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A CRITICAL REVIEW OF THE EFFECT OF INTERNAL CURING ON THE PROPERTIES OF ULTRAHIGH PERFORMANCE FIBER REINFORCED CONCRETE

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ABSTRACT

This study presents the outcomes of a research investigation to examine the advancement of an internal curing technique for ultra-high-performance concrete (UHPC). A range of commonly utilized materials have been employed to promote internal curing and alleviate self-desiccation in cement paste. These materials ultimately aid in reducing the probability of developing cracks in hardened concrete. This study also highlights the attributes of Ultra-High Performance Concrete (UHPC), including its density, shrinkage (both of which are autogenous and induced by drying), the microstructure of hydrated Cementitious Paste (CP), and mechanical properties (specifically compressive strength, splitting tensile strength, and flexural strength).

The results indicate that internal curing (IC) exerts a more significant influence on the splitting tensile and flexural strengths in comparison to the compressive strengths. Several studies have reported that the incorporation of micro steel fibers in high-performance concrete (UHPC) leads to a slight enhancement in compressive strength and an even greater increase in flexural strength. This indicates that micro steel fibers have an observed influence on the mechanical characteristics of the material.

The internal curing (IC) has allowed for a gradual improvement in the compactness and density of the interfacial transition zone (ITZ), leading to a boost in its strength. The application of super absorbent polymers (SAP) in internal curing (IC) is intended to tackle the issue of self-desiccation and autogenous shrinkage, which can lead to early cracking in ultra-high-performance concrete (UHPC). The experimental investigation revealed that portlandite partially occupied the cavities of the Superabsorbent Polymers (SAP) during the process of hydration of cement (CH). The application of SAP (superabsorbent polymers) as an internal curing agent has demonstrated effectiveness in decreasing the inside relative humidity and alleviating autogenous shrinkage.

KEYWORDS: Autogenous shrinkage, chemical admixture, internal curing (IC), mechanical properties, mineral admixture, ultra-high-performance concrete (UHPC).

Table(1):- List of abbreviations

Symbol	Description	Symbol	Description
ITZ	Interfacial transition zone	SEM	Scouldning electron microscopy
MPa	Mega Pascal	UHPC	Ultra-high-performance concrete
MK	Metakaolin	HPC	High-performance concrete
SF	Silica Fume	SCMs	Supplementary cementing materials
IC	Internal Curing	SAP	Super-absorbent polymers
SSD	Saturated Surface Dry	AAC	Autoclaved Aerated Concrete
LW	Lightweight	SCC	Self-curing concrete
SF	Silica Fume	CP	Cement paste
CH	Cement hydration		

1. INTRODUCTION

The recent developments in concrete and nanotechnology have opened up new avenues for the production of a durable and long-lasting material that possesses the following characteristics. However, normal type of concrete (30 MPa) has achieved definite ranges, which in these times could not fit all requirements for durability strength, safety, care, and low entertainment.

A full potential has been built to advance the durability and the strength of concrete. These factors are essential for the construction of high-rise buildings, long-span bridges, and a wide variety of other different products made of

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concrete [1]. Since UHPC is easily capable of meeting such characteristics, the primary benefits of using this material are its mechanical strength, its durability, and its workability. In accordance with the standard BS EN 206:2013, UHPC possesses a compressive strength of concrete that is greater than 100 MPa [2]. Compressive strength could be increased to a maximum of 250 MPa if the right apparatus and combination were used.

The concrete could meet all of the necessary requirements for its strength, durability, safety, and usability, among other things. As is the case with all other materials, UHPC has both positive and negative qualities. The most significant drawbacks may include a price that is disproportionately high; the absence of practical standards; a failure that is easily broken; a mixing method that is difficult to execute; significant autogenous shrinkage; and the paucity of long-term research on how well it holds up over time in specific conditions. In order to address the existing problems with the UHPC preparation methods currently in use, the comprehensive study is required.

These methods require the use of materials that are relatively expensive as well as technology that is relatively advanced. In a typical UHPC mixture, 500 kg/m3–1000 kg/m3 of Portland cement and up to 250 kg/m3 of silica fume are present, as stated by Aldahdooh et al. [3]. Researchers Yu et al. conducted experiments to improve particle size distribution and reduce the amount of Portland cement in UHPC. He came to the conclusion that it was possible to produce UHPC with a w/c value of 0.23 and a compressive strength of up to 160 MPa by lowering the amount of Portland cement used to 612 kg/m3 [3]. According to Sabet et al. (2013), the pricey silica fumes could be replaced with natural zeolite or fly ash [4]. Nazari and Riahi came up with the idea that ground granulated blast-furnace slag (GGBFS) should be used instead of silica fume and Portland cement [5].

They came up with this idea. Yoo et al. conducted research to investigate how the presence of varying amounts of fibres affects the fracture and mechanical behaviours of UHPC. According to the findings, adding steel fibres at a concentration of up to four percent (by volume) has a beneficial effect on reducing the likelihood of brittle failure [6]. Wang et al. (2012) proposed a straightforward method as an alternative to relying on more complex technology to produce UHPC. He proposed a straightforward strategy for increasing the dosage of (SP) superplasticizer and employing micro fillers with a coarser particle size [7]. UHPC could be made with a w/c ratio of 0.18 and a compressive strength of up to 175 MPa if the idea that was presented is followed. After conducting research,

Maruyama and Teramoto came to the conclusion that adverse autogenous shrinkage in ultra-high-performance concrete is a critical case, which is primarily due to pozzolanic reaction. This was one of the findings of their investigation. This fact might emerge as a result of the consumption of water by silica fume and the subsequent interaction with portlandite [8]. Zhutovsky and Kovler found in their research that internal curing has a staggering effect on deleterious autogenous shrinkage [9]. [9] They found this to be the case. Yoo et al. proposed using shrinkage reducing admixtures, or an adequate quantity of steel fibres as a means of overcoming the detrimental effects of autogenous shrinkage in their study [6].

There are a variety of low-cost solutions available, in spite of the fact that UHPC has some drawbacks. Curing is a term that is used to explain the series step of internal chemical reactions that occurs in hydrated cement paste and concrete; this develops the characteristics of hardened cement paste with adequate water and heat over the course of time [10, 11]. Curing is a term that is used to explain the series step of internal chemical reactions that occurs in hydrated cement paste and concrete.The curing process encourages hydration, stops water from escaping from the concrete, and maintains a state of saturation in the material for as long as possible or for a sufficient amount of time [12]. One type of concrete that possesses high strength, workability, and low permeability in order to be progressively durable is sensitive powder concrete [13]. Other types of concrete also possess these characteristics. In the areas of HPC and UHPC. However, the presence of a significant amount of ultra-fine cementations materials, such as silica fume (SF) and metakaolin (MK), as well as the requirement for a low w/c, makes it more difficult to supply curing water within the concrete, which results in chemical and drying shrinkage as well as early age micro-cracking [14].

The gradual increase in the use of ultra-high performance concrete (UHPC), which has a very low ratio of water to cementation materials (w/cm), sometimes falling below 0.25 and also raises it with the containment of supplementary cementing materials (SCMs), has decreased the influence of curing on hydration [15]. Internal Curing (IC) has the potential to lessen the effects of autogenous shrinkage while also improving concrete quality. For both ultra-high performance concrete (UHPC) and conventional concrete with a low water-to-cement ratio [16].

2. Objectives

This study discusses previous works on developing internal curing in UHPC for the internal curing approach, mechanisms of internal curing in UHPC and its effects on the physical, mechanical, and microstructure properties of UHPC, and the focus of the internal curing (IC) in this study was on using super absorbent polymers (SAP).

3. Materials of internal curing in UHPC

The contact zone of the UHPC is confined in the supplementary cementitious materials (the formation of pozzolanic material from hydration of $Ca(OH)2$). This distinguishing characteristic reinforces the ITZ, also known as the interfacial transition zone, which is located between the aggregate particles and the cement paste. Previous research has suggested a number of methods for carrying out internal water curing, including the use of superfine powders [17-20], saturated surface dry (SSD), lightweight (LW), fine aggregate [21-23], LW SSD coarse aggregate [24, and 25], and superabsorbed polymers (SAP) as shown in Figure.1 [26-28]. The theory behind internal curing materials was broken down into its component parts in Table 2.

IC first rose to prominence as a result of its capacity to mitigate autogenous and drying shrinkage cracking, as well as the effects of self-desiccation [29, and 30]. This ability helped IC capture the attention of researchers. As can be seen in Figure 2, preliminary information obtained from various studies and countries led researchers to conclude that the UHPC4 strain was the one that was used the most frequently. There are a variety of compelling arguments in favour of this proposition, including the fact that it is simple to implement during the mixing process, as well as its influence on drying shrinkage and autogenous shrinkage [28, 31, and 32]. While the significance of internal curing through the use of pre-wetted lightweight aggregate (LWA) lies in its ability to increase cement hydration and decrease early-age cracking brought on by internal desiccation [16, 33], it is also important to note that this method requires longer curing times. The utilisation of a super-LWA known as Leca UHPC3, which is illustrated in Figure 3 [28]and Shrinkage Reducing Admixture, which is demonstrated in Figure 6 [34]; supplies additional water, also known as added hydration, and prevents drying shrinkage and self-desiccation [35-37]. In order to assist IC, Byard and Schindler [38], Babcock and Taylor [39], and Song et al. [22] investigated the UHPC4 and its impact on voids in the dense cement paste. Francis et al. [40] focused their attention on the performance of UHPC2 with varying proportions of LWA. A sandstone quarry was used to produce lightweight fine aggregates by replacing a certain percentage of the normal-weight aggregate with a different amount. The replacement percentage ranged from 10% to 50%. According to the findings, the percentage of replacement that is best for the production of IC concrete is thirty percent. As can be seen in Figure 2, the effect of lowering the maximum size of normal density of coarse aggregate from 10 mm to 20 mm has resulted in a 16% increase in the prevalence rate of UHPC3 between the years 1990 and 2018. This is due to the fact that the maximum size of the aggregate has been reduced. The findings suggested that there was no discernible effect on the rate of autogenous shrinkage after seven days. In comparison to the sealed curing method, the UHPC2, as IC shows an improvement of up to 63% at an early age (between 3 and 7 days) [41]. In conclusion, it has been determined through analysis that the occurrence of ultrafine powders is significantly lower compared to that of other IC materials. This is because the porous structure of superfine powders with pores of nm size causes an increase in the internal moisture content [19, and 41]. The formation of water-filled macrospores in fresh and hardened concrete was controlled by fine particles when they were used as concrete additives [24, 27, and 42]. This was done to prevent the concrete from drying out on its own.

4. Effects of internal curing on the physical and mechanical properties of UHPC

This section describes the effects of internal curing on the compressive, tensile, and flexural strengths of UHPC.

4.1. Density

Several studies (22, 24, and 43) have examined the impact of (IC) on the density of concerns. It is widely acknowledged that the unit weight of Ultra-High Performance Concrete (UHPC) needs to be reduced for implementation in (IC) techniques during its initial phases of curing. Nevertheless, an increasing amount of research indicates the fact that there is an observed rise in the density of recently produced Ultra-High Performance Concrete (UHPC). This phenomenon is also observed in the lateral ages, particularly at 90 days, leading to the development of a matrix with an exceptionally compact microstructure [22, and 44]. The correlation between the mineralogical and chemical composition of aggregate and enhanced efficiency, quality, and outcomes in all Ultra-High Performance Concrete (UHPC), (IC) has been well-documented. Furthermore, it is vital to acknowledge that the utilization of SAP in the internal curing process of ultra-high performance concrete (UHPC) did not culminate in any statistically significant negative impacts on density.

Fig.(1):- Feature of Super absorbent polymer SAP

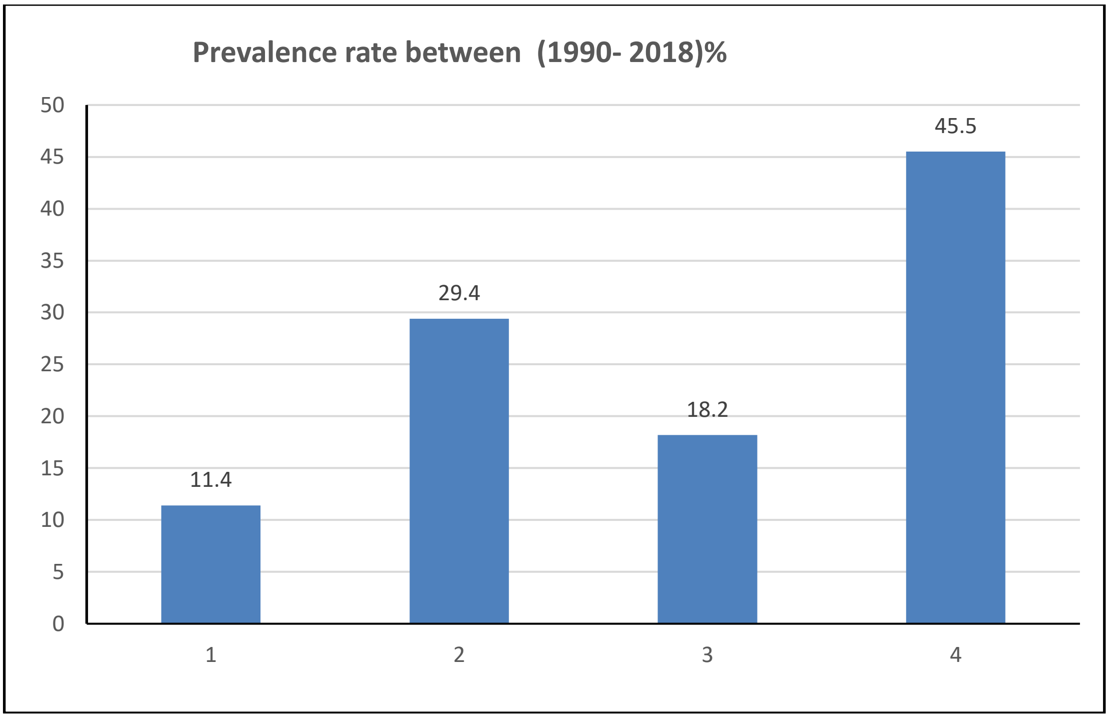

Fig.(2):- The prevalence rate of internal curing materials between (1990–2018), %.

Table (2):- Different internal curing types of UHPC

Different UHPC	**Techniques**	**Prevalence rate between (1990-2018), %**	**The most commonly used material**	**The hypothesis**
UHPC1	Superfine powders	11.4	Rice husk-ash	The porous superfine materials have a large fineness, which means increasing water demands further hydration of cementitious materials.
UHPC2	SSD LW fine aggregate	29.4	Pumice	The hypothesis was internal curing from the use of pre-wetted LWA may have increased the degree of cement hydration, resulting in a denser and less porous paste microstructure that reduces the mobility of ions and possibly slows the reaction rate and makes it difficult for micro-cracks to grow.
UHPC3	SSD LW Coarse aggregate	18.2	Recycled aggregate	The hypothesis was internal curing from the use of LW coarse aggregate is the higher porosity, permeability, and pores size of LW coarse aggrega.
UHPC4	SAP	45.5	Acrylamide / acrylic acid copolymer	The hypothesis was adding water to the combination of SAP with SCMs, then swollen particles due to the fast rate absorption of SAP. The absorbed water has an essential influence on the internal curing of concrete.

Fig.(3):- Feature of Leca

Fig.(4):- Pumice and rice husk ash

Fig.(5):- Autoclaved Aerated Concrete produced from lightweight aggregate

4.2. Shrinkage of concrete

The importance of incorporating (IC) in (UHPC) resides in its capacity to mitigate early-age cracking resulting from internal desiccation and enhance the process of cement hydration. Liu et al. [45] conducted a comprehensive investigation on the contribution of (IC) in mitigating the shrinkage of (UHPC) that has been subjected to damage. The effectiveness of utilizing ultrafine powder in reducing autogenous shrinkage has been investigated by researchers [34, and 46]. Among the various particle sizes of RHA tested, the range of 5.6 mm to 9.0 mm demonstrated the highest efficacy in reducing autogenous shrinkage in UHPC [34]. The efficiency of (IC) in (UHPC) when utilizing superabsorbent polymers (SAP) was found to be influenced by several factors. These factors include the properties of the cement-based materials, such as particle size (as indicated by references 7 and 47), type (as indicated by reference 7), dosage (as indicated by references 34 and 47), and the water-saturated state of the SAP (as indicated by references 26, 45, and 48). The chemical shrinkage of (UHPC) is influenced by the rate of cement hydration [49] and the extent of reaction of Supplementary Cementitious Materials (SCMs) [37]. Additionally, the introduction of (IC) water leads to an increase in both the degree of cement hydration [50, and 51] and chemical shrinkage. The phenomenon of chemical shrinkage undergoes a transition to autogenous shrinkage, which is influenced by factors such as pore structure, size distribution, and water content arising from hydration reactions [36]. Through the conducted research, it was determined that four potential beneficial elements can mitigate the detrimental effects of shrinkage in (UHPC) paste.

The replacement of a portion of the fundamental particle in the fine aggregate with ultrafine powders reduces the potential for a portion of the shrinkage expansion.

b-UHPC2- increase cement hydration and reduced interfacial transition zones (ITZ); the rate of fluid ingress and movement is reduced, which may, in turn, reduces the rate of a chemical reaction;

c-UHPC3- the extra pores provided by coarse aggregate LWA may provide obtainable layer sites for the gel in such a way as to reduce the pressure caused by expansion; and

d-UHPC4- The reduction in cracking and distress in the UHPC.

Fig.(6):- Shrinkage Reducing Admixture

4.3. Compressive strength

Numerous types of research have been conducted to examine the impact of IC on the compressive strength of UHPC. The compressive strength of the HPC1 increases by approximately 1–3% with the replacement of 5–10% (as an average) of ultrafine materials. The compressive strength then decreases when the replacement ratio exceeds 10% [43, 52]. Due to the fact that super fine materials are finer than Portland cement, it will also increase the density and homogeneity of the cement matrix by providing a better distribution of C-S-H and by restricting CH crystal growth, which may lead to the blockage of existing pores and, consequently, alter the pore structure [53, 54]. However, the results of previous studies[40, 55] indicating an increase in compressive strength for HPC2 and HPC3 indicate that for the same curing method using different percentages of LWA compared to using only normal aggregate in the control mixture (0% LWA), the compressive strength rises with 10% LWA and then falls gradually as the advance rises. It

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should be noted that some studies conducted in the present work indicate that the use of an equivalent quantity of fine LWA has a positive effect on compressive strength. According to these studies, the use of an equivalent quantity of fine LWA increased the compressive strength of samples by more than 18 percent. Francis et al. [56] examined the impact of water-soluble polyethylene-glycol as a substitute for normal-weight aggregate (gravel). The compressive strength increased at 7 and 28 days with additions of up to 30% LWA replacement, before decreasing by 40% and 50%. The primary conclusion was that a LWA percentage of 25% was optimal. Suwan and Wattanachai [25] proposed that 20%–40% LWA replacement may be the optimal proportion for AAC-LWA concrete. This result, which was achieved in accordance with IC by AAC aggregate replacement, which provided adequate bonding between the cement paste and aggregate at the ITZ, increased the formation of C--S--H. These were the primary factors that contributed to the concrete's strength. Kevern and Nowasell [57] discovered that replacing fine aggregates with small portions of pre-wetted LW fine aggregates and using LW coarse aggregates improved the performance of conventional IC concrete. The compressive strength of the UHPC2 and UHPC3 mixtures increased at 7 and 28 days, while the effect of the control mixture was minimal. In agreement with Weber and Reinhardt [58] and Lura [17], an increase in compressive strength occurs in HPCII and HPCIII due to the additional water supplied by saturated LWA, which promotes a higher degree of hydration, fills the pores with hydration products (gel), and increases the strength of cement paste. Saturated LWA exhibits IC behaviour. This IC water also enhances the interface transition zone (ITZ) between aggregate and cement paste, thereby decreasing the pore size of UHPC [59]. Other research has demonstrated that HPCIV increases compressive strength [28, 44, 60]. Song et al. [60] documented the impact of HPCIV on the compressive strength of concrete. The results revealed that an increase in compressive strength at 7 and 28 days is due to the continuous hydration of the samples by declaring absorbed water, and that 0.3% SAP (by the binder mass) could increase strength and attain the highest strength, as shown in Figure 7.

4.4. Splitting tensile and flexural strength

Several previous studies have investigated the influence of (IC) on the splitting tensile strength of (UHPC). In their research, Francis et al. (56) discovered that a 25% substitution of lightweight aggregate (LWA) yields the highest concrete strength in terms of compression, splitting tensile strength, and flexural or rupture modulus. Based on the findings of Zhutovsky and Kovler (39), it has been observed that the incorporation of IC has adverse implications on the splitting tensile strength. Notably, this decline in splitting tensile strength is particularly pronounced during the early stages of material maturity. Based on the results, it was observed that at the age of one day, the reductions in percentages were 20%, 20%, and 27% for water-to-cement ratios of 0.25, 0.21, and 0.33, respectively. The splitting tensile strength, however, exhibited equivalence to that of the fully cured concrete in the control group. According to Mousa et al. [28], the splitting tensile strength of IC concrete varies between 6.4% and 8.5%. The experimental findings indicate that the optimal level of tensile strength was observed at approximately 7.4% when utilising 15% saturated Leca ovutilizingod for 28 days. The findings presented in Figure 10 demonstrate a consistent trend in the development of cement when subjected to modifications involving an increase in polyethylene-glycol content. Specifically, the cement exhibited increases of approximately 7.4%, 14.8%, and 10% when combined with 1%, 2%, and 3% Ch, respectively. The observed result was ascribed to ongoing hydration reactions. The ability to bend exhibited a gradual increase over time. Particularly, at the 28-day mark, the respective increments in flexural strength for 10%, 15%, and 20% of Leca were measured at 1.6%, 7.2%, and 3.4%. Al-Attar et al. [61] have reported that incorporating Porcellanitic stone as a substitute for both fine and coarse aggregates, either partially or entirely, in the production of internal curing, leads to enhancements in splitting and flexural strength. An increase in splitting tensile strength ranging from 5.48% to 6.85% was observed. The flexural strength exhibited an increase ranging from 11.76% to 12.74%.

The improvement in performance can be attributed to the increased cohesion between the cement paste and the aggregate particles.

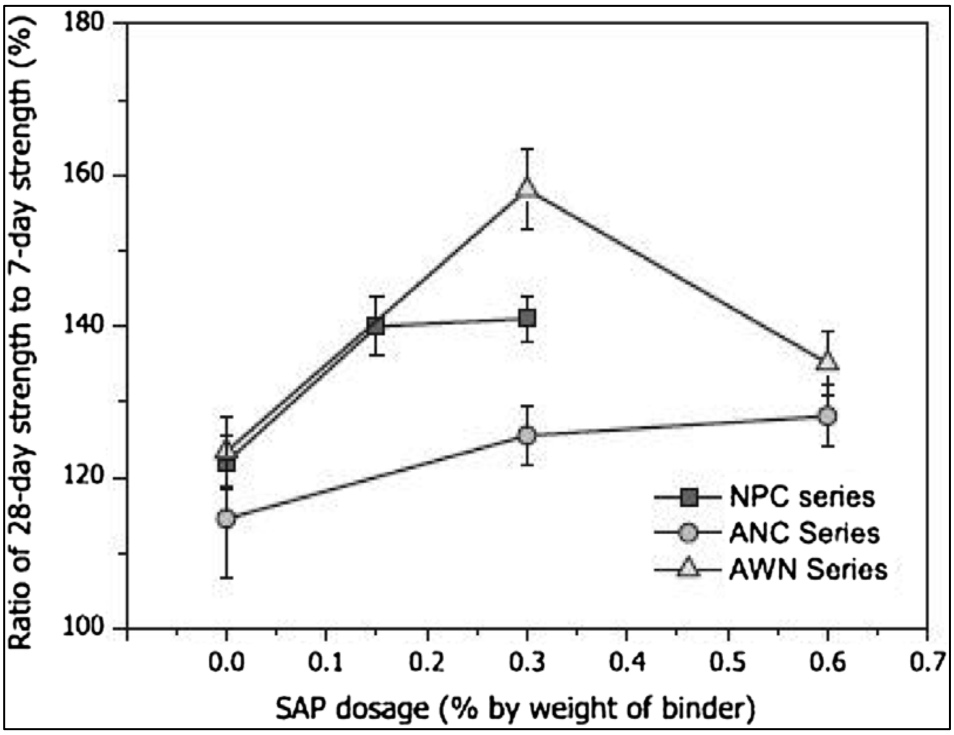

Fig.(7):- The ratio of 28-day strength to 7-day strength vs. SAP dosages, with the upper [60].

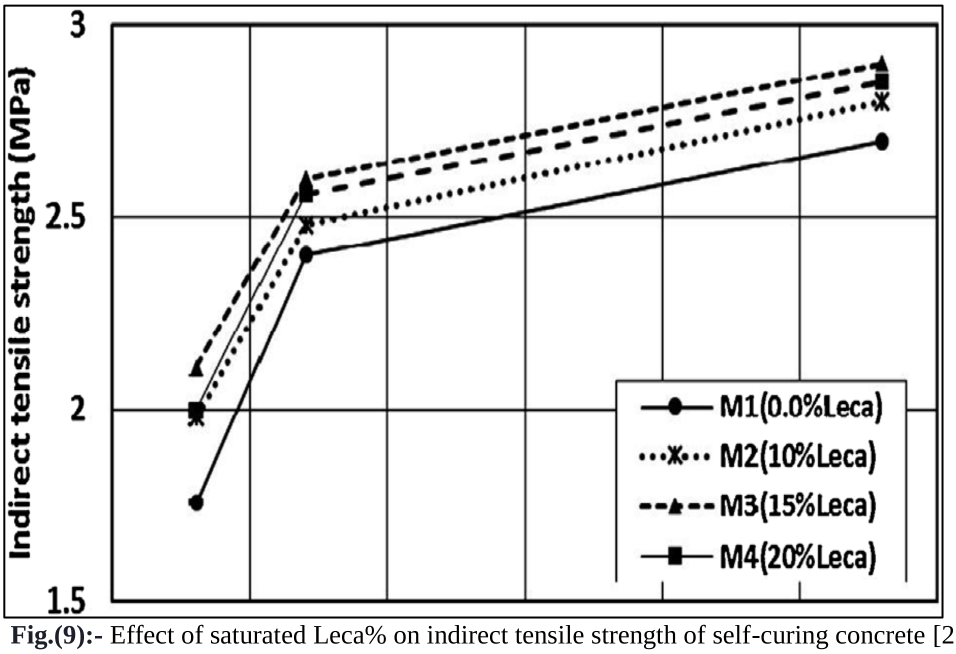

Fig.(9):- Effect of saturated Leca% on indirect tensile strength of self-curing concrete [28].

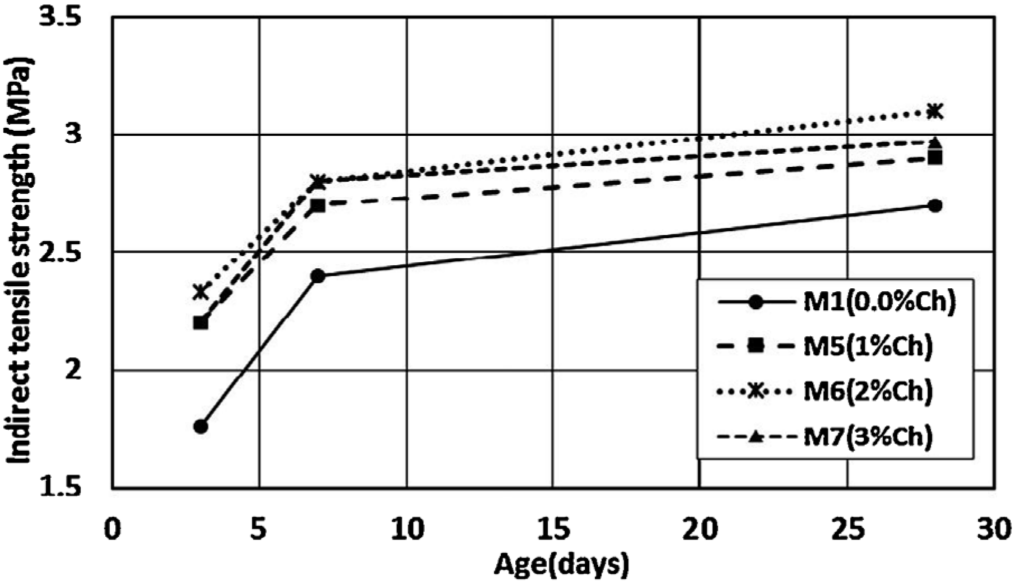

Fig.(10):- Effect of polyethylene-glycol (Ch.) % on indirect tensile strength of self-curing concrete [28]

5. Morphology by scanning electron microscopy (SEM)

Several scholarly investigations [25, 62-64] have examined the impact of internal curing morphology on the behavior of (HPC) as assessed through scanning electron microscopy (SEM) testing. The arrangement of calcium-silicate-hydrate (C-S-H) in significant quantities, as depicted in Figure 11 [62, 65], had an impact on the strength development of internally cured (IC) concrete at a later stage. As a consequence, the interfacial transition zone exhibited the development of dense microstructures.

The lack of significant amounts of unbound water within the voids of hydrated cement paste led to a progressive series of chemical reactions in internally cured (IC) concrete, which ultimately led to enhanced strength development at later stages. The presence of limited water availability within the large pores of lightweight aggregates (LWA) is a contributor to the decrease in autogenous shrinkage observed in mortars, as depicted in Figures 11 and 13 [11, 66]. It is expected that there will be an augmentation in capillary porosity with an increase in the concentration of lightweight aggregate (LWA) in the mixture. This assumption is primarily based on the inclusion of highly porous implications. It should be noted that the pores of lightweight aggregate (LWA) are slightly larger than the largest hairy pores [67]. While it has been observed that LWA has the potential to decrease the interconnected porosity of the paste matrix [68], it is important to note that it cannot completely eradicate it. Previous research (Studies 67, 69) has shown that the overall capillary porosity is not a reliable measure of the vulnerability of a mixture containing lightweight aggregate (LWA) to fluid penetration. This is because mixtures with LWA tend to have high porosity but low sorptivity. The observed phenomenon can be ascribed to the development of ettringite, with elongated ettringite crystals potentially occupying the voids within the paste matrix [70]. Although the augmentation of the water-to-cement ratio in cement paste has been observed to enhance hydration and ettringite formation [71], this approach proved ineffective in mitigating the initially elevated capillary porosity level. The augmentation in the effective water-to-cement ratio (w/c) resulted in a corresponding rise in porosity. Consequently, this increase in porosity facilitated the absorption of a substantial quantity of moisture during the wet-curing process. Moreover, it also contributed to a notable escalation in early-age expansion. The influence of IC on a compact, moderately permeable paste matrix has been documented [71].

It is widely acknowledged that when a structure having a specific type of symmetry is subjected to loading which additionally exhibits congruent symmetry, substantial time and computational resources can be conserved by solely analyzing the structure with congruent symmetry.

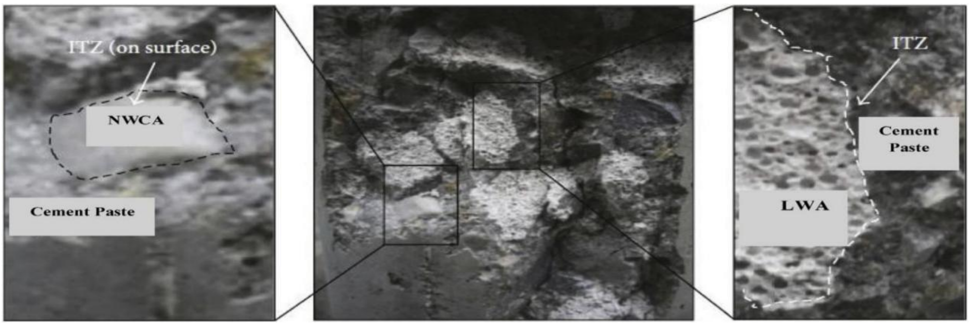

Fig.(11):- Normal-bonded NWA (left) and well-bonded LWA (right) [25] .

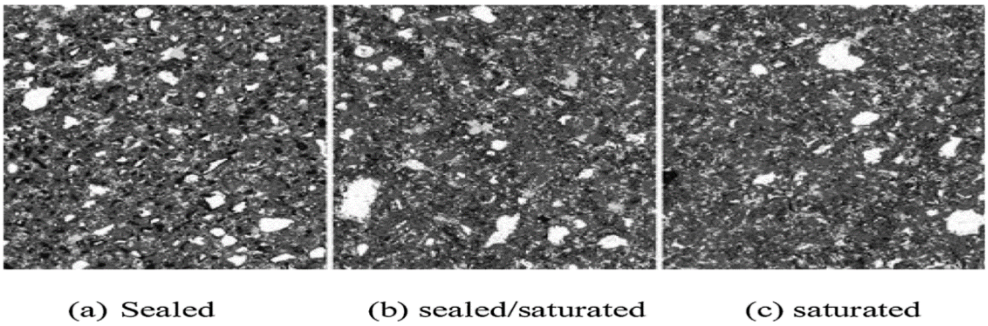
(a) Sealed (b) sealed/saturated (c) saturated

Fig.(12):- segmented SEM microstructures for w/c = 0.35 for 92 days [25].

6.CONCLUSIONS

The primary objective of this research was to demonstrate the effects of various types of IC on the action of UHPC. The following conclusions were drawn:

- Based on previous studies, the low density of internally curing concrete reduces the weight of the mixture because LWA has a low specific gravity.
- Numerous studies have demonstrated that IC is responsible for a reduction in the shrinkage of UHPC mixtures. Therefore, the volumetric stability of the cement matrix must be maintained. The former is due to a high degree of hydration in UHPC, while the latter is due to a moderate degree of self-desiccation; both are direct results of using IC.
- The compressive strength of mixtures with LWA may increase more than that of mixtures without LWA. The formation of ettringite facilitates the development of compressive strength. As previously stated, the degree of hydration is determined by the amount of accessible water in a hydrated CP. Therefore, the low compressive strength at an early age compared to all other mixtures at a later age could be explained by the low formation of ettringite in the presence of a low amount of available water. Numerous studies have reported an increase in the compressive strength of UHPC specimens when LWA and SAP were added to the mixture; this phenomenon is thought to result from a high level of hydration.
- IC is more effective for splitting tensile and flexural strength than for compressive strength.
- The IC concrete may produce a more dense hydrated cement paste than mixtures without inner supply water.
- Due to a lack of available capillary pore space for the precipitation of hydration products, however, precipitation may continue due to the additional space introduced by the SAP. In this instance, hydration should continue for as long as additional water is available, or, less likely, until all additional pore space has been filled.Some studies have shown that the use of micro steel fibres increases compressive strength and flexural strength by more than five times compared to materials without micro steel fibres.
- According to a number of studies, micro steel fibres will result in massive salt-scaling composition losses.

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