Influence of internal curing on the properties of non-fibrous high strength concrete—A critical review

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Abstract

The demand for the construction of high-strength concrete in the civil engineering zone is growing, particularly in the last couple of years, due to the construction of sustainable and economic buildings with an extraordinary slim design. Concrete curing in construction is an operative manner and essential to provide that concrete structures meet future performance and durability. High-strength concrete has a low water-to-binder ratio; proper concrete curing is important to ensure its planned performance and durability. Conventionally, exterior curing applied after placing and casting concrete stays warm and moist to provide continued cement hydration. Lately, theoretically and experimentally comprehends that internal curing is an important tool to provide additional moisture in the concrete to enhance cement's hydration. Internal curing of high-strength concrete is an active technique to lessen or even remove autogenous shrinkage and effects on chemical shrinkage, dry shrinkage, etc. Most studies recently have emphasized that a reduction in high strength concrete mixtures' shrinkage is due to internal curing, and the compressive strength can increase higher in mixtures with LWA or SAP than in mixtures without this agent rising degree of hydration by providing extra water in the hydrated cement paste. However, the use of internal curing leads to improving the durability of high-strength concrete.

1. Introduction

The popularity of high-strength concrete is growing gradually due to its outstanding mechanical and durability characteristics. However, the high early-age cracking sensitivity and early strengthening of HSC limit its application [1]. The high-strength concrete non-structural cracking is induced by normal desiccation and autogenous shrinkage [2]. Conventional curing systems are not efficient for HSC because curing water cannot penetrate due to the low permeability of concrete, as shown in Figure 1.

For this purpose, internal curing was proposed [3], which be provide a distributing internal curing water barrage within the concrete. Water-saturated lightweight aggregate. Super absorbent polymers (SAP) and other porous materials agents can act and serve as internally curing water reservoirs [3].

Mechanical properties of the porous internal curing materials are poor; therefore, they would have a damaging effect on the mechanical properties of HSC. Therefore, it was recommended to optimize the size and amount of IC agent in harmony with the concept or idea of protected paste volume. This perception recommends lessening the particle size of internal curing materials. Altogether the cement paste will surround a suitably tiny space from the IC agent's particle surface, causing internal curing water to penetrate. Existing of this circumstance, the paste of cement would be "protected" from normal dehydration. Refer to this idea; the most important limitation is "spatial proximity" of the IC water reservoir to the cement paste matrix must be implied; however that is standing by holds enough water for curing the paste in the perimeter of its neighborhood and that wholly of this water is eagerly obtainable for hydration after penetrating the surrounding paste. Current experimental information demonstrated some differences between the theory and behavior of internally cured HSC. In this head for investigation, the

outcomes of relevant research studies on IC are reviewed, and the applicability of protected paste volume (PPV) idea to IC is revised.

Figure 1. External and internal curing in concrete [2]

Various engineering parameters for the description of internal curing processes and their suitability as design criteria are discussed.

2. Internal curing

High-strength concrete has its economic benefits, pointedly reducing maintenance budgets and enhancing service life [4]. The enhanced durability of HSC causes its usage very attractive in environments where ordinary concrete would not suffice. The HSC has a continuously increasing amount of applications, high-rise buildings, marine structures, piers and bridge decks, airport pavements, thin-

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wall shells, and several others. Though, HSC progression is restraining by its strength and early-age cracking sensitivity.

HSC produced with enormously low w/c ratios is disposed to self or normal desiccation due to autogenous shrinkage [5]. Autogenous shrinkage is inhibiting internally by aggregates and externally by neighboring structural elements and members, causing tensile stresses to make possible cracking and even fracture [6] and knowing that crack causing reduction of mechanical properties and decline durability of concrete. To reduce or eliminate autogenous shrinkage in HSC and prevent its early cracking, it was proposed to present into the HSC mix pre-saturated lightweight aggregates (LWA), which would serve as IC tanks internal curing water to counteract self-desiccation [6]. This process was termed internal curing (IC).

Internal curing (IC) currently attracted large research curiosity and was experimentally demonstrated to be capable of preventing or greatly contracting autogenous shrinkage [7]. It was established that it could be effectively functional to obtain improved high-strength concrete with reduced cracking. Later, IC was extended to utilize additional materials as an IC agent. SAP, wood-derived materials, and waste reused aggregates were informed as suitable curing agents for IC of HSC [3].

The internal curing agent's main character is to serve as internal storage to provide curing water for hydration. Hence, IC agents are commonly very permeable materials with poor mechanical properties. The presentation of very porous weak material into the dense matrix of HSC can have harmful effects on the superior mechanical properties and durability of HSC. The effects of IC on HSC properties and how to eliminate these destructive effects remain the attention of considerable research effort.

In early-age strength, IC's destructive things on concrete were reported in recent research [8]. Though, the Effect of IC on the matured concrete strength is inconstant and consists of the agent type, present content, chemical admixtures, and aggregate content. A major lessening of E-modulus is stated in the literature pieces when IC is applied, even when strength was not reduced. It seems that IC has a slight effect on creep. (Wyrzykowski et al., 2011) Most research shows that the alteration of 30% or more of normal aggregate weight by pre-saturated LWA has a negligible impact on creep. Consequently, a design admixture procedure would optimize the IC agent content, size, type, etc., required for frustrating the undesirable effects of internal curing and maximize their helpful influences.

It might not necessarily be to complete autogenous shrinkage elimination. Optimally, only the quantity of IC agents, which would be adequate to reduce the risk of cracking due to eliminating and restrained autogenous shrinkage to a satisfactory level, should be used. This will be economically good-looking and lessen the undesirable side effects such as adverse or opposite influence on rheological, mechanical, and durability properties of HSC [10]. For this reason, for this prep, it was recommended to take over the idea of volume paste protected for minimizing the quantity of IC agents introduced to concrete [11]. According to this idea, smaller elements or particles of IC materials, such as lightweight fine aggregate (LWFA), are more helpful and beneficial for the active IC.

3. The idea of protected paste volume (PPV)

The freeze confrontation provided by air entrainment is the origin of the concept of (PPV), and it is specified as the volume of cement paste "protected" from freeze injury by an arrangement of air voids in the paste of cement [12]. Each air void is surrounded by a preserved shell of cement paste, which Powers called a "sphere of influence" [17]. The schematic representation of the spheres of influence for two adjacent air voids is presented in Figure 2. This perception implies that the frozen resistance of concrete is ensured if the cement paste resides within a suitably tiny space from the air bubble, called the "spacing factor." Spacing factors for voids 1 and 2 are designated L1 and L2 in Figure 2, respectively. Plenty of research has established that for normal strength the concrete spacing factor below $200\ \mu\text{m}$ guarantees frost durability [13].

In the year 1999, both Bentz and Snyder suggested extending the idea of PPV to internal curing. After this idea, it is supposed that if the cement paste is positioned within an adequately slight distance from the IC agent surface, the cement paste would be preserved from

normal or self-desiccation, and autogenous shrinkage would be lessened [11].

Figure 2. Schematic representation of the sphere of influence [5]

Bult Bentz and Snyder paper the spacing factor for internal curing, or in terms of the "spatial proximity" of IC water to cement paste, is measured and striped by the internal curing agent size particles. The author's assumption that "the passage of water will be excellently limited to distances on the order of 100 to $200\ \mu\text{m}$ as the capillary pore space in the cement paste de percolates during curing". Therefore the "well normal self-dispersed system of minor LWFA saturated particles would be most useful to the curing of field concrete, alike to the situation of air voids caring concrete from damage due to freezing and thawing," which is in contract with the protected paste volume idea for air voids, which proposes that a finely dispersed scheme of small air voids will be superior to one composed of bigger air voids in state of equal air contents.

4. Recent investigational results review

Since the internally curing (IC) was projected to counteract the self-desiccation of HSC, there has been an embarrassment of researches done on this subject. Studies recently tried to put on the protected paste volume for IC. These attempt works involved the hard work to minify the IC agent's particle size and, consequently, the spacing factor for IC to attain a higher percentage of protected paste volume. The studies will be censoriously reviewed to evaluate the protected paste volume idea validity and determine the variety of parameters required to be careful to guarantee the IC agent's full effectiveness.

Lura et al. studied the Effect of LWA size on IC efficiency. They cooperate with fine LWA ($0-4\ \text{mm}$) with coarse LWA aggregates ($4-8\ \text{mm}$ and $8-16\ \text{mm}$). The fine LWA has good performance, although the difference was minor. Far ahead, the idea of internal curing (IC) in terms of saturated LWA was used to optimize it to eliminate autogenous shrinkage with the lowest possible amount of LWA [14]. In this effort's progression, the particle size of LWA used as a curing agent was reduced to minimize the paste-aggregate proximity, i.e., the space that permits the IC water should sufficiently diffuse. The reduction of the particle size up to $4-2\ \text{mm}$ was showed beneficially, however further a decrease of the particle size caused in a decrease of curing efficiency and autogenous shrinkage of concretes with size fractions of $2.36-4.75\ \text{mm}$ (Pumice2), $1.18-2.36\ \text{mm}$ (Pumice1), and $0.6-1.18\ \text{mm}$ (Pumice0) of lightweight pumice aggregate containing pre-saturated internal curing water $20\ \text{kg/m}^3$ of concrete is presented in Figure 3.

Investigation of the information recommends that the relationship between lessening in the spacing and minimization of autogenous or autogenous shrinkage does not always exist. In this study, the internal curing efficiency of $0.33\ \text{w/c}$ ratio concretes using various types of LWA was undertaken, and the results are shown in Figure 4. The LWA aggregates variance was their water absorption capacity (Perlite is $450\ \text{wt.}\%$, Hekla pumice is $70\ \text{wt.}\%$, Yali pumice is $26.7\ \text{wt.}\%$). In contrast, the aggregates' content in every single mix was attuned to entrain $20\ \text{kg/m}^3$ water of concrete, which is theoretically satisfactory to avoid normal desiccation. The content of LWA with smaller absorption required meeting the requirement for $20\ \text{kg/m}^3$ of water is higher, and thus the spacing between them is smaller [12].

Figure 3. Effect of particle size on free shrinkage of mixes with w/c ratio 0.33 containing the amount of pumice required to counteract self-desiccation [4]

According to the protected paste volume concept, their efficiency should be higher. However, it is not the case, as shown in Figure 3, the Perlite LWA provided the greatest performance, exhibited by an absence of any autogenous shrinkage after the progress of initial swelling. The lowest absorption and smaller spacing of Yali pumice exhibited the uppermost autogenous shrinkage afterward, the first swelling.

Figure 4. LWA type effect on free shrinkage of mixes with w/c ratio 0.33. LWA fraction is between 1.18 and 2.36 mm [4]

With SAP as internal curing material, one might assume that, where nearly all of the particles' volume is water-saturated, the system would more closely follow the idea of the protected paste volume. Smaller size SAP particles would yield enhanced efficiency. However, the information for SAP particles in the range of 250 μm down to 45 μm showed just the opposite trend [15], as shown in Figures 5 and 6. For the different schemes in these graphs, the trend was always for improved efficiency of the bigger SAP particles: they provided higher initial swelling values and reduced autogenous shrinkage afterward.

5. Discussion

The analysis of the previous information in the section submits that the idea of spacing cannot always account for the efficiency of internal curing schemes concerning the reduction in autogenous shrinkage. It has been revealed that for together types of IC agent, LWA and SAP, reduction in the spaces between the IC reservoirs does not necessarily result in reduced autogenous shrinkage, and even the reverse trend may occur. This apparent discrepancy suggests that other influences are necessary to be considered, and they may override the spacing factor's influence.

Figure 5. The autogenous strain of cement pastes with w/c 0.3 and 20% silica fume addition, with different w/b with no SAP or 0.6% SAP by cement weight [16]

Figure 6. The autogenous strain of cement pastes with w/c 0.3 and 20% silica fume addition, with different w/b with no SAP or 0.3% SAP by cement weight [16]

In lightweight aggregate, the IC water drive is taking control by a driving force, which is the gradient of tube pressure known as capillary between the water in the LWA and the water nearby around the paste matrix. It detected that the LWA particles smaller are recognize by minor absorption, recommend a finer pore structure of the IC reservoir, and the consequence is a lower driving force for the water to penetrate from the IC reservoir into the surrounding matrix paste. This show that in the systems studied and reported in studies, two competing mechanisms take place upon the reduction of the particle size of the LWA: reduction in the spacing factor, which should improve the productivity, and enhancement of the pore structure of the LWA which should result in the reduction of the efficiency. The result that the experimental outcomes indicate is that a reduction in the efficiency upon a reduction in the LWA size proposes that the structure of the LWA in IC is the more vital parameter.

Similar opinions could be completed concerning the influence of the SAP particle size. Figures 5-7, the water is held by Van Der Waals forces and not by capillary pressure as in LWA. The water will initially dry out of the particle rapidly. The drying rate is still reduced later since water has to diffuse through more side-chains that interact with the water molecules by their ionic character [17]. Besides, bigger SAP particles have higher water absorption [15]. Thus, the greater size of SAP elements water discharge will happen more facily than in the minor particles, causing two compete processing while the reduction in the size of the SAP cause higher IC efficiency due to smaller spacing, and reducing IC efficiency because of a tendency for tighter hold of the water.

Figure 7. Autogenous deformation of SF-modified pastes with different sizes of SAP and w/c 0.3, IC water absorption capacity of 12.5 ml/g of dry gel [16]

The PPV idea is occupied after the formation of freeze resistance, and then, the value of the critical spacing factor of 200 µm was resulting [4] and applied in various references. However, reviewing the literature submits that the spacing factor's proportion is necessary for internal curing of HSC is higher magnitude order in the range of numerous millimeters.

Measurements indirectly can simplify this spacing parameter's valuation by hypothesizing that the protected paste volume percentage is nearly equal to autogenous shrinkage reduction. The calculation of autogenous shrinkage is built on the shrinkage moment starting after the initial point of expansion, which usually occurs in IC systems within the first day, near the final setting. The portion that changes the curve's length in the Figure is a reasonable estimation of the developments generated by normal drainage, which occur directly after cementitious matrix setting. Even though the length changing may not be uniform in the paste around the IC agent, the autogenous shrinkage value calculation may estimate a weighted average. Based on this, one can compute water passage space [16]. An implied statement in this calculation style is that the calculated distance presents a range where there is no shrinkage, and beyond it, the autogenous shrinkage is uniform. Thus, the calculated value may be considered as an estimate presenting the "effective value." As shown later, the effect estimate of the value is quite like the variety of values obtained by new direct measurement techniques of a water passage from the IC agent. Closeness curves for the information in Figures 3 and 4 are presented in Figures 8 and 9, respectively, and the estimate of the efficient space of water passage is there given built on the values of the relative autogenous shrinkage reduction. The values obtained from the range from 0.1 to 3 mm, which relate positively with the LWA absorption capacity Figure 11, also correlated inversely with the autogenous shrinkage reduction Figure 10. The tendencies in Figures 10 and 11 sustain the conclusions reached in the previous discussion part that the exceeding parameter controlling the IC reservoirs.

Figure 8. Assessment of space of water passage for mixes containing different pumice fractions with a w/b ratio of 0.33 [16]

Figure 9. Assessment of space of water passage for mixes of different types of LWA [16]

Figure 10. Relationship of spacing factor and reduction of shrinkage [16]

Figures 8 and 9 show the IC water could transportable to a space of many millimeters. For instance, perlite reminds on the sieve 1.18 mm, which passed through the sieve of 2.36 mm, successfully eliminated any autogenous shrinkage. As presented in Figure 9, to attain the complete elimination of autogenous shrinkage in the admixture, water must be penetrated at least 2.7 mm into the cement paste matrix.

Tests based on the absorption of X-ray showed that penetration of IC water into cement paste could be about a distance of 4 mm from the LWA surface when pumice was used as an IC agent, and 2 mm expanded shale aggregate was used [15].

Figure 11. Relationship of spacing factor and water absorption of LWA [16]

The X-ray and neutron tomography study of internally cured cement paste by expanded clay demonstrated that internal curing water was the passage to at least 3 mm [18]. Micro-tomography of X-ray mortars internally cured through extended shale confirmed that internal curing water immigrates to the space of about 2 mm [4]. Neutron radiography applied to cement paste with saturated expanded shale aggregate indicated water transport distances between 3 and 8 mm [19]. The direct link penetration test also estimates the water travel distance of a millimeter and more Figure 12.

Figure 12. Blue-ink corona around a Leaper aggregate [20]

The calculations based on autogenous shrinkage analysis, in addition to the direct water migration measurements, mark that the sphere of the impact of the IC agents is on the order of degree of few millimeters. Thus, there is no cause to border the spacing factor to 200 μm , as suggested earlier. In case the value 200 μm was the truth, the authorized one then high replacement level of normal aggregate weight by an internal curing material would have been required, that is not the situation in practicing.

The 200 μm spacing factor reported as a maximum spacing factor for internal curing should be taken from frozen resistance requirements [20]. One should note that the latter value in frozen resistance is effective for normal-strength concrete. It is of interest to the memorandum that Okada et al. have clarified that the spacing factor of 200 μm is not valid for w/c ratios below 0.4, for freeze resistance, as shown in Figure 13, which is the range in which IC is applied and studied. The sphere of Effect and the spacing factor undoubtedly have a physical sense for internal curing. However, it could not be used as design principles like it is done in freeze resistance design.

Figure 13. Air-void spacing versus water to cement ratio for concrete mixtures subjected to 300 rapid freezing and thawing cycles [20]

As shown by the present simulations, the water transport in the cured paste at early ages of hydration is almost instantaneous compared to the hydration process's characteristic times and the corresponding self-desiccation process. By the time the de-percolation of capillary porosity occurs in the cement paste, which water-cement ratio is 0.25, at the time of life 1–1.5 days, a major portion of the water absorbed in the SAP has already been released and is homogeneously distributed through the paste. These observations are in very good harmonization with the experimental work by [21], who reported that during the first day of hydration, approximately 90% amount of the water was released from the SAP and hardly any gradients of saturation at growing distances from the SAP reservoirs were visible. The steep reduction in the paste's permeability may result from the de-percolation of capillary pores that strongly inhibit water passage from the internal reservoirs. It is shown that sometime before the de-percolation of capillary pores, at a permeability equal to nearly $1 \times 10^{-19} \text{ m}^2$, water mobility for distances even shorter than 1 mm may be inhibited.

Moreover, the phenomenon of inhibited transport starts

approximately at the equivalent time for all points within the cured volume. This includes points that are placed closer to the reservoir than the maximum distances. When the effective permeability further drops to extremely low levels of roughly $5 \times 10^{-23} \text{ m}^2$, considerable differences in water distribution intensity occur within the cured matrix volume for very large SAP cases, 2.4 mm for Cases A and B. The pores of the paste, which are at a maximum distance of 2.2–2.5 mm from the reservoir, receive four to five times less water per unit of time than those in the direct vicinity of the SAP. However, when the SAP's size is reduced to 800 μm in the swollen state, case C, the maximum distance reduces to roughly 740 μm from the reservoir surface. In that case, the pores at the maximum distance receive at most approximately 20% less additional water per time unit than those in the direct vicinity of the SAP. Hence, in that case, the amounts of received water may still be considered to be sufficiently high. Igarashi et al. (2010) suggested that even if only part of the volume is initially provided with a greater amount of curing water, it will act as an additional water reservoir for the regions at a greater distance from the SAP. The additional water will be further redistributed from higher saturation regions that drained more water from SAP to those of lower saturation. The present model allows this phenomenon to be explicitly taken into account, and the results confirm the hypothesis of water redistribution in the volume of cured paste. As presented in the simulations, this mechanism of redistribution of curing water is efficient enough to occur on distances of approximately 1 mm from the reservoir surface case C.

Moreover, case C, assumed to be the realistic case, refers to possibly the largest particles among the SAP size distribution in a mixture. Obviously, in practical applications, many SAP particles smaller than 800 μm in the swollen state will also be present in the mixture, further decreasing the distance to be enclosed by the internal curing water. Therefore, no considerable water distribution problems are likely to occur in mixtures used for practical applications, even at very low permeability. The observation of continuous redistribution of water in the cement paste leads to discussing another interesting and important aspect [17]. The concept of a strictly determined self-desiccation-protected distance. It needs to be underlined that the determination of the strict water flow distance is debatable because of the mentioned redistribution phenomenon and because no exact curing waterfront can be observed, neither experimentally nor in the simulations presented in this paper. Instead, starting from a certain time instant (or more precisely, from a certain value of permeability), the amount of water provided by the internal reservoirs will decrease gradually with a growing distance from the reservoirs' surface. Still, at the same time, redistribution of water previously received by the paste will occur [16]. The observations described that the internal curing at the macroscopic level, where the influence of SAP on self-desiccation and autogenous shrinkage, is studied for materials treated as homogeneous [9]. In that approach, the presence of internal curing is described and a volume-averaged additional source term for water, which is based on the hypothesis of symmetrical distribution of curing water in the space volume of the cured material. As shown by the simulations, such a hypothesis can be considered justified.

6. Conclusions

There are quite a lot of key limitations of internal curing that influence and regulator it is effectiveness. After highlighting the influence of internal curing on the properties of non-fibrous high strength concrete, the following conclusions could be drawn:

- The total amount, particle size, type, and grade of IC agent saturation, influence the outcome on IC, besides the matrix permeability, which is a function of the binder's composition and the w/b ratio. For optimizing internal curing of concrete, the internal curing agent water must be already introduced and regulated to be available to be discharged by the time of concrete setting to the surrounding cementitious matrix uniformly.
- The void structure of LWA and the size of SAP particles are two important agent parameters of IC that appear to be mainly in control for the accessibility of internal curing water, and they are more important than the spacing factor.
- The idea of protected paste volume with the recommendations for limitation the spacing factor by nearly 200 μm , which are common freeze resistance requirements of concrete, cannot be extended to internal

curing of high-strength concrete, at early ages of hydration, a major portion of the water absorbed in the SAP becomes uniformly and practically distributed within the complete volume of the cured maturing material. This observation is in agreement with recent experimental data obtained by neutron tomography.

- iv. Most studies recently have emphasized that a reduction in HSC mixtures' shrinkage is due to IC, and the compressive strength can increase higher in mixtures with LWA or SAP than in mixtures without this agent rising degree of hydration by providing extra water in the hydrated cement paste. However, the use of internal curing leads to improving the durability of high-strength concrete. Therefore, it is predicted that future applications will progressively move toward internal curing, as IC becomes well known through good practice and high performance.
- v. The internal curing technique, even though the agent type are used in the proses, have a significant contributing role in executing the structural members that cannot be cured perfectly by external curing or circumstance difficulties during the curing process such as column or beam in the high building; therefore, the Super-absorbent polymers as IC agent seems to be a reasonable, useful solution to enhance the durability of the structure.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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