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Influence of superabsorbent polymer on shrinkage properties of reactive powder concrete blended with granulated blast furnace slag

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HIGHLIGHTS

- Autogenous shrinkage of RPC decreased as the content of GBFS increasing.
- IC by means of SAP further reduced autogenous shrinkage.
- Drying shrinkage became serious as the total W/B and content of GBFS increasing.
- The influence of IC on drying shrinkage was not obvious.
- The total shrinkage of samples with GBFS and IC was lower than references.

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ABSTRACT

This study involved investigating the contributions of granulated blast furnace slag (GBFS) and internal curing (IC) by means of superabsorbent polymer (SAP) on shrinkage behaviour, hydration heat, and mechanical strength of reactive powder concrete (RPC). The results indicated that autogenous shrinkage decreased with an increase in GBFS content, and a combination with IC completely mitigated autogenous shrinkage and even led to a net expansion. The mechanical strength decreased with the addition of GBFS. However, compressive strength still exceeded 100 MPa even when the replacement level of GBFS corresponded to a maximum of 50%. Although IC by means of SAP slightly reduced the strength, this reduction was acceptable given the important role that it played on mitigating autogenous shrinkage. The drying shrinkage and mass loss increased significantly with an increase in the GBFS content. The IC did not exhibit an obvious effect on drying shrinkage and mass loss. However, it counteracted high drying shrinkage by significantly reducing autogenous shrinkage. The total shrinkage of RPC with IC and GBFS was significantly lower than that without IC and GBFS. The combination of GBFS and IC can adequately solve serious shrinkage deformation and provide an environmental friendly and low cost method to produce RPC.

1. Introduction

RPC is a type of ultra-high performance concrete that is developed through microstructural enhancement techniques [1,2]. It generally exhibits high mechanical properties, high impact resistance, and high durability [3–6]. Furthermore, it also exhibits good repair and retrofit potential for concrete structures [7]. However, the production of RPC involves the consumption of large amount of cements [2], and this increases cost but and leads to high energy consumption and serious pollution. Additionally, high content of silica fume makes RPC prone to cracking at early ages, and this is caused by a combination of high autogenous shrinkage and drying shrinkage. RPC typically experiences significant self-desiccation exceeding those of ordinary concrete due to its extremely low water to binder ratio (W/B). Autogenous shrinkage is significantly related to self-desiccation [8,9]. Therefore, it is necessary to maintain internal relative humidity to alleviate self-desiccation to mitigate high autogenous shrinkage of RPC. However, RPC is characterized by dense microstructure and extremely low permeability [5]. A traditional external curing method is not suitable for RPC. It is necessary to apply other curing options on RPC to reduce shrinkage deformation.

An effective method involves implementing internal curing (IC) by means of superabsorbent polymers (SAP). The SAP covalently cross-links by copolymerization of acrylic acid and acrylamide,

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which is proven as effective with respect to applications in concrete due to its good chemical stability and high swollen ability in a strong alkaline saline concrete pore solution [10,11]. The SAP can absorb mixing water and act as a water-reservoir. The water stored in SAP is released as cement hydration occurs through which the decrease in internal relative humidity is delayed and self-desiccation is partially mitigated [12]. Schröfl et al. [13] reported a reduction in the autogenous shrinkage of high performance concrete due to the presence of SAP. Justs et al. [14] measured a maximum shrinkage of 650 μm/m for ultra-high performance concrete at 28 d. The shrinkage reduced to approximately 150 μm/m after the addition of SAP. Wang et al. [15] argued that the water released by SAP promotes hydration of its surrounding cement paste, reduces porosity, and enhances the micro hardness of the affected zone. Jensen et al. [16] found that the autogenous shrinkage of cement paste was successfully mitigated by SAP and even exhibited an amount of net expansion.

The high content of cement causes high hydration heat and high temperature differential between the surface and core of an element [17]. Thermal cracking occurs due to thermal stress caused by the differential. These problems can be solved by replacing partial cement with mineral admixtures. Granulated blast furnace slag (GBFS) is a common admixture that is used in the construction industry. It is a by-product of the production of pig iron that exhibits a fine, granular, and glassy form and possesses latent hydraulic properties [18,19]. Concrete blended with GBFS often exhibits a low temperature increase due to the low content of C_3S and C_3A in the compound composition of the binder [20–22]. Additionally, it can improve the workability of mixtures and act as a micro-filler to optimize the pore structure of a hardening matrix [23]. Previous studies also examined the influence of GBFS on the shrinkage of concrete. Snoeck [24] reported that early age autogenous shrinkage was reduced by the addition of GBFS. A study by Huo indicated that the shrinkage of high performance concrete containing GBFS was even lower than that of normal concrete [25]. However, a few previous studies reported that the drying shrinkage of mortar and concrete increased with the addition of GBFS. The studies revealed that the samples exhibited higher drying shrinkage strains when the content and fineness of GBFS increased [26,27]. The fore-mentioned results are normally obtained from an experiment on conventional concrete or high performance concrete. There is a paucity of extant research examining the effect of GBFS on the shrinkage of RPC. Moreover, studies examining the effects of SAP on the autogenous and drying shrinkage of RPC containing GBFS are even more rare.

The present study involved designing an experimental program to assess the influence of SAP on autogenous and drying shrinkage of RPC containing GBFS that is cured at room temperature. The hydration heat of pure paste and the mechanical properties of RPC were also analysed in the study.

2. Experimental program

2.1. Materials

The raw materials used in this study included Portland cement (PC), silica fume (SF), GBFS, quartz sand, quartz powder, SAP, and a superplasticizer (SP). A brass-coated steel fibre (13 mm long with a 0.2 mm diameter) was employed to enhance the ductility of RPC.

A PC (cementⅡ42.5R) complied with China National Standards GB175-2007 [28] was used, and its chemical composition is presented in Table 1. Additionally, SF with SiO_2 content exceeding 94% was used in the study. It exists in the form of nattier blue powder. The GBFS used in the study was produced in Jiangsu Province, China. The particle size distribution and chemical composition of the binders (cement, SF, and GBFS) are listed in Fig. 1 and Table 1, respectively.

Quartz sand with a particle size distribution in the range of 0.075–0.6 mm was used as an aggregate. Quartz powder produced in Guangdong, China was added as a micro-filler. The mean particle diameter of the quartz powder corresponded to 5.47 μm, and 97% of the particles were less than 18 μm. Additionally, SAP with a dry bulk density of 0.85 g/cm^3 was manufactured by employing a bulk polymerisation technique and subsequently crushed in the form of an irregular particle shape. The particle size varied from 150 μm to 180 μm. A commercial SP with high range water reducing ability was employed in the study. In order to eliminate the influence of SP on the setting time of RPC mixtures and hydration heat of RPC pure pastes, its dosage in all the samples was maintained at a rate of 2.4% of the binder mass.

2.2. Mix proportions and mixing procedure

A series of samples were prepared to study the effect of GBFS and SAP on the properties of RPC. The W/B of reference C-17 corresponded to 0.17. Furthermore, GBFS was added at four dosage levels, and the amount of SAP was varied as 0.24%, 0.4% and 0.64% with respect to the weight of binders in the study. Correspondingly, the ratios of water entrained by SAP to that if the binder (W/B)e corresponded to 0.03, 0.05, and 0.08 respectively, and this indicated that the total W/B ($(W/B)_T$) of specimens that employed IC varied from 0.20 to 0.25. For every samples employed IC by means of SAP, a corresponding sample with the same total W/B and same amount of GBFS was considered as a control. The details of all mixture composition are presented in Table 2. In the table, the mix nomenclature is as follows: when C-IC-20 is considered as an example, the first part denotes that the specimen does not contain GBFS, the middle part denotes internal curing by SAP, the last part denotes the $(W/B)_T$. With respect to the B15-IC-20, the first part denotes the mass replacement ratio with GBFS and the last two parts denote the same as that in the C-IC-20. The abbreviation without "-IC-" specifies that this specimen does not involve conducting internal curing by SAP.

The mixing procedure was an important factor that significantly influenced the properties of cementitious materials [29]. The mixing method of RPC is different from that of normal concrete considering its special composition. Based on previous studies, the mixing procedure adopted by this paper is as follows:

(1) All dry mixing powders (cement, SF, GBFS, quartz powder, quartz sand) were added and mixed for 2 min (noticed that for the samples employed IC, the SAP should be added in dry form and dry mixed with powder).
(2) During the dry mixing process, the steel fibre was added.
(3) 50% of water containing 50% SP was added; and wet mixing for 3 min.
(4) The rest of water and SP were added.
(5) Mixing for 5 min.

When the mixing sequences were completed, the mixture was poured into specific moulds for the corresponding experiment. The setting time was measured in RPC mixtures without fibres. The isothermal calorimetry test was measured on pure pastes in the study. The preparation of pure pastes was similar to that of RPC with the exception of those for the sequence (1) and (2). The quartz powder, quartz sand, and steel fibre did not necessitate pure pastes.

2.3. Methods

2.3.1. Setting time

With respect to a restrained concrete element, the deformation prior to initial setting exerts a negligible influence on stress