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Effects of mix proportion and curing condition on shrinkage behavior of HPFRCCs with silica fume and blast furnace slag

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HIGHLIGHTS

- Ultimate autogenous shrinkage of HPFRCCs is insignificantly affected by curing condition.
- Lower W/B ratio and higher amount of Zr SF result in higher autogenous shrinkage but lower drying shrinkage.
- After heating curing, there are no increases of autogenous and drying shrinkage strains of HPFRCCs.
- Total shrinkage of SC150 and SC120 is effectively reduced by applying heat curing.

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ABSTRACT

This study investigated the effects of mixture proportion and curing condition on the mechanical and shrinkage behaviors of high-performance fiber-reinforced cementitious composites (HPFRCCs). Different water-to-binder (W/B) ratios and amounts of mineral admixtures, such as zirconium silica fume (Zr SF) and blast furnace slag were evaluated. The test results indicate that initial steam-heat curing accelerated the strength development and was sufficient to develop its full strength. The ultimate autogenous shrinkage was insignificantly affected by the curing conditions, but the heat curing accelerated the development of autogenous shrinkage. HPFRCC with a lower W/B ratio and greater amount of Zr SF exhibited higher autogenous shrinkage but lower drying shrinkage. In addition, the amount of total shrinkage of HPFRCC was more effectively reduced by providing heat curing when a higher W/B ratio and a smaller amount of Zr SF were used. There were no increases in the autogenous and drying shrinkage for HPFRCC immediately after finishing the initial heat curing, meaning that there is no possibility of shrinkage cracks forming in HPFRCC elements after the heat curing process. Finally, the autogenous shrinkage behaviors of HPFRCC were simulated with several prediction models from literature and an optimized model, considering equivalent age, was suggested.

1. Introduction

For several decades, concrete has been one of the most widely used construction materials because of its several advantages, such as high compressive strength, durability, and economic efficiency. However, because it has relatively poorer tensile strength and toughness than compressive strength and toughness, steel reinforcements, i.e., deformed reinforcing bar (rebar) or prestressing strands, are generally included inside concrete structures. Due to its poor tensile properties, concrete is easily cracked by small-magnitude external tensile or flexural forces, leading to a corrosion of the steel reinforcements, a deterioration of its durability, and a decrease in its service life. Increasing the tensile strength or incorporating multiple discontinuous fibers can prevent the generation of cracks in concrete. A higher tensile force needs to be applied to generate cracks in concrete having a higher tensile strength, thus limiting the occurrence of cracks. In addition, the discontinuous fibers can effectively inhibit the formation, propagation, and widening of micro-cracks. Therefore, they can increase the tensile strength slightly and control the widening of cracks substantially. Several researchers [1–6] have developed several types of high-performance fiber-reinforced cementitious composites (HPFRCCs), which have a high tensile strength and include a high volume of discontinuous fibers, including ultra-high-performance fiber-reinforced concrete (UHPFRC), engineered cementitious composite

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(ECC), slurry infiltrated fiber concrete (SIFCON), and slurry infiltrated mat concrete (SIMCON), etc.

In the early 1980s, Lankard [3] first introduced SIFCON having a high fiber volume fraction (v_f), normally 5–12%, and a cement-based slurry with high fluidity. Excellent tensile strength and strain-hardening response could be achieved due to its high fiber volume contents. In the early 1990s, ECC and SIMCON were introduced by Li and Wu [4] and Hackman et al. [5], respectively. The concept of SIMCON was very similar to that of SIFCON, with a difference being that the fibers are placed as a mat instead of as discontinuous fibers with a slightly lower v_f, 4–6% [7]. The terminology "pseudo strain-hardening" was first used by Li and Wu [4] to explain ECC's excellent post-cracking tensile behavior with the formation of multiple micro-cracks. Initially, the ECC, including polyethylene fibers, exhibited a tensile strength of 5 MPa and a strain capacity of 5%. Subsequently, Li et al. [6] developed a new type of polyvinyl alcohol (PVA)-ECC with a tensile strength of 4.5 MPa and a strain capacity exceeding 4% with a moderate v_f of 2%. In the mid-1990s, Richard and Cheyrezy [1] introduced reactive powder concrete (RPC) having both ultra-high strength (compressive strengths ranging from 200 to 800 MPa) and excellent energy absorption capacity (fracture energy up to 40 kJ/m^2). This is the forerunner of UHPFRC currently available worldwide. They [1] optimized the granular material's sizes and provided a heat curing under pressure to achieve such excellent strength along with addition of moderate volume fraction (v_f = 1.5–3%) of steel fibers.

The Korea Institute of Civil Engineering and Building Technology (KICT) has conducted a huge research project to practically apply such HPFRCCs that have similar mix proportions and steel fiber amounts to RPC, for architectural buildings and civil infrastructure. The developed HPFRCCs have low water-to-binder (W/B) ratios ranging from 0.2 to 0.23 and a large amount of fine mineral admixtures, i.e., zirconium silica fume (Zr SF) and ground granulated blast furnace slag (GGBFS). However, due to the low W/B ratios and large amounts of fine admixtures, high early age shrinkage strains were obtained, and as a result, shrinkage cracks, which deteriorate durability, frequently occurred in thin structural elements made from HPFRCC that was cured at either ambient or high temperatures. Recently, Yoo et al. [8] experimentally verified the formation of shrinkage cracks in thin slabs fabricated from HPFRCC. Therefore, to prevent shrinkage cracks in HPFRCC, its shrinkage behaviors need to be examined for both ambient and heat curing conditions and a prediction model to precisely simulate its shrinkage behaviors needs to be suggested. However, unfortunately, very limited studies [9–11] are only available on the effect of curing temperature on the shrinkage behaviors of HPFRCCs.

Accordingly, in this study, the free autogenous and drying shrinkage behaviors of HPFRCCs with various mixture proportions were evaluated under ambient and heat curing conditions. In addition, mechanical and microstructural properties, and pore size distributions of the HPFRCCs were evaluated to obtain fundamental information as well as to analyze the measured shrinkage behaviors thoroughly. Lastly, the autogenous shrinkage of HPFRCCs, which accounts for the highest proportion of their total shrinkage, was predicted using several prediction models from literature, and a proper model was suggested by considering equivalent age.

2. Test program

2.1. Mix design, specimen preparation, and curing regime

In this study, three mix proportions were designed to have three different compressive strengths of approximately 120, 150, and 180 MPa, designated to SC120, SC150, and SC180, respectively. Herein, the letters SC denote "Super Concrete," which is related to the research project conducted by KICT, and the numerals indicate the design compressive strength. The detailed mixture proportions are summarized in Table 1. The SC180 mixture is well known as a type of UHPFRC, which was introduced in a previous paper [11]. For the SC180 mixture, type I Portland cement and Zr SF were used as the cementitious materials, while cement, Zr SF, and GGBFS were used as the cementitious materials for the SC120 and SC150. The type I Portland cement was manufactured by a domestic company (Sungshin Cement Co., Ltd.), while the Zr SF having more than 90% SiO_2 and a Blaine fineness greater than 15,000 cm^2/g was imported from China. The type III GGBFS, domestically produced by steel mill, with a Blaine fineness greater than 4000 cm^2/g was also used. As given in Table 1, the amount of Zr SF was higher for the concrete with a higher design compressive strength. The chemical compositions and physical properties of the cementitious materials used are summarized in Table 2. It is well known that the compressive strength of concrete is strongly influenced by the W/B ratio [12]. Therefore, two different W/B ratios, 0.2 for the SC150 and SC180 and 0.23 for the SC120, were used with a similar weight of cement per cubic meter. Silica sand with a particle diameter between 0.2 mm and 0.3 mm was used for the fine aggregate. As a filler, silica flour (S-SIL10) with a median diameter of 4.2 μm was used for the SC150 and SC180 mixtures, while cement kiln dust (CKD) with a mean diameter of 3.62 μm was used for the SC120 mixture. Both of the silica sand and filler had SiO_2 greater than 95% and were imported from Australia. Like the mixture of UHPFRC that is commercially available in North America [13], a coarse aggregate was not included in the mixture to allow the inclusion of a high volume fraction of steel fibers and to prevent the deterioration of tensile or flexural performance. Since the mixtures of SC120, SC150, and SC180 had high volumes of fine admixtures and low W/B ratios, they exhibited sufficient viscosity but insufficient flowability. Thus, to improve their flowability, a high-range water reducing admixture, superplasticizer (SP), was also incorporated. Very high slump flow values, between 625 mm and 760 mm (Table 2) were measured according to ASTM C1611 [14], which means the mixtures can be considered self-consolidating concrete. Therefore, no vibration was applied during specimen production. According to a previous study [15], the inclusion of 1% by weight of cement (or 0.8% by weight of total binder) shrinkage reducing admixture (SRA) effectively decreased the autogenous shrinkage of UHPFRC by approximately 15%, so 1 wt% SRA was incorporated into all samples to reduce the shrinkage.

To achieve excellent post-cracking tensile performance, a high volume fraction (1.5%) of high-strength straight steel fibers was included. Based on the test results of Ryu et al. [16], in commercially available UHPFRC, 0.5% of the steel fibers could be reduced using a mixture including hybrid 0.5% 16.3-mm straight steel fibers and 1% 19.5-mm straight steel fibers without any deterioration of flexural strength. Since the steel fibers account for a significant portion of the total production cost of UHPFRC, the use of the mixture of 0.5% 16.3-mm and 1% 19.5-mm straight steel fibers with a diameter of 0.2 mm was also adopted for sample preparation. The high-strength straight steel fibers were domestically produced, and their geometric and mechanical properties can be found in elsewhere [11].

A 120 L capacity pan mixer was used for making the HPFRCC samples. Because the mix design did not include a coarse aggregate, a unique mixing sequence was applied, as follows. First, all the dry components were placed in the mixer and premixed for approximately 5 min. Then, water that was premixed with SP was deposited into the mixer and mixed for another 5 min. Once the mixture became flowable, it was mixed for an additional 2 min. Then, the steel fibers were incorporated very carefully and