DEVELOPMENT OF INTERNALLY CURED CONCRETE FOR INCREASED SERVICE LIFE

M.Gopal[1] and S.O.Sunitha[2]

(1) Selection Grade Lecturer, Department of Civil Engineering, M.E.I Polytechnic, Bangalore – 560 010.
(2) Selection Grade Lecturer , Department of Civil Engineering, M.E.I Polytechnic, Rajajinagar, Bangalore – 560 010.

Abstract: Internally cured concrete (ICC) represents a significant advancement in concrete technology, aimed at enhancing durability and extending the service life of structures. This study investigates the development and application of ICC through the incorporation of lightweight aggregate and superabsorbent polymers (SAPs) that retain and release water during hydration. By optimizing the water-to-cement ratio and integrating internal curing agents, we evaluate the effects on hydration kinetics, shrinkage, and long-term performance under varying environmental conditions. Experimental results demonstrate that ICC exhibits reduced autogenous shrinkage and improved resistance to cracking, permeability, and environmental degradation. These enhancements contribute to the longevity of concrete structures, making ICC a viable solution for infrastructure facing severe conditions. The findings underscore the potential of ICC to not only improve the mechanical properties of concrete but also to support sustainable construction practices by reducing maintenance costs and extending service intervals. This research lays the groundwork for further exploration and implementation of ICC in modern concrete applications.

Index terms: **concrete, autogenous shrinkage, superabsorbent polymers, hydration, lightweight aggregate**

1. INTRODUCTION

Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration. In the 21st century, internal curing has emerged as a new technology that holds promise for producing concrete with increased resistance to early-age cracking and enhanced durability. Since concrete service life is a key component of providing a sustainable infrastructure, internal curing can provide a positive contribution to increasing the sustainability of our nation’s infrastructure.

In 2010, the American Concrete Institute (ACI) defined internal curing in its ACI Terminology Guide as “supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation (American Concrete Institute, 2010).”

ACI Committee 308 is rewriting the Curing Guide 308R to include Internal Curing as an alternate process to that of external curing of concrete so that the potential properties of the mixture may develop. The result is that the design engineer and the ready mixed concrete (RMC) producer will assume more of the responsibility for curing instead of leaving it to the contractor

or his agent to cure the concrete, sometimes under adverse conditions.

This definition identifies the two major objectives of internal curing:

- Maximizing hydration and
- Minimizing self-desiccation (and its accompanying stresses that may produce early-age cracking).

The goal of internal curing of concrete is to provide internal reservoirs that supply the hydrating cement paste with the water needed to maintain saturation within the paste’s capillaries throughout the first days or weeks of hydration. It’s been suggested that this water availability is especially critical during the first day of hydration in high-performance concretes, because without it, significant autogenous shrinkage and cracking can occur.

In general, the water reservoir may function based on several different physical or chemical principles:

- Chemically bound water, e.g. crystalline water,
- Physically adsorbed water, e.g. water in superabsorbent polymers,
- Physically held water, e.g. capillary water in fine pores, and
- Unbound water, e.g. encapsulated water.

There are many benefits associated with internal curing that include

- increased cement hydration,
- higher strength,
- less autogenous shrinkage and cracking,
- reduced permeability and higher durability.

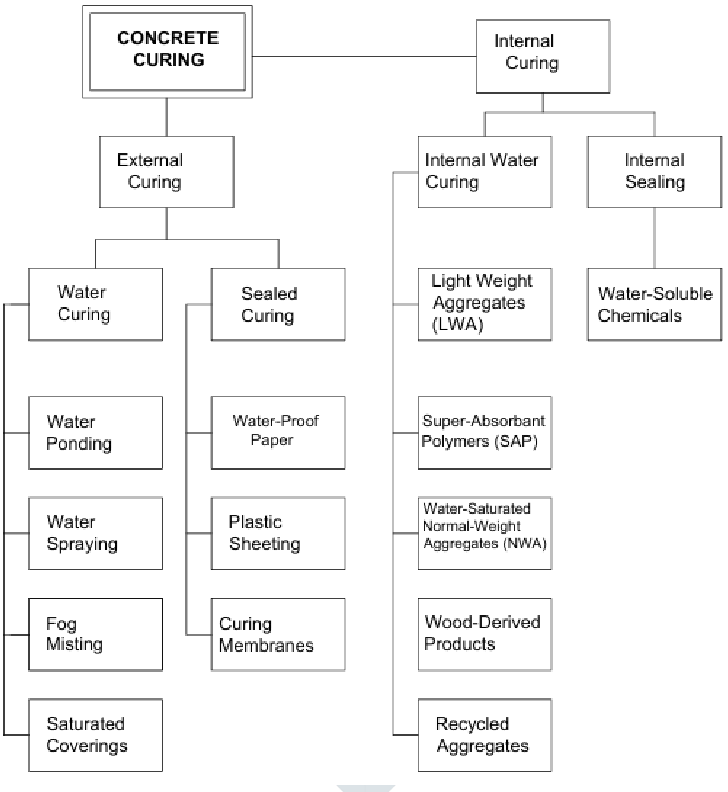


Fig. 1: Classification of methods of curing concrete to maintain moisture content

2. HISTORY

For the past 50 years coarse lightweight aggregate has been used, not for the purpose of supplying the extra water in the mix, but for the economy of its saving weight in bridge decks and multistory buildings. It was observed that its absorbed water supplied the function of internally curing the concrete, with the result that there was a great reduction in expected cracking.

It has been found, in the last five years, that the replacement for natural sand in the mix of as little as 100 lbs. per cubic yard of saturated lightweight aggregate sand will supply the water needed to properly hydrate the cement at a w/c ratio of 0.43.

- The first published recognition of the internal curing potential of lightweight aggregates was likely that of Paul Klieger in 1957, who wrote "Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration (Klieger, 1957)."

- Concrete technologist Robert Philleo to write these prophetic words in 1991, "Either the basic nature of Portland cement must be changed so that self-desiccation is reduced, or a way must be found to get curing water into the interior of high-strength structural members.The latter is possible through the use of saturated lightweight aggregate.
- A partial replacement of fine aggregate with saturated lightweight fines might offer a promising solution. (Philleo, 1991)" (italics added for emphasis).
- By the mid-1990s, a variety of research groups in Germany (Weber & Reinhardt, 1995), the Netherlands (van Breugel & de Vries, 1998), and Israel (Bentur, Igarishi, & Kovler, 1999) had followed through on Philleo's concept by actively investigating internal curing via the use of pre-wetted lightweight aggregates.
- In the years soon after that, other materials that could function as internal water reservoirs, such as superabsorbent polymers (SAP) (Jensen & Hansen, 2001) (Jensen & Hansen, 2002) and pre-wetted wood fibers (Mohr, Premenko, Nanko, & Kurtis, 2005) were also investigated.
- As with many new technologies, the path from research to practice has been a slow one, but as of 2010, hundreds of thousands of cubic meters of concrete containing pre-wetted LWA for internal curing have been successfully placed throughout the U.S. (Villareal, 2008).

3. DIMENSIONAL CHANGES IN EARLY-AGE CONCRETE

3.1 Self-desiccation

It is the localized drying resulting from a decreasing relative humidity (RH) which could be the result of the cement requiring extra water for hydration. It is the reduction in the internal relative humidity of a sealed system when empty pores are generated, Or

The phenomenon of the reduction of relative humidity in hardening cement paste due to consumption of capillary water in the progress of cement hydration is called self-desiccation. Self-desiccation typically occurs in a sealed system when empty pores are generated.

3.2 Autogenous Shrinkage

It is as a volume change in concrete occurring without moisture transfer from the environment in to concrete. It is due to the internal chemical and structural reactions of the concrete. Autogenous shrinkage is prominent in HPCs due to the reduced amount of water and increased amount of various binders used. At early ages (the first few hours), before the concrete has formed a hardened skeleton, autogenous shrinkage is often due to only chemical shrinkage. At later ages (>1+days), the autogenous shrinkage can also result from self-desiccation since the hardened skeleton resists the chemical shrinkage. The Japan Concrete Institute defines the autogenous shrinkage as the one which occurs after setting, while the volume change before setting, due to chemical shrinkage, is included in plastic shrinkage .

4. INTERNAL CURING

Most high-strength or high-performance concretes having a low water to binder ratio (w/b) contain insufficient mixing water to maintain water-filled coarse capillaries needed to sustain cement hydration and pozzolanic reactions. For this reason, it is generally accepted that methods based on adding of water (internal water supply) are more effective for this type of concrete.

Internal curing is another concept of curing concrete, which is different from externally applied curing. This term implies introduction to the concrete mixture a component, which serves as a curing agent. This agent can be either a normal aggregate introduced into the concrete mixture in specific conditions (for example, in water-saturated state) or a new component (for example, an admixture or special aggregate).

4.1 Concrete Deficiencies that IC can address

The benefit from IC can be expected when

- Cracking of concrete provides passageways resulting in deterioration of reinforcing steel,
- Low early-age strength is a problem,
- Permeability or durability must be improved,
- Need for reduced construction time, quicker turnaround time in precast plants, lower maintenance cost, greater performance and predictability.

5. METHODS OF INTERNAL CURING

Internal curing can be classified into two categories:

- Internal water curing (sometimes called "water entrainment"), when the curing agent performs as a water reservoir, which gradually releases water, and
- Internal sealing, when the curing agent is intended to delay or prevent loss of water from the hardening concrete.

Among different methods of internal water curing, those based on using pre-saturated light weight aggregates (LWA) and super-absorbent polymers (SAP) are under development.

6. POTENTIAL MATERIALS FOR IC

The following materials can provide internal water reservoirs:

- Lightweight Aggregate (natural and synthetic, expanded shale),
- LWS Sand (Water absorption =17 %),
- LWA 19mm Coarse (Water absorption = 20%),
- Super-absorbent Polymers (SAP) (60-300 mm size),
- SRA (Shrinkage Reducing Admixture) (propylene glycol type i.e. polyethylene-glycol),
- Wood powder.

7. USE OF LIGHTWEIGHT AGGREGATE FOR INTERNAL CURING

In 1991, Philleo suggested incorporating saturated lightweight fine aggregate into the concrete mixture to provide an internal source of water to replace that consumed by chemical shrinkage during hydration of the paste. LWAs typically have 24-hour absorptions in the range of 5% to 25% and, if properly preconditioned prior to their introduction into the mixture, can provide additional internal water for curing the concrete.

The researchers suggested incorporating saturated lightweight fine aggregate into the concrete mixture to provide an internal source of water necessary to replace that consumed by chemical shrinkage during hydration.

8. MECHANICS OF INTERNAL CURING

For LWA to function successfully as an internal curing reservoir, the pores containing the water must be larger than those in the surrounding cement paste, so that water will preferentially move from the LWA to the hydrating cement. X-ray absorption studies of cement-based materials have indicated that during drying, water will preferentially move from coarser pores to finer ones, regardless of whether the coarser pores are present due to an increased *w/c* for a single cement or due to a coarser cement at a constant *w/c*. In the case of internal curing, the coarser pores are present due to the intentional incorporation of internal water reservoirs during the mixture proportioning. This ability of the LWA to release water at high relative humidity's can also be quantified by measuring the absorption/desorption properties of the LWA particles.

The following mechanism listed:

- During hydration, a system of capillary pores is formed in the cement paste. The radii of these pores are smaller than the pores of the LWA. As soon as the RH decreases (due to hydration and drying), a humidity gradient develops.
- With the LWA acting as a water reservoir, the pores of the cement paste absorb the water from the LWA by capillary suction. The unhydrated cement particles from the cement paste now have more free-water available for hydration. The new hydration products grow in the pores of the cement paste thus causing them to get smaller.
- The capillary suction, which is the inverse to the square of the pore radius, increases as the radius becomes smaller and thus enabling the pores to continue to absorb water from the LWA.
- This continues until all the water from the LWA has been transported to the cement paste.

The use of mineral admixtures, such as fly ash and silica fume, tend to refine the pore structure towards a finer microstructure. If there is a finer microstructure, the water consumption will be increased and the autogenous shrinkage due to self-desiccation will be increased.

At the surface of the concrete, an additional humidity gradient occurs due to evaporation from the concrete surface. This accelerates the appearance of the localized humidity gradient. The water from the LWA near the surface is then used up faster than in the interior of the concrete thus causing the near-surface layer of the concrete to become denser in a shorter period of time. This helps reduce the amount of water that would normally evaporate and contributes to improve internal curing of the concrete. It also leads to reduced or no stresses due to drying, and helps eliminate surface cracking.

Bentz and Snyder developed equations to estimate the replacement level of saturated LWA fines that would be needed to provide all of the water needed for the complete curing of a HPC.

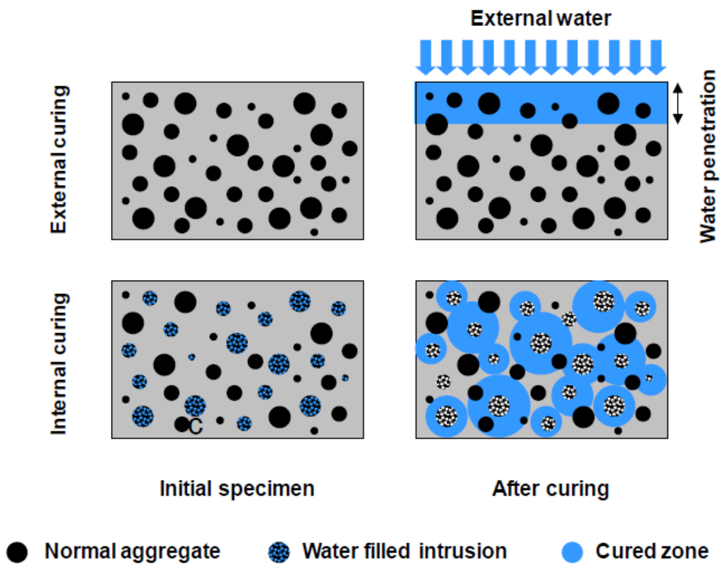


Fig. 2: Illustration of the different between external and internal curing. The water filled inclusions should be distributed uniformly and spaced close enough to provide coverage for the entire paste system. (Castro, De La Varga, Golias, & Weiss,2010).

8.1 Water in LWA for Internal Curing

About 67% of the water absorbed in the LWA can get transported to self-desiccating paste. Some water remains always in the LWA in the high RH range and it becomes useful when the overall RH humidity in concrete is significantly reduced. The water retained in LWA in air-dry condition may not be enough to prevent autogenous shrinkage whose magnitude, however, may be reduced significantly. The fine lightweight aggregate, in saturated condition, produce a more uniform distribution of the water needed for curing throughout the microstructure. The grain size of the LWA used as curing agent should be less in order to minimise the paste– aggregate proximity, i.e. the distance to which the internal curing water could diffuse. The grain sizes of down to 2–4 mm are found to be beneficial.

8.2 Utility of LWA near Surface of Concrete

At the surface of the concrete, as the water evaporates from the concrete surface, a humidity gradient develops. This accelerates the appearance of the localized humidity gradients. The water from the LWA near the surface is then used up faster than in the interior of the concrete thus causing the near-surface layer of the concrete to become denser in a shorter time. This helps reduce the amount of water that would normally evaporate and contributes to improve internal curing of the concrete. It also leads to reduced or no stresses due to drying helping in eliminating the surface cracking.

8.3 Effect of Particle Size and Content of LWA

Internal curing by saturated lightweight aggregate can eliminate autogenous shrinkage with the smallest possible amount of lightweight aggregate. The grain size of the LWA used as curing agent needs to be reduced in order to minimize the paste aggregate proximity, i.e. the distance to which the internal curing water should diffuse. The reduction of the grain size (down to 2–4 mm), is shown to be beneficial. However, the further reduction of grain size could result in a decrease of curing efficiency. The effectiveness of internal curing depends not only on whether there is sufficient water in the LWA, but also on whether it is readily available to the surrounding cement paste as well. Hence, if the distance from some location in the cement paste to the nearest LWA surface is too great, water cannot permeate fully within an acceptable time interval. This distance can be called the paste– aggregate proximity. Alternatively, aggregate distribution can be described by means of aggregate– aggregate proximity, which is the distance between two nearest LWA surfaces, often called spacing. For a given amount of aggregate, the paste–aggregate proximity can be adjusted by the size of the aggregate. The finer the aggregate size, the closer will be the paste– aggregate proximity. The LWA can be used for internal curing without considerable detrimental effects on strength when added in the amounts just required to eliminate self-desiccation.

8.4 Protected Paste Volume- Concept in internal curing

For IC, besides providing necessary quantity of water inside the matrix, it is essential to ensure the proximity of the cement paste to the surfaces of the source of water so that required high RH is generated around the cement grains for hydration reaction. In this regard, the "protected paste volume" concept is useful to recognize the effective volume of cement paste. For this, the aggregates are represented by impenetrable spherical or ellipsoidal particles and each aggregate particle is surrounded by a soft penetrable shell representing the interfacial transition zone. Instead of the interfacial transition zones, the saturated LWA (fine aggregate) particles surrounded by a shell of variable thickness can be assumed for evaluation. Then, by systematic point sampling, one can determine the volume fraction of paste contained within these shells and hence the relative proximity of the cement paste to the additional water.

8.5 Distribution of Internal Water Reservoirs for Curing

The transport distance of water within the concrete is limited by depercolation of the capillary pores in low w/c ratio pastes. With water-reservoirs well distributed within the matrix, shorter distances have to be covered by the curing water and the efficiency of the internal-curing process is consequently improved. The concept of internal curing was established, based on dispersion of very small, saturated LWA throughout the concrete, which serve as tiny reservoirs with sufficient water to compensate for self-desiccation. The spacing between the LWA particles is conveniently small so that the water travels smaller distances to counteract self-desiccation. The amount of water in the LWA can therefore be minimized, thus economising on the content of the LWA.

8.6 Travel of Water from Surfaces of LWA

Estimates of travel of internal water from the surface of water reservoir in the concrete matrix are:

- early hydration — 20 mm
- middle hydration — 5 mm
- late hydration — 1 mm or less
- "worst case" — 0.25 mm

(Early and middle hydration estimates in agreement with x-ray absorption-based observations on mortars during curing).

8.7 Size of pores for Internal Water Storage

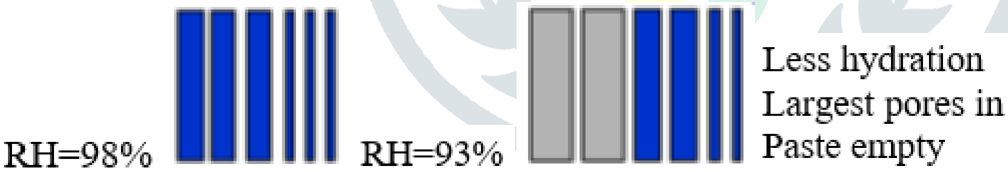
Water is held in pores primarily by capillary forces. Only pore sizes above approximately 100 nm are useful for storage of internal curing water. In smaller pores the water is held so tightly that it is not available for the cementitious reactions. Since some of the water absorbed by the LWA in the smaller pores will not be released to the hardening cement paste, an amount of water more than sufficient to counteract self desiccation should be absorbed in the LWA. A great quantity of water is in fact entrapped in the internal porosity of the larger particles; one should consider that only about half of it is available for internal curing. In case of smaller fraction, the opposite seems to hold: the absorption is lower, but almost 80 % of the water is lost by 85% RH.

8.8 Pore Sizes in Internal Reservoirs & Capillary Pores

Internal curing distributes the extra curing water throughout the 3-D concrete microstructure so that it is more readily available to maintain saturation of the cement paste during hydration, avoiding self desiccation (in the paste) and reducing autogenous shrinkage. Because the autogenous stresses are inversely proportional to the diameter of the pores being emptied, for IC to do its job, the individual pores in the internal reservoirs should be much larger than the typical sizes of the capillary pores (micrometers) in hydrating cement paste.

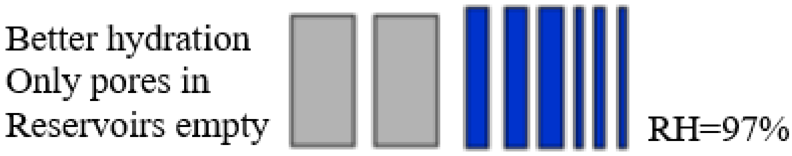
Empty and Full pores

Saturated Curing Sealed Curing



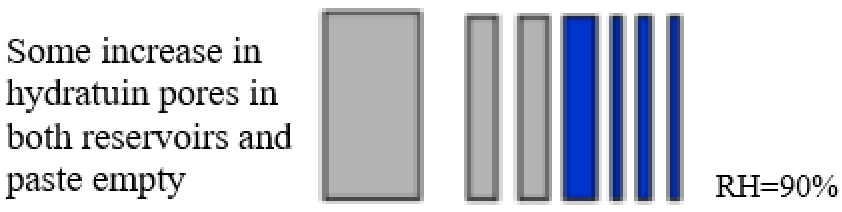
Pores in cement paste Pores in cement paste

Sufficient Internal Curing



Pores in IC reservoir Pores in cement paste

Insufficient internal Curing



Pores in IC reservoir Pores in cement paste

Fig. 3: Illustration of potentil for under curing with internal curing. Blue indicates water-filled pores within the internal curing reservoir or hydrating cement paste. While grey indicates empty pores.

Table1: Distance of Water Travel from the Surfaces of Internal Reservoirs (Bentz, Koenders, Monnig, Reinhardt, VanBreugel, & Ye, 2007)

Hydration Age	Estimated Travel Distance of Water
Early (i.e. -1 day)	20 mm
Middle (i.e. 1 day to 3days)	5mm
Late (i.e. 3 days to 7 days)	1mm
Worst Case (i.e. > 28 days)	0.25mm

9. ROLE OF WATER-FILLED LIGHTWEIGHT AGGREGATE AT THE SURFACE OF A CONCRETE EXPOSED TO DRYING IMMEDIATELY AFTER PLACEMENT

Immediately after placement, the system is in a fluid state and the aggregate and cement particles tend to settle due to gravity, simultaneously forcing pore fluid (water) to the surface. This is commonly observed in practice as 'bleed water'. During this initial period, a thin layer of bleed water covers the surface of the concrete and evaporates at a relatively constant rate. As a result, this is referred to as the constant rate period of drying. During this time, the system continues to consolidate in the vertical direction resulting in settlement of the surface. After some time, the rate of settlement dramatically reduces as the particles begin to come in contact with one another. Assuming that the rate of evaporation is relatively high, the layer of bleed water will be lost from the surface. When the water available to evaporate decreases, a slower rate of evaporation occurs, referred to as the falling rate period. During the falling rate period, evaporation draws water from between the particles resulting in the development of capillary stresses in the system that produce further consolidation and may lead to plastic shrinkage cracking. In conventional concrete systems, the stresses will rise relatively dramatically during this period.

Table 2: Protected Paste Volume as a functions of Distance from the LWA Surfaces (Bentz, Lure & Roberts, 2005)

Distance from LWA Surface	Protected Paste Fraction
0.02mm	0.0459
0.05mm	0.1281
0.1mm	0.2804
0.2mm	0.5629
0.5mm	0.9783
1.0mm	1.0000

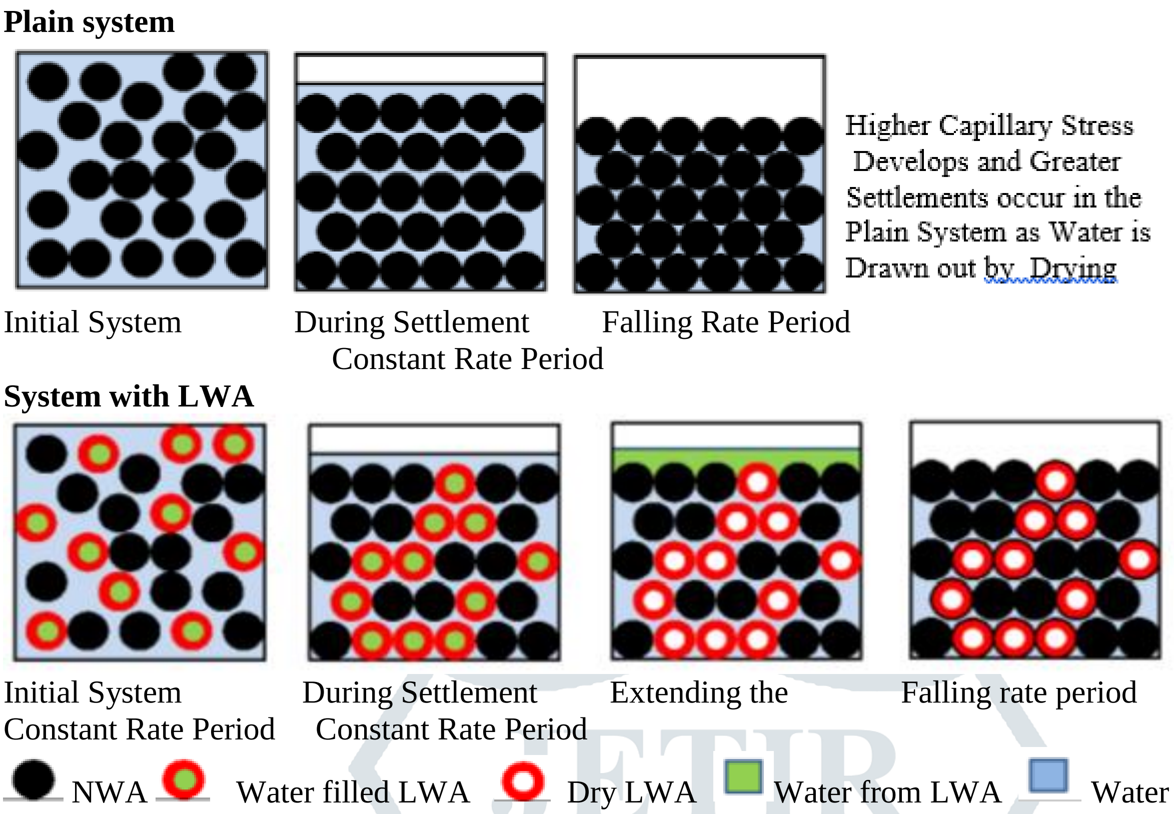


Fig. 4. A conceptual illustration of the role of water-filled lightweight aggregate at the surface of a concrete exposed to drying immediately after placement (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010).

In a system with internal curing, however, water is provided by the pre-wetted and rigid LWAs to replenish the water evaporating from the surface of the concrete. This helps to reduce the capillary stress during the falling rate period. The water from the rigid LWAs reduces the capillary stress in the system resulting in less consolidation and settlement and a dramatically lower potential for plastic shrinkage cracking. This preferential removal of water from LWA while the surrounding cement paste remains saturated during a drying exposure of the fresh material has been verified using three-dimensional X-ray absorption micro tomography measurements.

10. IMPROVING THE TRANSITION ZONE

"Internal curing" refers to the process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water.

"Contact Zone" refers to two distinctly different phenomena:

(1) the mechanical adhesion of the cementitious matrix to the surface of the aggregate;

(2) the variation of physical and chemical characteristics of the transition layer of the cementitious matrix close to the aggregate particle.

The contact zone of lightweight aggregate concrete has been demonstrated to be significantly superior to that of normal weight concretes that do not contain supplementary cementitious material.

The following three characteristics of the LWA must be taken into consideration:

- The LWA must be able to absorb an appropriate volume of curing water. This volume is determined based the amount of internal void space created by the hydrating cement. This volume can be approximated as the volume of chemical shrinkage, however strictly
- The LWA must be able to desorbs (i.e, release) a large portion of its absorbed water during the hydration of the cement paste. To accomplish this, the pores of the LWA must be larger than the pores of the hydrating cement paste. If the pores in the LWA are not larger than the pores in the paste, the water will remain in the pores of the LWA and cannot be used for internal curing.
- The LWA must be well dispersed throughout the system so that the water can physically travel to all regions of the paste. It was shown that water could travel on the order of 2 mm after set during the first 75 h in cement paste with a w/c of 0.30. Better dispersion is achieved by using finer LWA aggregates and higher LWA replacement volumes.
- Therefore, fine aggregates typically will perform far better than coarse aggregates. Higher absorption LWA may suffer from a lack of dispersion as these materials require lower replacement volumes for a given amount of chemical shrinkage.
- Internal curing with pre-wetted LWA can improve the shrinkage and cracking performance (i.e., reduce shrinkage and reduce or eliminate cracking) of concrete.

11. SUPER ABSORBENT POLYMERS

A new method tor prevention of self-desiccation by use of super-absorbent polymer panicles as concrete admixture was proposed recently. During concrete mixing, the particles of super-absorbent polymer absorb huge amount of water and form macro-inclusions containing free water This free water is consumed during cement hydration providing internal curing to the surrounding paste matrix and preventing self-desiccation.

A superabsorbent polymer, SAP, is a polymeric material which is able to absorb a significant amount of liquid from the surroundings and to retain the liquid within its structure without dissolving. SAPs are principally used for absorbing water and aqueous solutions. With the present polymer types the theoretical maximum water absorption is approx. 5000 times their own weight. The absorption of water in the SAP is based on secondary chemical bonds, and the water is so loosely held that all of it essentially can be considered bulk water. (SAPs are principally used for absorbing water and aqueous solutions; about 95% of the SAP world production is used as a urine absorber in disposable diapers)

Superabsorbent polymers are swellable substances which can absorb many times their own weight of liquids by forming a gel. The absorbed liquid is not released even under moderate pressure. The picture shows a dry, collapsed and a swollen suspension polymerized SAP particle

Compared with lightweight aggregate SAP has some peculiarities. SAP can be used as a dry concrete admixture since it takes up water during the mixing process. Furthermore, the use of SAP permits free design of the pore shape and the pore size distribution of the hardening concrete, however, the pores introduced by the SAP in the concrete may preferably be selected in the range 50-300 µm.

12. QUANTIFYING EFFECTIVENESS OF IC

IC can be experimentally measured by:

- Internal RH
- Autogenous deformation
- Compressive strength development
- Degree of hydration
- Restrained shrinkage or ring tests
- 3-D X-ray micro tomography (Direct observation of e 3-D microstructure of cement-based materials).

13. ADVANTAGES OF INTERNAL CURING

A 20% sand replacement with LWA enables the almost complete elimination of autogenous shrinkage and reduces the risk of cracking 50%.

The effects of different amounts of LWA on autogenous shrinkage were investigated at the National Research Council Canada on large prismatic concrete specimens under fully-restrained autogenous shrinkage (specimens were sealed against external drying).

The specimen with20% LWAS, however, demonstrated

- less internal drying (i.e. enhanced internal curing),
- a clear reduction of autogenous shrinkage and
- a much reduced tensile stress to strength ratio not higher than 0.5 (i.e. a minimum safety factor of 2).

It was also shown that LWAS in the amounts tested in the study did not adversely affect the air content, strength or modulus of elasticity of the concrete. With cracking eliminated, or largely so, and with permeability reduced, water, salt and other deleterious substances which could adversely affect the reinforcing steel are hindered from entering the concrete.

- Internal curing (IC) is a method to provide the water to hydrate all the cement. In low w/c ratio mixes absorptive lightweight aggregate, replacing some of the sand, provides water that is desorbed into the mortar fraction (paste) to be used as additional curing water. The cement, not hydrated by low amount of mixing water, will have more water available to it.
- IC provides water to keep the relative humidity (RH) high, keeping self-desiccation from occurring.
- IC eliminates largely autogenous shrinkage.
- IC maintains the strengths of mortar/concrete at the early age (12 to 72 hrs.) above the level where internally & externally induced strains can cause cracking.
- IC can make up for some of the deficiencies of external curing, both human related (critical period when curing is required is the first 12 to 72 hours) and hydration related (because hydration products clog the passageways needed for the fluid curing water to travel to the cement particles thirsting for water).

- Reduces permeability,
- Protects reinforcing steel,
- Increases early age strength sufficient to withstand strain,
- Provides greater durability,
- Greater utilization of cement,
- Lower maintenance,
- Use of higher levels of fly ash,
- Reduces effect of insufficient external curing.

14. INTERNAL CURING IN PRESENT PRACTICE

As of the end of 2010, internal curing has been employed in a variety of concrete mixtures for diverse applications including bridge decks, pavements, transit yards, and water tanks.

One of the first documented field studies of concrete with internal curing was a large railway transit yard in Texas requiring 190000 m3 of concrete, constructed in 2005 (Villarreal & Crocker, 2007).

- In this application, an intermediate sized LWA (178 kg/m^3concrete) was blended with NWAs to fill in a gap in the overall aggregate gradation.
- The internal curing provided by the pre-wetted intermediate LWA resulted in a noticeable (> 15 %) increase in 28 d strength, elimination of plastic and drying shrinkage cracking, and a reduction in concrete unit weight that may translate into reductions in fuel requirements and equipment wear (Villarreal & Crocker, 2007).
- Since 2007, several informal crack surveys have been conducted at the railway transit yard, with only two or three cracks found (one of these being where a construction joint was inadvertently omitted).

In 2006, internal curing was employed for a continuously reinforced concrete pavement placed using a slip-form paving machine (Friggle & Reeves, 2008). The concrete mixture with internal curing was formulated to meet the Texas Department of Transportation (TxDOT) requirements of a minimum flexural strength of 3.93 MPa and a minimum compressive strength of 24.1 MPa, both at 7 days. Internal curing has been used in bridges in New York, Ohio, and Indiana. In Ohio, the department of transportation employed a modified HPC mixture that contained 356 kg/m^3 of cementitious materials and silica fume (http://www.nesolite.com/appofmonth.htm). Approximately 120 kg/m^3 of LWA were used. The NYDOT has also used internal curing on 9 bridges that have been built and it is planned for several additional bridges. The NYDOT uses a special mixture design that is similar to their conventional deck design (nearly 385 kg/m3 of cementitious material with silica fume), where 120 kg/m^3 of fine LWA is used.

15. CONCLUSION

The following conclusions can be drawn based on the results from this study:

- It is important the lightweight aggregate able to provide a sufficient volume of water (e.g., 24 hr absorption), has a structure that allows the water to be released to the paste as needed (i.e., enables a large volume 90%+ to be desorbed by 92%RH), and is small enough so that they can be appropriately spaced in the matrix (i.e., fine aggregate is preferred).
- A reduction or elimination of autogenous shrinkage is observed for internally cured mixtures. This reduces or eliminates the potential for early age cracking.
- Plastic shrinkage cracking is reduced in internally cured concrete.
- Internally cured concrete has a higher degree of hydration resulting in reduced water absorption.
- Internally cured concrete mixtures are less susceptible to early age thermal cracking.
- Large scale testing showed a reduction in the cracking potential when internal curing was used.

Based on the above analysis, the objective of internal curing is to provide a source of readily-available additional water so that the capillary porosity of the hydrating cements paste remains saturated, thus minimizing the autogenous stresses and strains. This additional water will also promote a maximization of the hydration of the cement and pozzolans in the mixture, potentially contributing to increased strengths and reduced transport coefficients.

Conventionally, some of this additional water has been provided by external curing techniques such as ponding, fogging, misting, and the application of wet burlap. However, in the higher-performance concretes that are now being used, the capillary porosity becomes disconnected during the first few days of hydration (Powers, Copeland, & Mann, 1959), such that this external water may only penetrate a few mm into the concrete from the curing-applied surfaces (Bentz, 2002), while the interior of the concrete undergoes substantial self-desiccation. The goal of internal curing is to provide additional water in the proper amount and with a proper spatial distribution so that the entire three-dimensional microstructure of hydrating cement paste remains saturated and autogenous stress free.

REFERENCES

[1] Internal Curing: A 2010 State-of-the-Art Review (National Institute of Standards and Technology, US)

[2] ACI 308, Guide to Curing concrete, ACI

[3] Hoff,George.C., “The use of Lightweight Fines for Internal Curing for Concrete”

[4] Bentz,Dale.P., Laura Peitro,Roberts,John.W. “Mixture Proportioning for Internal Curing”

[5] Bentz,Dale.P., Sultzman,Paul.E. “Curing, Hydration and Microstructure of Cement Paste”

[6] Bentz,Dale.P., Koenders,E.A.B., Monnig.S., Reinhardt,H.W., vanBreugel.K and Ye,G., “Materials Science Based Models in Support of Internal Water Curing”