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Effectiveness of shrinkage-reducing admixture in reducing autogenous shrinkage stress of ultra-high-performance fiber-reinforced concrete

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ABSTRACT

This study describes the effect of shrinkage-reducing admixture (SRA) on free and restrained autogenous shrinkage behaviors of ultra-high-performance fiber-reinforced concrete (UHPFRC). To investigate the cracking potential, tensile strength development was experimentally obtained and predicted on the basis of the degree of hydration model. Three different SRA to cement weight ratios of 0, 1, and 2% and three different reinforcement ratios of 1.3, 2.9, and 8.0% were considered. A higher SRA content contributed to a slightly higher tensile strength and a lower autogenous shrinkage. In addition, a higher SRA content and a lower reinforcement ratio resulted in better restrained autogenous shrinkage behaviors, such as lower autogenous shrinkage stress and cracking potential. Therefore, it can be concluded that the use of SRA or a lower reinforcement ratio is favorable for improving the restrained shrinkage behaviors of UHPFRC.

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1. Introduction

Recently, in order to overcome several drawbacks of conventional concrete such as low tensile strength, low ductility, and low strength to weight ratio, ultra-high-performance fiber-reinforced concrete (UHPFRC) has been developed with excellent strength, i.e., compressive strength > 150 MPa and tensile strength > 8 MPa, ductility, energy absorption capacity, and durability [1]. These outstanding properties are attributed to a low water-to-binder ratio (W/B) equal to 0.2, an optimization of particle sizes of compositions, and high volume contents of steel fibers. Thus, this material has been attractive to thin-plate structures, i.e., long-span bridge decks, roofs, and thin-walls, and field-cast joints for precast bridge decks [2,3]. However, owing to its high early-age autogenous shrinkage and small cross-sectional area for thin-plate structures, UHPFRC is highly vulnerable to premature shrinkage cracking [2].

Cracking and residual stress that occur in concrete structures by the restraint of shrinkage are the main concerns with respect to durability. The restrained shrinkage behavior of concrete is quite complex, since it is affected by many factors, such as the rate and magnitude of free shrinkage, developments of strength and elastic modulus, stress relaxation and creep, degree of restraint, and geometry of element [4]. In particular, because of stress relaxation and creep characteristics of concrete, free shrinkage measurement alone is insufficient to predict the cracking potential due to the restraint of shrinkage. A conceptual view of the restrained shrinkage behavior of concrete with an internal reinforcing bar (rebar) is shown in Fig. 1. If no rebar exists, concrete will be freely deformed in a direction of $\Delta\varepsilon^{+}$ by shrinkage ε_{sh} (b). On the contrary, if the shrinkage of concrete is restrained by the internal rebar, and if no creep effect is assumed, the strain can be divided into two categories: elastic restraint strain by rebar ε_{e} and elastic rebar stain $\varepsilon_{e,r}$ (c). However, in reality, owing to the tensile creep of concrete ε_{cr}, the strain obtained in rebar (or in concrete) by shrinkage decreases to ε_{r} (d). Therefore, the free shrinkage strain ε_{sh} is equal to the summation of ε_{e}, ε_{cr}, and ε_{r}.

In order to mitigate the early-age shrinkage of UHPFRC, the use of shrinkage-reducing admixture (SRA) has been investigated by Soliman and Nehdi [5]. Their studies were focused on investigating the implication of adding SRA on the free shrinkage, and the

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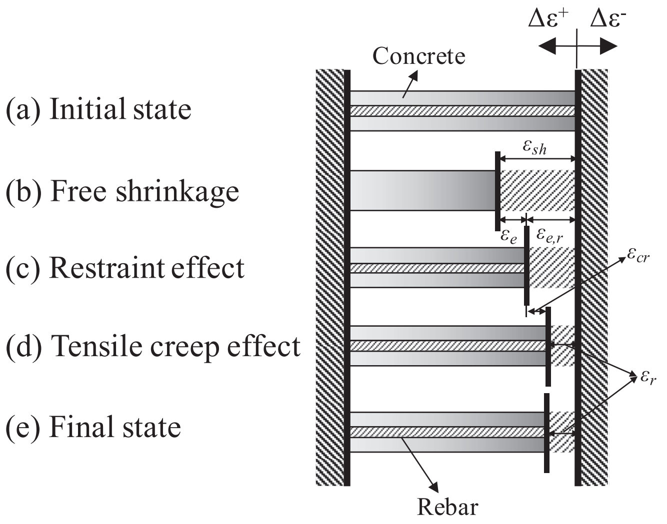

Fig. 1. Conceptual view of restrained shrinkage behavior of concrete with internal rebar.

effectiveness of SRA on reducing the shrinkage strains has been reported. However, although steel rebars are generally included in UHPFRC structures [6,7], no published study exists on the effects of using SRA on the shrinkage behavior of UHPFRC restrained by internal steel rebars. This restricts the practical use of SRA to the UHPFRC structures in spite of its numerous advantages.

Accordingly, in this study, the effect of SRA on both the free shrinkage and restrained shrinkage (by internal steel rebar) behaviors of UHPFRC was investigated. Owing to its extremely high autogenous shrinkage but insignificant drying shrinkage [2], autogenous shrinkage tests were conducted according to the recommendation by Japan Concrete Institute (JCI) [8]. Correspondingly, three different SRA to cement weight ratios were used, and deformed steel rebars with three different diameters were applied in restrained autogenous shrinkage tests in order to provide various degrees of restraint. In addition, tensile strength development of UHPFRC was measured and predicted to evaluate the cracking potential.

2. Experimental program

2.1. Materials and mix proportions

The used mix proportions are presented in Table 1. Type 1 Portland cement with a specific surface area of 3413 cm^2/g and a density of 3.15 g/cm^3 and silica fume with a specific surface area of 200,000 cm^2/g and a density of 2.10 g/cm^3 were used as cementitious materials. The chemical and physical properties of the cementitious materials can be found elsewhere [2]. Sand with grain size smaller than 0.5 mm and silica flour with a diameter of 2 μm including 98% SiO_2 were added to the mixture. For all test series, a W/B of 0.2 was used. Smooth steel fibers with a diameter of 0.2 mm and a length of 13 mm were incorporated at a 2% volume fraction within a mortar matrix. The detailed mechanical and geometrical properties of the steel fibers are given in Table 2. A high-performance water-reducing agent, polycarboxylate superplasticizer (SP) with a density of 1.06 g/cm^3, was also added to provide suitable fluidity. In addition, to investigate the implication of SRA contents on shrinkage behaviors of UHPFRC under both free and restrained conditions, three different SRA to cement weight ratios (0, 1, and 2%) were considered (Table 1) using the glycol-based SRA (METOLAT® P 860) produced in Germany.

2.2. Experimental setup and procedure

2.2.1. Flow and direct tensile tests

In order to quantitatively measure flowability, a flow table test was carried out according to ASTM C 1437 [9]. The average flow was calculated by averaging the maximum flow diameter and the corresponding perpendicular diameter. The average flow values are listed in Table 1. The fluidity was slightly increased by adding SRA, even though identical W/B and amount of SP were used.

To evaluate the cracking potential, the tensile strength development of UHPFRC with age was investigated. Dog-bone-shaped specimens with a middle cross-section of 50 mm × 100 mm were fabricated and cured at a room with a temperature of (23 ± 1)°C and a humidity of (60 ± 5)%. The details of the geometry and test setup are shown in Fig. 2. A pin-fixed end condition was used to avoid secondary flexural stress and to ensure a centric-loading condition. The alignment of the specimen was also carefully checked using a plumb before testing. Three specimens for each variable were used at each age, and the load was applied through displacement control using a universal testing machine (UTM) with maximum load capacity of 250 kN. The displacement was increased at a rate of 0.4 mm/min and the applied load was measured using a load cell attached to the bottom of the crosshead.

2.2.2. Autogenous shrinkage tests under free and restrained conditions

Prismatic specimens with cross-sectional dimension of 100 mm × 100 mm and length of 1000 mm were used for measuring free autogenous shrinkage. In order to precisely measure the autogenous shrinkage from a very early age, a dumbbell-shaped strain gage that has a nearly zero stiffness and a coefficient of thermal expansion (CTE) of 11 $\mu\varepsilon/°C$ – similar to that of hardened UHPFRC – and a thermocouple were set horizontally in the middle of the mold before concrete casting, as shown in Fig. 3. Teflon sheet and polyester film were placed on the mold to eliminate the friction between the mold and the concrete. After concrete casting, the top surface of each specimen was covered with a polyester film to prevent the moisture evaporation.

In order to estimate restrained autogenous shrinkage stress of UHPFRC, prismatic specimens that have a dimension identical to that used in free autogenous shrinkage tests were prepared. Deformed steel rebars with three different nominal diameters of

Table 1
Mix proportions.

Name	Relative weight ratios to cement							Steel fiber (V_f)	Flow (mm)
	Cement	Water	Silica fume	Silica sand	Silica flour	SP	SRA		
UH-S0	1.00	0.25	0.25	1.10	0.30	0.018	0.00	2%	235
UH-S1							0.01		245
UH-S2							0.02		240

[Note] SP = superplasticizer and SRA = shrinkage-reducing admixture.

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