



Internal curing – A suitable method for improving the performance of heat-cured concrete



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HIGHLIGHTS

- Internal curing (IC) was used to improve the performance of heat-cured concrete.
- IC significantly improved the degree of hydration of heat-cured concrete.
- Heat-cured mortar with IC has a better ITZ with more homogeneous distribution.

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ABSTRACT

Heat curing decreases the maximum achievable degree of hydration, long-term rate of increase of compressive strength, anti-permeability, and durability of concrete as it ages. In this study, we explored the suitability of internal curing for solving these problems and improving the performance of heat-cured concrete. Internal curing significantly improved the rate of increase in the later-stage strength, degree of hydration, and penetration resistance of heat-cured concrete; this was especially true when subsequent standard curing was also performed. It also resulted in a better interfacial transition zone with a more homogeneous distribution as well as a microstructure with a lower porosity around the internal curing material (lightweight fine aggregate) in the case of the heat-cured mortar. The characteristics of the internal curing material used to improve the performance of heat-cured concrete should be consistent with the heat-curing regime and match those of the cement paste.

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1. Introduction

Heat curing is used widely in case of precast concrete elements, as it is an efficient and easy way of controlling the quality of concrete products. Curing at elevated temperatures promotes the cement hydration kinetics and accelerates the hydration of cement, resulting in high early-stage strength [1,2]. However, the elevated temperatures also cause the hydration products to precipitate more rapidly, leading to a denser hydration product shell that forms around the unhydrated clinker particles. It also results in a microstructure with a more heterogeneous distribution in the initial stage [3]. Furthermore, as the heat-cured precast concrete elements age, their porous microstructure and the poor curing conditions in the field lower their maximum achievable degree of hydration as well as their compressive strength growth, anti-permeability, and durability [4–8]. In recent years, using mineral

admixtures and a subsequent curing treatment has become the method of choice for overcoming these problems.

A few researchers have tried to use mineral admixtures such as fly ash, granulated blast furnace slag, and silica fume, in order to improve the later-stage performance of heat-cured concrete and have achieved some success, especially with the use of silica fume [4,8,9]. However, in these studies, most of the specimens were cured in a mist room or a water bath after heating; this provided additional water, causing the further hydration of the cement and the generation of calcium hydroxide (CH), resulting in the secondary hydration of the mineral admixture. In contrast, in practice, precast concrete is simply placed outdoor after heating and the poor microstructure forms during the heat-curing period, eventually leading to a water shortage and a lowering of the maximum achievable degree of hydration of the heat-cured concrete. Therefore, the mineral admixture is poorly hydrated in the later-stage in the absence of enough water and calcium hydroxide. As a result, the effectiveness of using the admixtures is limited.

A few factories tried to improve the later-stage performance of heat-cured concrete by immersing the concrete elements in tap

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water for several days. However, the high strength and dense structure that result after heating prevented the water from permeating into the concrete. As a result, subsequent tap water curing caused only a slight improvement in the performance of heat-cured concrete. Moreover, immersion in tap water may lead to the leaching of calcium from the concrete, resulting in a decrease in the degree of alkalinity of the concrete; this can cause C–S–H gel and steel passivation membranes to become unstable.

To further hydrate the mineral admixtures, water is needed and so is the calcium hydroxide generated by the hydration of cement. Further, external water does not readily penetrate into concrete during subsequent water curing. Hence, the key factors for improving the performance of heat-cured concrete are increasing the inner humidity and the maximum achievable degree of hydration of the concrete.

Internal curing (IC) can help external water provided throughout a freshly placed cementitious mixture via the prewetted lightweight fine aggregate (LWFA) or through superabsorbent polymers and other reservoirs, which can efficiently release water as needed for cement hydration [10–12]. In contrast to curing with external water using a water bath, which results in the penetration of water to a depth of only several millimetres into the high-strength concrete, internal curing allows water to be distributed more evenly, resulting in coverage over the entire paste system [12]. The internal curing water supplied by internal curing can promote the hydration of cement, resulting in a denser bulk of concrete. Moreover, the LWFA can form a denser interfacial transition zone (ITZ) [13]. Therefore, internal curing can improve the degree of hydration, increase the strength, reduce the permeability, and increase the durability of concrete [12–15].

In this work, internal curing was explored as a way of overcoming the disadvantages associated with heat curing and for improving the performance of heat-cured concrete. Interestingly, the curing regimes were designed to simulate the practical conditions distinguished with above research. We investigated the effects of internal curing on the compressive strength, degree of hydration, and penetration resistance of heat-cured concrete. The decrease of strength caused by adding LWFA was also solved. The effects of subsequent standard curing on the performance of heat-cured concrete are also discussed. In addition, we performed a microstructural study of the ITZ surrounding the LWFA, formed under the interaction of heat curing and internal curing. The results of this study should lead to new insights on how to improve the performance of heat-cured concrete.

2. Materials and methods

2.1. Materials and mixture proportions

P1 52.5 Portland cement, deionised water, ISO sand, and LWFA were used in this study. The LWFA was came from Yichang of Hubei Province, China, which was based on expanded shale. The chemical compositions of the cement and the LWFA

Table 1
Chemical and mineralogical compositions of the cement and LWFA used (% by weight).

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	Loss
Cement	21.72	4.92	3.01	62.14	2.27	0.65	0.22	1.78
LWFA	65.46	16.75	7.63	1.08	2.43	3.82	0.94	0.27

Table 2
Gradation of the ISO sand and the LWFA (% by weight).

Sieve (mm)	1.18–2.36	0.6–1.18	0.3–0.6	0.15–0.3	0.075–0.15	<0.075	Fineness modulus
ISO sand	27.43	32.49	8.21	24.15	7.72	0	2.478
LWFA	31.22	31.56	20.29	12.7	4.15	0.08	2.728

used in the mixture are listed in Table 1. The Bogue calculation was used to determine the approximate proportions of the four main minerals in the cement: C₃S = 48.5%, C₂S = 25.8%, C₃A = 8.0%, and C₄AF = 9.2% (by mass). The results of a sieve analysis of the ISO sand and the LWFA are listed in Table 2. The LWFA have a 24-h water absorption rate of 24.67% by dry mass (according to ASTM C128–07a). The densities of the 24-h-prewetted LWFA (saturated surface dry) and the ISO sand were 1580 kg/m³ and 2450 kg/m³, respectively. A polycarboxylate-type superplasticizer was added to achieve the same fluidity of mortars.

The mixture proportions are listed in Table 3; the water/cement (w/c) ratio was 0.35 and the volume fraction of the aggregates in the mortar was 62.5%. The amount of LWFA was calculated based on the degree of chemical shrinkage using Eq. (1), which was developed by Bentz [13]; 19.39% of the ISO sand (on a volume basis) was replaced by saturated LWFA. The amount of water supplied by internal curing was 37.92 kg/m³.

$$C_f \times CS \times \alpha_{max} = S \times \Phi_{LWA} \times M_{LWA} \quad (1)$$

where C_f (=560 kg/m³) is the cement content of the mixture, CS (=0.07 ml water/g cement [16]) is the chemical shrinkage of the cement, α_{max} (=0.97) is the expected maximum degree of hydration, Φ_{LWA} (=24.67% kg water/kg dry LWA) is the absorption capacity of the LWA used (24-h absorption value), and S (=1) is the expected degree of saturation of the LWA expressed as a function of the assumed absorption value, M_{LWA} (kg/m³) is the mass of LWA.

2.2. Specimen preparation and curing regimes

The mortars were mixed and cast at room temperature (25 °C). The mortar prisms (4 cm × 4 cm × 16 cm) were prepared such that their compressive strengths corresponded to the EN 196-1 standard. Cylinders of the mortars with a diameter of 100 mm and length of 200 mm were prepared to test the transport properties. During the delay period before steam curing, the specimens were covered with polyethylene sheets and kept at 25 °C for 3 h. The curing regimes are shown in Fig. 1. The maximum temperature during heat curing was 55 °C and the heating rate was 15 °C/h. The duration for which heat curing was performed at 55 °C was 4 h. Then, the temperature was lowered to room temperature at a cooling rate of 15 °C/h. After being heat cured, the specimens were removed from the moulds. The curing regimes used subsequently are shown in Fig. 1. Standard curing meant that the specimens were stored in lime-saturated water in a mist room (T = 20 °C, relative humidity (RH) > 98%). Indoor curing meant that the specimens were stored indoors at a certain temperature and relative humidity (T: 25 ± 3 °C, RH: 70 ± 5%). The various specimens were labelled as follows:

Control/IC–indoor: These specimens (Control group and Internal Curing group) were cured indoors after being heat cured.

Control/IC–3d/7d/28d–indoor: After being heat cured, these specimens (Control group and Internal Curing group) were cured in the standard curing environment for 3 days/7 days/28 days and then moved indoors.

2.3. Test methods

2.3.1. Degree of hydration test

The degree of hydration was determined from the amount of chemically bound water. Three samples (4 cm × 4 cm × 4 cm) were cut from the mortar prisms, and all of them were crushed such that the resulting powders could pass through 1.18 mm sieves. This was to reduce the error caused by the uneven distribution of the fine aggregate. The samples were dried in an oven at 105 °C for 24 h, in order to remove all the evaporable water, and then heated at 1050 °C for 3 h to remove all the chemically bound water. The amount of chemically bound water was calculated as the mass loss between 105 °C and 1050 °C; the loss on the heating of the dry cement, ISO sand, and LWFA was corrected for. The ratio of the amount of chemically bound water to the degree of hydration was assumed to be constant at 0.25 [17].

Table 3
Mixture proportion (kg/m³).

Mixture	Cement	ISO sand	Prewetted LWFA	Deionised water	SP
Control	560	1532	–	195	3.22
IC	560	1235	192	195	1.8

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