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Water movement in Internally Cured Concrete

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Abstract. Currently, ordinary cement concrete uses external curing. For high-strength or high-performance concrete, implementing external curing is difficult and inefficient. In these types of concrete, the rather large cement content and low water-binder ratio form very dense cement paste. Thus, not only the autogenous shrinkage of concrete is increased, but the effectiveness of external curing is also reduced. To ensure the quality of the concrete, Internal Curing (IC) has been proposed. With IC, water is generally supplied via internal reservoirs such as saturated lightweight aggregates and superabsorbent polymers. The volume of internal water, which is not part of the volume of the mixing water, cures the concrete from the inside.

This paper presents our results of theoretical research and calculations on water movement in internally cured concrete. The efficacy of internal curing depends on parameters such as the volume of internal curing water, the structure of the porous system in lightweight aggregates and cement matrix, curing temperatures. To demonstrate those factors’ dependence on water displacement, we set up a theoretical function through a model that, based on the law of fluid flow and the system’s law of capillary attraction, connects the capillary in lightweight aggregates with the capillary in the cement stone. From the empirical relationship of hydrated thermal of cement and porosity ratio in concrete, we make preliminary calculations of the water movement distance in internally cured and differently aged concrete. These analyses show the feasibility and effects of internal curing.

Keywords. Internal Curing, Internal Water, Lightweight Aggregates, Water Movement, Relative Hydrated Coefficient.

1. Introduction

The essence of Internal Curing (IC) is to supply water to concrete through reservoir materials, such as lightweight aggregates (LAs). These materials contain microscopic, which hold water and, over time, supply it to the concrete as needed. This amount of water, though not included in the total volume of concrete mixing water, can be transferred to the surrounding binders’ paste to compensate for the chemical shrinkage and maintain the humidity saturation in the porous system of the concrete.

The efficiency of internal curing depends on the amount of water stored in the LAs; their water retention capacity and distribution; the permeability of the cement stone, the temperature of the system… When applying IC to concrete, an estimate of how much internal water can be transferred to porous microcapsules in the cement matrix is important. However, because the sizes of the capillaries
in the binder stone vary and change over time, such estimations are highly complicated. It is nonetheless possible to model the capillaries in LA as cylinders of identical and constant radii, which are directly connected to the smaller capillaries and resize according to the degree of hydration of the binder. Using this model together with the theory of capillary suction, the flow law of water and empirical data on hydrate of cement, an equilibrium flow equation can be established to calculate the extent to which water moves in the capillaries of the cement stone.

2. Internally Cured concrete

2.1. An overview of Internal Curing

In 1947, Power\(^1\) demonstrated that the hydration of cement shalt if the Relative Humidity (RH) in the capillary pores of cement matrix drops below 80%. Thus, provided with enough internal water and an RH over 80%, external addition of water to the concrete is unnecessary. One should note that external curing prevents water loss caused by evaporation. The use of water-reducing additives and active mineral admixtures such as fly ash as a partial replacement of cement in high strength and high-performance concretes creates Calcium Silicate Hydrates (CSH) as result of the pozzolanic reaction. This reaction occurs at later stages and requires sufficient internal water, which can be supplied from reservoirs such as pre-wetted lightweight aggregates. In addition, the secondary reaction also creates micro-pore systems and increases autogenous shrinkage and self-drying of the cement matrix, thus requiring further supply of internal water\(^2, 3\).

According to ACI 308, “Internal curing refers to the process by which the hydration of cement occurs because of the availability of additional internal water that is not part of the mixing water”. Internal water is generally provided via internal reservoirs, such as saturated lightweight aggregates, superabsorbent polymers… In this study, pre-wet lightweight aggregates are used as internal reservoirs.

In the cement stone and lightweight aggregate of concrete exist a system of interconnecting pores that stores moisture. The migration of water in concrete is described in Figure 1.

**Figure 1.** Model moving of water in the concrete incorporate IC, with \(r(t) < Ra\)

Consider the pore with an equivalent radius \(Ra\) in LA connected to a capillary of equivalent radius \(r(t)\) in the cement stone with \(r(t) << Ra\). From the thermodynamic equilibrium between the liquid phase surface and the capillary surface\(^4\), we have:
Where

Ra and r(t) are the radii of capillary in LA and of binder matrix respectively;
P, Pa, P(m) are the vapor pressures on the flat surface, the curved surface of the pore and the curved surface of the capillary respectively;
σ, σ_m are the surface tensions of the liquid in the (fill this in) respectively;
φ and φ_m are the wet angles of the water and liquid in capillaries respectively;
From (1) and (2) we have:

\[ \Delta P(t) = P_a - P(m) = \frac{2 \sigma_m \cos \varphi_m}{r(t)} - \frac{2 \sigma \cos \varphi}{Ra} = f(t) \gg 0 \]  

Here, \( \Delta P(t) \) is the capillary attraction in the capillary system.

Because of difference in vapor pressure \( \Delta P(t) \), the internal water of LA moves to the pores of the cement matrix to maintain the moisture inside and the hydration of the cement, and compensate for the shrinkage of the concrete.

2.2. Calculating the amount of water needed for Internal Curing

The volume of internal water needed to compensate for the chemical shrinkage of the binder (in concrete) can be determined according to the formula by Bentz D.P. and Snyder K.A. \cite{5} as follows:

\[ V_n = B \cdot CS \cdot \alpha_{\text{max}} / \rho_n \]  

Where:

\( V_n \) (m\(^3\)/m\(^3\) concrete) - The volume of the internal water;
\( B \) (kg/m\(^3\) concrete) - The content of the cementitious material (binder);
\( CS \) (kg water/1 kg binder) - Chemical shrinkage due to hydration by binder(s), \((\approx 0.06 - 0.07)\);
\( \rho_n \) (kg/m\(^3\)) - Specific gravity of water, \((\approx 1000)\);
\( \alpha_{\text{max}} \) - Maximum degree of hydration of cementitious material.

Assume that \( CS = 0.065 \) and \( N/B \leq 0.36 \), we have:

\[ \frac{W_{IC}}{B} \approx 0.18 \frac{W}{B} \]  

Where:

\( W_{IC} \) (kg) - The amount of internal water to completely perform internal curing;
\( B \) (kg) - Binder(s) content in concrete.

3. Calculations of moving of internal water

In equation (3), if we consider \( \varphi_m = \varphi \) and \( \sigma_m = \sigma \) and both of which are constant over time, then \( \Delta P(t) \gg 0 \) and thus the water in the empty aggregate will transfer to the pore system of the cement, whose moisture and size decrease due to the hydration of minerals in the cement.

The flow of water supplied from the LA is equal to the amount of water required to maintain the moisture saturation in the voids of the cement surrounding it. It can be argued that the transportation of
liquids in the system is subject to the flow law. Because water in the system is a Newton liquid, the distance of infiltration, L (m), according to the hydrodynamic theory applied to the flowing fluid in the small cylinder, the flow-rate Q (m³/s) is described by the Hagen-Poiseuille equation [6]

\[ Q = \frac{\partial V}{\partial t} = \frac{\pi r^4(t) \Delta P(i)}{8\eta L} = \frac{\pi r^2(t) k \Delta P(i)}{\eta L} \]  

(6)

Where:
V (m³) - Volume of moving liquid;
k = r²(t)/8 - Factor of the permeability of cement mortar;
L (m) - Moving distance of internal water in to the capillary of binder matrix;
\( \eta \) (Pa.s) - Viscosity of the liquid in the pore;

Note that the flow of water from the LA into the cement paste to balance the volume of water needed to compensate for the chemical shrinkage that takes place in concrete and depend on the time [5, 7, 8]. We can describe the volume V_n need to compensate the chemical shrinkage of the binder, depending on hydrate ratio and time t, by:

\[ \frac{\partial V_n}{\partial t} = CS \cdot \frac{\partial \alpha}{\partial t} \cdot \frac{B}{\rho_n} \]  

(7)

In which:
CS - chemical shrinkage of Binder;
B (kg/m³) - Binder(s) content in 1 m³ concrete;
\( \alpha \) - Factor \( \frac{\partial \alpha}{\partial t} \) of the hydrate level of the binder;
Callable factor \( \frac{\partial \alpha}{\partial t} \phi \) is the empty volume part in the cement mortar to keep the saturation state.
The volumetric variation of water V_n over time for a volume part \( \phi \) is the penetration velocity of the water in the capillary:

\[ \frac{\partial V_n}{\partial t \phi} = \frac{CS \cdot \frac{\partial \alpha}{\partial t} \cdot B}{\rho_n \phi} \]  

(8)

The flow-rate Q will be determined:

\[ Q = \pi r^2(t) L \cdot \frac{\partial V_n}{\partial t \phi} = \pi r^2(t) L \cdot \frac{CS \cdot \frac{\partial \alpha}{\partial t} \cdot B}{\rho_n \phi} \]  

(9)

From (6) and (9) we have:

\[ L = \sqrt{\frac{k \phi \Delta P(i) \rho_n}{\eta \cdot \frac{\partial \alpha}{\partial t} \cdot CS \cdot B}} \]  

(10)

The value can be determined on the base hydrated thermal of the cement over time.
Table 1 presents hydrated thermal (enthalpy) of the main components of the cement clinker.
Table 1. Hydrates formed from main minerals of portland cement

| Component   | Hydration product | Hydration water (g/g solid) | ΔHhydration (J/g) (dry) |
|-------------|-------------------|----------------------------|-------------------------|
| C₃S        | C-S-H, CH         | 0.24                       | -517                    |
| C₂S        | C-S-H, CH         | 0.21                       | -262                    |
| CS₂         | Mono-sulfate      | 0.8                        | -1144                   |
| C₃A        | Ettringite        | 2.13                       | -1672                   |
| C₄AF       | C₆AFH₁₂           | 0.37                       | -418                    |
| CaSO₄ soluble anhydrite |           | 0.26                       | -200                    |
| CaSO₄₀.5H₂O | CaSO₄₂H₂O        | 0.19                       | -124                    |
| CaO        | CH                | 0.31                       | -1166                   |

From Table 1 and the mineral composition of cement, we can approximate the full hydrated thermal of cement. Table 2 presents the enthalpy of hydration of minerals in cement clinker over time (by KIND). Table 3 shows components of typical minerals of some of Cement. Table 4 present the relative hydrated coefficient (α) of a number of cements, calculated from table 1, 2 and 3.

Table 2. Hydrated thermal of main minerals of portland cement

| Type of mineral | Time (t), days |
|-----------------|----------------|
|                 | 3  | 7 | 28 | 90 |
| C₃S             | 96.6 | 100.6 | 116.2 | 124.3 |
| C₂S             | 15.1 | 24.8 | 39.6 | 43.9 |
| C₃A             | 141 | 157.6 | 208.6 | 221.7 |
| C₄AF            | 42.3 | 59.6 | 90.3 | 99.4 |

Table 3. Typical mineral components of a number of cements in Vietnam

| Type of cement (PC40 Grade) | Type of mineral (CaSO₄₂H₂O: 3.5 - 4.0%) | % by weight |
|-----------------------------|----------------------------------------|-------------|
|                             | C₃S                                   | 51.0        |
|                             | C₂S                                   | 25.0        |
|                             | C₃A                                   | 8.2         |
|                             | C₄AF                                  | 10.0        |

Note: NS, HT, Hti, CF, FICO is Nghi Son, Hoang Thach, Ha Tien, Chinfon and FICO Cement Factory, respectively.

Table 5. Relative hydrated ratio of minerals (%), and calculated hydrated coefficient of cement vs. time

| Name of minerals and Cement | Rate of hydration of minerals (%) and cement hydrated coefficient over time, t (days) |
|-----------------------------|-----------------------------------------------------------------------------------|
|                             | 3 | 7 | 28 | 90 | 180 |
|                             | ln(t)                                               | 1.099 | 1.946 | 3.332 | 4.500 | 5.193 |
| C₃S                         | 36 | 46 | 69 | 93 | 94 |
| C₂S                         | 7  | 11 | 29 | 30 |    |
| C₃A                         | 82 | 82 | 84 | 91 | 93 |
| C₄AF                        | 70 | 71 | 74 | 89 | 91 |
| FICO                        | 0.36 | 0.43 | 0.57 | 0.75 | 0.77 |
| HT                          | 0.37 | 0.43 | 0.57 | 0.75 | 0.76 |
| CF                          | 0.34 | 0.41 | 0.53 | 0.72 | 0.73 |
| NS                          | 0.34 | 0.40 | 0.52 | 0.71 | 0.72 |

Note: NS, HT, Hti, CF, FICO is Nghi Son, Hoang Thach, Ha Tien, Chinfon and FICO Cement Factory, respectively.
Figure 2. The calculated relative hydrated coefficient vs. time
(Established from the data in Table 4 and Table 5)

Based on the data of table 4 and table 5, Figure 2 is established. The results in Figure 2 show that is linear with ln(t), with a very high correlation coefficient ($R^2 = 0.98$). The difference in the values of the coefficient of hydration is significant. This may be due to differences in the active-ability, fineness of the cements and curing conditions. However, the linear coefficients of the graphs vary insignificantly.

Table 6 presents results of the hydration experiment by TCVN 6070:1995 on Portland cements produced in Vietnam, from which the dependence of $\alpha(t)$ on ln(t) was determined (Figure 3).

| Type of Cement | Hydrated thermal (Cal/g) | Compressive Strength (MPa) | Hydrated coefficient of cement |
|---------------|-------------------------|---------------------------|-------------------------------|
|               | 7  28                   | 7  28                     |                               |
| HT            | 113 116                 | 34.5 57.3                | 0.77 0.89                    |
| CF            | 91 112                  | 35.8 51.2                | 0.69 0.85                    |
| NS            | 83 100                  | 29.7 48.8                | 0.68 0.81                    |
| HTi           | 74 94                   | 28.1 52.7                | 0.58 0.73                    |

We can choose one representative equation of them, for example of NS Cement:

$$\alpha(t) = 0.0917 \ln(t) + 0.444 \quad (11)$$

From (11) we have:

$$\frac{\partial \alpha}{\partial t} = \frac{0.0917}{t} \quad (12)$$

Assumption that the volume of the solid cement paste is the total volume of the cement and the chemical water, the porosity ($\Phi$) of the cement matrix can be approximated as follows.
\[ \phi = 1 - \frac{V_{sc}}{V_{oc}} = 1 - \frac{1 - \varepsilon_{ai} \cdot \rho_c^{-1} + 0.23 \alpha(t)}{1 - \varepsilon_{sh} \cdot \rho_c^{-1} + W/C} \]  

(13)

Where:
- \( V_{sc}, V_{oc} \) - Volume of solid cement paste and volume of binder matrix, respectively;
- \( \varepsilon_{ai}, \varepsilon_{sh} \) - Relative air volume ratio, relative shrinkage ratio of binder matrix, determined by experiment, respectively;
- \( \rho_c \) (g/cm\(^3\)), W/C - Gravity of cement and water - cement ratio, respectively.

To calculate \( L \) according to equation (10), assume that the liquid in the system is water at 25\(^\circ\)C, the wet angle of the capillary \( \phi_m \approx \phi \approx 0 \), the surface tension \( \sigma \approx \sigma_m = 0.07196 \) N/m and the viscosity of water \( \eta = 0.000892 \) Pa.s.

Using the composition of the cement paste in concrete as shown in Table 7 and assigning the equivalent capillary radius values in LA and in solid cement paste, we obtain the distances of water movement in the concrete at the age of the internally cured concrete, which are presented in Table 8.

### Table 7. The composition of the cement paste

| Materials, and properties | NS Cement (OPC40) | Mixture Water | Internal Water | Fine LA | Superplasticizer | \( \varepsilon_{ai} \) | \( \varepsilon_{sh} \) |
|---------------------------|-------------------|---------------|----------------|---------|------------------|----------------|----------------|
| Mass, kg                  | 600               | 180           | 135            | 135     | 3.0              | 0.02           | 0.005          |
| Density, g/cm\(^3\)       | 3.10              | 1.0           | 1.0            | 1.0     | 1.1              |                |                |
| Water absorption, %       |                   |               |                |         | 24.0             |                |                |
| Equivalent radius \( R_a \), \( \mu m \) |           |               |                |         | 10.0             |                |                |

In low W/C ratio pastes in well-hydrated conditions, the size of capillary pores in hardened cement paste may range from 10 – 50 nm; In higher W/C pastes it can be as large as 3 to 50 \( \mu \)m at ages less than 28 days \([1, 11, 12]\). Additionally, water in small capillaries (5-50 nm) is held by capillary tension and its removal usually renders volume reduction, which is the principal cause of shrinkage of the cement paste \([2, 3, 10]\).

Determining the functional form of \( r(t) \) is very difficult. However, one could assign \( r(t) \) to representative values to calculate \( L \) at different ages, the results of which are shown in Table 8.

### Table 8. The calculation values of infiltration internal water (\( L \))

| \( t \), days | \( r(t) \), nm | \( \alpha(t) \) | \( \phi \) | \( L \), mm |
|---------------|---------------|----------------|---------|------------|
| 3             | 1000          | 0.545          | 0.291   | 2.19       |
| 7             | 500           | 0.622          | 0.263   | 2.31       |
| 14            | 100           | 0.686          | 0.240   | 1.43       |
| 28            | 50            | 0.750          | 0.217   | 1.36       |
| 90            | 20            | 0.857          | 0.178   | 1.40       |
| 120           | 10            | 0.883          | 0.168   | 1.11       |
| 180           | 1             | 0.920          | 0.155   | 0.41       |

The results show that the internal water moved into the cement stone, up to more than 2 milimeters in early ages, and about 1 milimeter at later. However, these calculations do not include other obstructions due to discontinuity and changes in the shape and cross section of the capillaries.
4. Conclusions

From the results on hydration of cement by us other authors, the correlations between the hydration coefficients and the hydration rate of the cement over time have been determined.

The relationship between the hydration coefficient of the cement $\alpha(t)$ and the natural logarithm of time $\ln(t)$ from 3 to 180 days is linear. The relationship between hydration rate of cement and time is functions of the form $y = a/x$.

Theoretical and experimental co-ordination, hydration coefficients over time of some types of cement in Vietnam have been identified, and thus determined the equation for preliminary calculation of moving distance of internal water in the concrete.

These results show that, under the effect of capillary suction, the water in the voids of the reservoir could be moved to the cement paste. The distance of movement decreases with age of the concrete, from a few centimeters in early age to a few millimeters in late age.

These results may help to determine the required distribution of reservoir materials such as LA in internally cured concrete.

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