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Influence of water to cement ratio on the efficiency of internal curing of high-performance concrete

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HIGHLIGHTS

- The effect of w/c ratio on cracking of HPC with internal curing was studied.
- Cracking potential of internally cured HPC decreased with w/c ratio reduction.
- Total shrinkage of internally cured concretes decreased with w/c ratio reduction.

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ABSTRACT

Internal curing technology has been developed as a method for the reduction of autogenous shrinkage and cracking potential in high-performance concretes. The combination of autogenous and drying shrinkage, i.e. total shrinkage, of internally cured concrete is reported in the literature, almost unchanged after exposure to drying in a long term. On the other hand, the studied range of water to cement ratios is quite narrow. Accordingly, great interest aroused in the research of the effect of water to cement ratio on total shrinkage, as well as cracking potential of internally cured concrete. In this research, the restrained drying shrinkage of concrete with water to cement ratio of 0.33, 0.25 and 0.21, internally cured by means of water-saturated lightweight aggregate was studied. Strength, free drying shrinkage and mass loss of these concretes were also tested. The experimental results demonstrate that water to cement ratio has a considerable impact on cracking potential of internally cured concrete.

1. Introduction

The popularity of high-performance concrete (HPC) has been continuously increasing due to its superior mechanical and durability properties [1,2]. However, HPC has also its own drawbacks. Traditional curing methods fail due to extremely low water to binder ratio and low permeability of HPC. Curing water cannot penetrate into the internal core of structural element made of HPC. For this reason, HPC exhibits self-desiccation and autogenous shrinkage that lead to cracking [3]. Increased sensitivity to cracking of HPC that is caused by autogenous shrinkage is referred by many researchers and practitioners as the Achilles heel of HPC [4]. Internal curing technology has been developed with intention to provide a solution for the problem of increased early-age cracking sensitivity of HPC [4,5]. Internal curing of HPC is provided by the introduction into a concrete mixture of material with high water absorption that is able to prevent reduction of relative humidity and generation of capillary pressure inside the cement matrix.

Internal curing provides well-distributed curing water from inside of the element, reducing by these means the distance that water have to travel. Internal curing is able to significantly reduce or even completely eliminate autogenous shrinkage of sealed HPC specimens in the lab [5–8]. However, at a construction site, concrete structures are usually exposed to drying conditions from an early stage. Drying of concrete starts at the ages from one to several days after placing. However, in many cases concrete is exposed to drying right after demolding. After the exposure to drying conditions internally cured high-performance concrete exhibits higher drying shrinkage than concrete without internal curing. Therefore, the total shrinkage of HPC is not reduced by internal curing [9–12]. Accordingly, internally cured HPC is still susceptible to cracking in the period of drying [13].

The experimental data available in the literature on the drying shrinkage of internally cured HPC were obtained predominantly for the concrete made of water to cement (w/c) ratio of 0.3 or higher [9–12]. There is experimental data indicating that with

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reduction of w/c ratio the efficiency of internal curing increases with regard to the extension of cement hydration [14]. However, there is little experimental evidence about the cracking potential and drying shrinkage of internally cured concretes with w/c ratios lower than 0.3. Hence, the knowledge of the influence of internal curing on drying shrinkage and cracking sensitivity of HPC with low w/c ratios is limited. The objective of the presented research was to study the effect of internal curing on drying shrinkage and cracking sensitivity of HPC with low water to cement ratios and extend the knowledge in this area. Free sealed and drying shrinkage, as well as cracking potential of concretes with water to binder ratios of 0.33, 0.25 and 0.21 were measured in the current research. The experimental results demonstrated that drying shrinkage of concretes with w/c ratio as low as 0.21 can be significantly reduced by internal curing. This means that internal curing can be very effective for reduction of the cracking potential of concretes with extremely low water to cement ratios.

2. Materials and methods

2.1. Mix proportions

The mixes of HPC with w/c ratios of 0.33, 025, and 0.21 were studied. The amount of superplasticizing admixture was adjusted in order to keep the concrete workability in the desired range. The calcium naphthalene sulphonate type superplasticizer (SP) was used in all mixes, for this purpose. In this research, the cement of CEM I 52.5N type was used. The Blaine fineness of cement was 421.7 m^2/kg. Vacuum-saturated lightweight aggregate (LWA) – pumice from mount Hekla, Iceland – was used as the internal curing agent. A single fraction of pumice sand with a particle size between 2.36 and 4.75 mm was sieved for this purpose. The water absorption of pumice under vacuum after 1 h was 73.1% by weight and specific weight in the oven-dry state was 782 kg/m^3.

The amount of water available for internal curing (IC water) has to exceed the chemical shrinkage of cement, in order to eliminate self-desiccation [15]. Accordingly, the dosage of saturated LWA incorporated into the concrete mix was adjusted to contain the amount of absorbed water equal to the experimentally measured chemical shrinkage of cement paste with the same w/c ratio at the age of 7 days [16].

For each mix with internal curing, a concrete mix with the same w/c ratio, content of cement and coarse aggregate was used as a reference. The proportions of all concrete mixes are presented in Table 1. The weights of aggregates given in Table 1 are oven-dry weights. Crushed dolomite with the grain size between 2.36 mm and 9.5 mm was used as the coarse aggregate. The water absorption capacity of coarse aggregate was 1.5% by weight. In order to exclude the effect of coarse aggregate content on concrete properties the volume of coarse aggregate was kept constant in all mixtures. Natural sea sand with grain size below 0.6 mm and water absorption capacity 0.4% by weight was used as the fine aggregate.

2.2. Testing procedure

The potential for cracking of concrete in this research was determined by means of the restrained ring test following the procedure of ASTM C1581-04 standard [17]. The specimens were demolded and exposed to drying at one day in an environmentally room with relative humidity of 50 ± 4% and temperature of 20 ± 2 °C. The strains developed in the steel ring were continuously monitored and recorded. Accordingly, the results of a ring test were obtained in terms of strain-time curves. Cracking was identified by a sharp sudden drop in the strain. From the strain measured in the restraining steel ring, it is possible to calculate the stress in the concrete $\sigma_t(t)$ by means of the equation reported by See et al. [18]:

$$\sigma_t(t) = E_s \varepsilon_s(t) \frac{r_{ic} h_s}{r_{is} h_c} \tag{1}$$

E_s – modulus of elasticity of steel ring;
$\varepsilon_s(t)$ – elastic strain in steel ring at time t;
r_{ic} – internal radius of concrete ring;
h_s – thickness of steel ring;
r_{is} – internal radius of steel ring;
h_c – thickness of concrete ring.

The ASTM C1581-04 standard provides two possible criteria for classification of the cracking potential, i.e. sensitivity to cracking. One criterion is the net time to cracking in the ring test. This is the time that is measured from the initiation of drying. Another criterion is the stress rate at cracking, which is determined by the procedure outlined in the standard. The ASTM C1581-04 cracking sensitivity classification is presented in Table 2.

The compressive and splitting tensile strength was measured on 50 mm cubes. The samples for strength tests were cured at the temperature of 20 °C and 50% of relative humidity, which matches the curing conditions of ring specimens for the standard test of cracking potential according to ASTM C1581-04 [17].

Shrinkage tests were carried out using the testing rig similar to that described in [19]. The apparatus consists of steel molds that can be detached and transferred to a vibration table for the compaction of concrete. The specimens size was 70 × 70 × 1000 mm. The displacement was measured independently at each end of the specimen by a linearly variable displacement transducer (LVDT). This system allows starting the measurement of deformations immediately after the casting. Each measuring sequence consisted of 1000 displacement measurements during 1 ms and the averaged result was recorded.

Concrete was directly cast into the molds of the testing apparatus. In order to reduce friction, a Teflon sheet was placed between the specimen and the mold. The specimens were cured in a environmentally controlled room at a temperature of 30 ± 1 °C in sealed conditions. The sealing was provided with polyethylene sheets, which covered the concrete by five layers. Temperature change due to the heat of hydration was determined using three

Table 1
Mix proportions (kg/m^3).

Mix notation	Cement	Mix water	IC water	Fine aggregate	Coarse aggregate	LWA	Superplasticizer*	Slump**
21	667	140	-	532	1145	–	4.2%	163
25	600	150	-	562	1145	–	3.2%	120
33	506	167	-	572	1145	–	2.6%	95
21L	667	140	40.0	348	1145	54.7	4.2%	130
25L	600	150	36.0	396	1145	49.2	3.4%	140
33L	506	167	30.4	432	1145	41.5	2.6%	75

* Superplasticizer content is given by cement weight percent.
** Slump is given in mm.