributed to a weak inter-transition zone (ITZ) between the aggregates and the cement paste. The smooth surface of the PCA was found to be responsible for the weak ITZ.

![Figure 3: 28-day gain of compressive strength of PCA mixtures correlated with the control mixture](image-url)
IC could also be a reliable technique to enhance UHPC effectiveness if PSAs with suitable physicochemical properties were used. On the other hand, IC is rarely applied to enhance UHPC. Since low-shrinkage UHPCs exhibiting appropriate mechanical performance and durability were desired, it was necessary to understand the real mechanisms impacting the performance level of UHPC, including PSA [39]. Figure 4 illustrates how saturated lightweight fine aggregate (LWFA) is internally cured in the UHPC. Because of the pore pressure and humidity gradient, the internal water in the LWFA is released into the matrix during the mixing of UHPC. It has also been disclosed that IC is more reliable when LWFA is distributed uniformly [39].

### 4.3 Internal water curing using SAPs

The excellent IC agent is characterized by a high water absorption capacity and easily releases the absorbed water into the cement matrix in the face of an impending drop in relative humidity. Moreover, SAP particles can accumulate a huge quantity of water during the mixing process and then swell to yield a hydrogel, restricting self-desiccation during cement hydration due to the production of water-filled incorporation [40]. Therefore, IC using SAP is regarded as the effective method for reducing autogenous shrinkage by lowering the decline in IRH exacerbated by self-desiccation [41,42]. The chemical properties of SAPs have been reported to have defined their effectiveness as an IC material, content [43,44], particle size [45], and w/b of the matrix [46]. SAP is a suitable candidate for IC of UHPC because its ability to release water absorbed into the matrix makes it viable to reduce the shrinkage of UHPC [28].

Justs et al. [16] studied the IC of UHPC using SAP. They used a solution of polymerized SAP with irregular particle sizes of approximately 63 μm in the dry state. The pore fluid absorption capacity of SAP particles was determined using a cement paste without SAP and a cement paste with SAP, both with a 10% SF addition by weight of cement. The authors reported that IC with SAP could significantly decrease self-desiccation and autogenous shrinkage in UHPC. The continued hydration response caused by the addition of SAP porosity was responsible for the increased compressive strength. However, it has been noted that using SAP significantly decreases the cementitious composite’s workability [39]. Mechtcherine et al. [47] decreased the internal shrinkage of UHPC using IC with SAP. They concluded that internal UHPC curing with the addition of SAP significantly reduced internal shrinkage. The study by Wang et al. [48] showed that external curing, such as water curing, cannot prevent self-desiccation of UHPC, but IC can. Although the IC effectively mitigated desiccation and shrinkage of UHPC, a gradual strength development was observed when a high internal RH was maintained. Similarly, it was reported that SAP aggregates could reduce the autogenous shrinkage of UHPC without altering its fresh behavior, mechanical properties, or density [49]. Further, cement hydration can be improved by SAP re-desorption, leading to self-healing characteristics [50,51]. Figure 5 presents the compressive strength of UHPC with SAPs.

![Figure 4: Function of physicochemical characteristics for LWFA in desorption mechanisms in UHPC [39].](image-url)
4.4 Microstructural properties of UHPC

UHPC is made up of aggregates as well as a robust matrix phase that includes hydration products. A reactive interface forms between the partially hydrated core and the hydration products. The use of pozzolanic mineral admixtures in UHPC leads to the development of a dense and compact structure. Wang et al. [52] have reported that when just 26% of the cement has hydrated in UHPC at low w/b, the capillary pores become intermittent compared to 54% in HPC at w/c = 0.33. They have further concluded that UHPC exhibits very low porosity under heat curing. The range of the pore diameter of UHPC is between 2 and 3 nm with an overall porosity of 2.23%, as reported by Long [53].

Scanning electron microscope (SEM) observations, as shown in Figure 6, revealed that the hardened paste was very dense due to the lower water content in the matrix, cement hydration, and the pozzolanic action of SF and GGBS. The primary hydration product comprises of homogenous C–S–H gel with no, Ca(OH)$_2$, or ettringite detected [54]. Figure 6(b) shows that UHPC possessed a well-compacted ITZ devoid of noticeable pores. Figure 6 shows the micrograph of SAP cement paste. Furthermore, the initiative time and heat curing time can alter the rate of hydration, leading to a variation in the UHPC’s microstructure and mechanical properties [39].

Figure 7 shows that the SAP reservoirs are partly filled with hydration products. Based on these findings and morphology, the appearance of needle-like crystals portlandite was evident [39].

Because of the following fundamental effects, UHPC has a very dense and uniform microstructure consisting...
of dense packing of solid particles and improving the ITZ between aggregates and bulk matrix [55].

5 Gaps and future challenges

This study attempted to determine and summarize previous research on the effect of IC on UHPC. Many researchers have conducted in-depth studies that take into account various aspects of curing of UHPC. However, limited studies have also been noticed in a few areas that serve as scope for future research. After reviewing the works of earlier researchers, the following can be possible gaps to be investigated for future studies:
1. The hardened properties of UHPC may be adversely affected by the LWS of large particle size, which is a serious concern. Investigation into the effect of the aggregate size on the mechanical properties of UHPC is of great importance.
2. UHPC exhibits very low porosity under heat curing. Further research findings are necessary.
3. There is limited literature on the effect of IC on UHPC. Detailed experimental studies are needed to fully investigate the influence of IC on the hardened and microstructural properties of the UHPC.

6 Conclusions

Previously, researchers studied the effect of curing on the performance of UHPC on physical, chemical, and microstructural properties. Furthermore, numerous research findings on the impact of curing on fresh, hardened, durability, and microstructural properties have been established. After reviewing the findings of the research, the following conclusions were reached in this study:
1. External curing, such as water curing, cannot prevent self-desiccation of UHPC, but IC can.
2. IC with PSAs aids in preventing self-desiccation in UHPC.
3. IC technique can significantly improve the UHPC’s mechanical properties, thus making it more efficient over time.
4. IC with SAPs can effectively reduce self-desiccation and autogenous shrinkage in UHPC. The chemical properties of SAPs have been reported to have defined their effectiveness as an IC material.
5. IC of UHPC results in a significant improvement of its microstructure. It was discovered that portlandite fills the cavities of the UHPC.
6. There is limited literature on the effect of IC on UHPC. More experimental studies are needed to fully understand the influence of IC on the hardened properties of the UHPC.

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