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Early age cracking behavior of internally cured mortar restrained by dual rings with different thickness

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HIGHLIGHTS

- Tensile stress resistance of samples were calculated based on fracture test.
- Free internally cured mortar has lower Tensile stress resistance than that of a plain one.
- High stress lead to the decrease of real tensile stress resistance of plain mortar.
- Low damage is an advantage of internally cured mortar to diminish the risk of cracking.

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ABSTRACT

This paper presents the results of research which examined the early age cracking behavior of internally cured and plain mortars under restraint. Residual stress development, cracking stress and age of internally cured and plain mortars restrained by dual rings with different thickness were studied in detail. Tensile stress resistance was calculated according to the results of fracture test. Autogenous volume deformation was tested also. The obtained results reveal that, internally cured and plain mortars are unlike to crack at first 2 days due to the low residual stress. After that age, residual stress in plain mortar goes up quickly and induces the damage of material, which implies the higher possibility to crack with the past of age. Compared to plain mortar, lower shrinkage or expansion, lower elastic modulus and less damage are advantages of internally cured mortar to diminish the risk of cracking.

1. Introduction

Shrinkage is usually the reason of cracking of concrete or mortar with low water to cementitious materials ratio (w/c) under restraint, regardless it is induced by chemical reaction in hydration, self-desiccation, and/or water evaporation. The idea of internal curing was developed to mitigate the shrinkage of low w/c concrete or mortar in recent decades by introducing additional water. Several types of agent are employed, such as pre-soaked lightweight aggregate (LWA) [1], super absorption polymer (SAP) [2] or returned porous waste aggregate [3,4]. Water in internal curing agent immigrates into paste of concrete or mortar from the beginning of accelerated period of cement hydration [5]. It prevents the decline of inside relative humidity (RH), and provides additional water for evaporation and hydration of cement [6]. Autogenous shrinkage, dry shrinkage and plastic shrinkage are all reduced therefore. Concrete and mortar with internal curing shrink less than a conventional one or expand under sealed condition [7–12].

However, mechanical properties of internally cured concrete and mortar differ from that of a plain counterpart due to the enhanced hydration and porosity of internal curing agent. Decreases of tensile strength and elastic modulus were observed [13] at early age of 7 days if LWA was used as internal curing agent. Decrease of compressive strength at early age was also reported [3,8] but accompanying with increase of it at later age. If porous ceramic waste aggregate was employed, there was significant increase of compressive strength and slight increase of splitting tensile strength of internally cured concrete from 3 days to 28 days [4].

Compared with a plain one, internally cured concrete and mortar show a lower risk of cracking. In restraint cracking test [7,8,14], internally cured concrete and mortar showed lower residual stress and later cracking age than that of plain sample. The more internal curing water is, the later the cracking age is. Plastic shrinkage cracking could also be mitigated with internal curing [15].

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In this study, development of residual stress, cracking stress and age of internally cured and conventional plain mortars, which were restrained by three dual rings with different degree of restraint (DOR), were compared. Fracture test was conducted to obtain the elastic modulus, critical stress intensity factor and critical crack tip opening displacement. The tensile stress which sample can resist at different ages was calculated based on the fracture test. Compressive strength and elastic modulus, splitting tensile strength and autogenous shrinkage were also tested. This paper aims to provide a quantitative understanding of how internal curing mitigates the cracking risk of low w/c ratio concrete and mortar.

2. Materials and methods

2.1. Materials and mixtures

ASTM C150 type I ordinary Portland cement was used. Silica fume, with a specific surface area of 16 m^2/g, replaced 10% of cement by weight. The normal weight fine aggregate (NWA) used was natural river sand with a specific density of 2.61 g/cm^3, a fineness modulus of 2.71, and a surface saturated dry (SSD) water absorption of 2.2%, respectively. Expanded shale was used as internal curing agent with a specific density of 1.37 g/cm^3 and a 24 h SSD water absorption of 19.6%. A high rang polycarboxylate water reducer was employed.

Water to cementitious materials ratio was 0.3. Volume fraction of total aggregates was 55%. For internally cured mortar, mass content of LWA was calculated by Eq. (1) [16,17].

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

where M_{LWA} (kg/m^3) is the mass content of LWA; C_f (kg/m^3) is the content of cement or silica fume; CS (kg of water of per kg cementitious material) is the chemical shrinkage of cementitious material, and it is 0.06 and 0.18 kg water per kg cement and silica fume, respectively; $\alpha_{\max}$ is the maximum degree of hydration, and can be decided as (w/c)/0.4; S is the expected degree of saturation of LWA; ϕ_{LWA} (kg water per kg dry LWA) is the water absorption of LWA; mass of LWA is the sum of LWA for cement and silica fume. Mixture proportions are presented in Table 1.

2.2. Experiments

2.2.1. Mechanical properties test

Compressive strength, elastic modulus, and splitting tensile strength at 2 days, 4 days, 7 days and 14 days were tested according to ASTM C39 [18], C469 [19], and C496 [20], respectively. Six cylinders with dimensions of 101.6 mm × 203.2 mm (4 in. × 8 in.) were prepared for tests of each age. Three cylinders were employed for compressive strength and elastic modulus test, and the other three were used for splitting tensile strength test. All samples for mechanical properties and fracture test were sealed in plastic tubes after demoulding.

2.2.2. Fracture test

Fracture test was performed according to RILEM recommendation [21] with a MTS machine. Three beams were prepared with the length of 254 mm, depth of 50.8 mm, and thickness of 25.4 mm (10 in. × 2 in. × 1 in). Depth of notch was 17 ± 1 mm. Test spam was 203.2 mm (8 in.). Crack mouth opening displacement (CMOD) was measured by a clip gage (as shown in Fig. 1). Load and CMOD were recorded by a computer. Crosshead loaded at a constant rate of 0.02 mm/min, and unloaded at the point of 95% peak load after peak point with the rate of 0.06 mm/min.

2.2.3. Measurement of free autogenous deformation

Corrugated tube protocol [7,21–24] was adopted to measure the autogenous deformation of specimen. For each mixture proportion, two corrugated polyethylene tubes, with a length of 400 mm and a diameter of 30 mm, were used. Strain was monitored by LVDT and reordered by a computer every 5 min.

2.2.4. Cracking test

A dual concentric ring test [25] was employed to evaluate the cracking behaviors of internally cured and plain mortars. Three mini dual rings with different wall thickness were used. Dimensions of rings are presented in Table 2. There were 4 and 3 strain gages on outer surface of outer ring and inner surface of inner ring, respectively, to measure the strain of rings in test. Strain of rings was recorded by computer every 5 min. Average of strain gages on outer and inner ring was taken as the strain of outer and inner ring, respectively. Dual rings were placed on three cold plates (Fig. 2). Cold plates and rings were isolated by polystyrene foam in test to avoid the water loss and stabilize the temperature of samples. A programmable chiller was connected with cold plates to comply the temperature control.

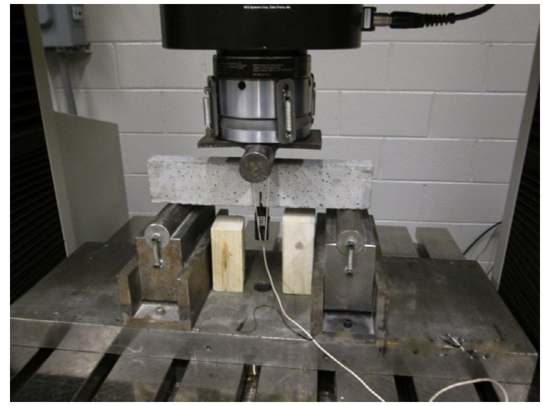

Fig. 1. A view of fracture test.

Three temperature schedules were run in the test. For schedule 1, temperatures of plain mortars were kept at 23 °C till all samples cracked. Then the same temperature and age for internally cured mortar. For schedule 2 and 3, temperatures of samples were kept at 23 °C at first 2 and 7 days, respectively, and then drop to 0 °C at a rate of 2 °C/h.

2.3. Calculations

2.3.1. Calculation of fracture parameters

Slope of the load curve at load range from 0 to 200N was taken as initial compliances. Unload compliance was slop of unload curve at load range from 70% to 40% of peak load. Young's modulus (E), critical effective crack length (a_c), critical stress intensity factor (K^s_{Ic}) and critical crack tip opening displacement ($CTOD_c$) were calculated from Eqs. (2)–(5) [21] (all parameters are in SI unit).

$$E = 6Sa_0V(\alpha_0)/(C_i d^2 b) \quad (\mathrm{N/m^2}) \quad (2)$$

$$EC_u d^2 b = 6Sa_c V(\alpha_c) \quad (\mathrm{m}) \quad (3)$$

$$K^s_{Ic} = 3(P_{\max} + 0.5W_0 S/L)\frac{S(\pi a_c)^{0.5}F(\alpha_c)}{2d^2 b} \quad (\mathrm{N\,m^{-3/2}}) \quad (4)$$

$$CTOD_c = \frac{6P_{\max}Sa_c V(\alpha_c)}{Ed^2 b}\left[(1-\beta) + (1.108 - 1.149\alpha_c)(\beta - \beta^2)\right]^{0.5} \quad (\mathrm{m}) \quad (5)$$

where $V(\alpha_0)$ and $V(\alpha_c)$ have the same form as Eq. (6). $F(\alpha_c)$ can be calculated from Eq. (7).

$$V(\alpha_0) = 0.76 - 2.28\alpha_0 + 3.87\alpha_0^2 - 2.04\alpha_0^3 + \frac{0.66}{(1-\alpha_0)^2} \quad (6)$$

$$F(\alpha_c) = \frac{1.99 - \alpha_c(1-\alpha_c)(2.15 - 3.93\alpha_c + 2.7\alpha_c^2)}{\sqrt{\pi^{0.5}(1+2\alpha_c)(1-\alpha_c)^{1.5}}} \quad (7)$$

2.3.2. Calculation of tensile stress resistance

Splitting tensile strength was usually used to evaluate the resistance of specimen to tensile stress [12,26]. In this study, considering the difference of geometry between samples in mini dual ring and usual ring, tensile stress resistance [27], taking influence of sample size on strength into account, was used.

Table 1
Mixture proportions kg/m^3.

	Water	Cement	Silica fume	Sand	Lightweight aggregate	Water Reducer
Plain	218	655	73	1465[a]	–	4.4
Internally cured	218	655	73	1003[b]	284[c]	4

Note: [a,b,c] Are all in SSD condition.