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Shrinkage and cracking of restrained ultra-high-performance fiber-reinforced concrete slabs at early age

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HIGHLIGHTS

- Time-zero is suggested as the deviation point between temperature and shrinkage.
- Combined use of SRA and EA has a beneficial effect on strength and free shrinkage.
- Higher concrete thickness improves the shrinkage cracking resistance.
- Combined use of SRA and EA is beneficial in reducing shrinkage crack width.

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ABSTRACT

In this study, the combined effect of shrinkage-reducing admixture (SRA) and expansive admixture (EA) on the shrinkage and cracking behaviors of restrained ultra-high-performance fiber-reinforced concrete (UHPFRC) slabs was investigated. For this investigation, six full-scale UHPFRC slabs with three different thicknesses (h = 40, 60, and 80 mm) were fabricated using two different mixtures. Test results indicated that the combined use of 1% SRA and 7.5% EA is beneficial to improve the mechanical strengths and to reduce the free shrinkage strain of approximately 36–42% at 7 days. Regardless of SRA and EA contents, the slabs with the lowest thickness of 40 mm showed shrinkage cracking at a very early age, while the slabs with higher thicknesses of 60 and 80 mm showed no cracking during testing. However, the UHPFRC slab including 1% SRA and 7.5% EA exhibited a shallow crack with a very small maximum crack width of below 0.04 mm, while the slab without SRA and EA showed through cracks with a large maximum crack width of 0.2 mm.

1. Introduction

In comparison with other construction materials, concrete has superior mechanical properties, durability and economical efficiency. However, it has also some limitations including its relatively low tensile strength, low ductility and low strength to weight ratio. In recent years, to overcome these limitations, ultra-high-performance fiber-reinforced concrete (UHPFRC) exhibiting outstanding strength and ductility as well as exceptional durability has been developed [1,2]. These remarkable properties can be achieved by optimizing the granular mixture based on the packing theory with a low water-to-binder (W/B) ratio, which homogenizes the microstructure, and by adding a high volume of steel fibers. In particular, the superior strengths and unique strain-hardening behavior of UHPFRC make it attractive for use in thin plate structures such as thin walls, roofs, and long span bridge decks [3–6].

Despite these advantages, however, the application of UHPFRC in real structures has been limited due to the high cost, lack of design and analysis techniques, and high potential of early-age shrinkage cracking, of which limited information is available. Furthermore, research on the shrinkage cracking behavior of UHPFRC is relatively deficient.

UHPFRC presents very high ultimate autogenous shrinkage of approximately 800 $\mu\varepsilon$ [7] due to the use of low W/B and high fineness admixtures, and a significant part of this shrinkage occurs at a very early age [8]. Thus, thin plate structures constructed using UHPFRC are highly vulnerable to early-age cracking caused by the restraint of shrinkage. For this reason, some researchers [9–12] have recently carried out various restrained shrinkage tests for

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UHPFRC using ring-test (ASTM C 1581 [13]), drying shrinkage crack test (KS F 2595 [14]), and a special device for restrained shrinkage test [12]. To improve the volume stability of UHPFRC, Park et al. [10] performed a number of restrained ring-tests with various compositions: without admixtures, with 1% and 2% (by cement mass) of shrinkage-reducing admixture (SRA), with 5% and 7.5% (by cement mass) of expansive admixture (EA), and with a combination of 1% SRA and 7.5% EA. In their study, a significant result was obtained whereby the combined use of 1% SRA and 7.5% EA showed the best performance regarding the restrained shrinkage behavior. A similar observation, that the combined use of SRA and EA is more effective on dimensional stability for high-strength mortar than the use of SRA or EA alone, has been also reported by Maltese et al. [15]. From these results, the UHPFRC mixture including 1% SRA and 7.5% EA has been applied to parts of real structures built in Korea [16]. However, even though the combined effect of SRA and EA on the shrinkage performance of UHPFRC was investigated using the above mentioned test methods at a material level, to the best of the authors' knowledge, until now no study has been reported on the restrained shrinkage and cracking behaviors of full-scale UHPFRC structures.

Accordingly, this study investigated the combined effect of SRA and EA on the shrinkage and cracking performances of full-scale UHPFRC slabs with three different thicknesses. The specific objectives are to evaluate the effect of using SRA and EA on: (a) the mechanical strengths with age, (b) time-zero, internal temperature gradient, and free shrinkage behavior, and (c) shrinkage and cracking behaviors of restrained UHPFRC slabs.

2. Research significance

Due to its high autogenous shrinkage, thin plate structures made of UHPFRC are highly vulnerable to early-age shrinkage cracking. To overcome this problem, a few investigations on the restrained shrinkage behavior of UHPFRC according to various admixtures have been conducted at material level, but unfortunately there is no study reporting the actual restrained shrinkage and cracking behaviors of full-scale UHPFRC structures. Therefore, in this study, a total of six full-scale UHPFRC slabs were fabricated and tested to examine the influence of combined use of SRA and EA on these restrained shrinkage and cracking behaviors.

3. Experimental program

An experimental program was designed to estimate the effect of combined use of SRA and EA on the shrinkage and cracking behaviors of UHPFRC slabs with three different thicknesses. First, the influence of SRA and EA on the mechanical strengths with age was investigated. Second, the effect of SRA and EA on the free shrinkage responses of UHPFRC was evaluated. The initial behavior of internal temperature was also analyzed to determine the zeroing point of shrinkage measurement. Finally, the restrained shrinkage and cracking behaviors of full-scale UHPFRC slabs were evaluated according to the SRA and EA contents and the slab thickness.

3.1. Materials and specimen preparation

The mix proportions used in this study are summarized in Table 1. UN-N indicates the mixture without SRA and EA and given by Park et al. [17], while UH-A indicates the mixture with 1% SRA and 7.5% EA. For cementitious materials, Type 1 Portland cement produced in Korea and silica fume (SF) produced in Norway were used. In addition, CSA EA produced in Japan and Glycol based SRA (METOLAT P 860) produced by Münzing Chemie GmbH in Germany were used. The chemical and physical properties of the cement, SF, and EA are summarized in Table 2 and these are exactly identical to those used in a previous study [10]. Sand with a grain size smaller than 0.5 mm was used as a fine aggregate, and silica flour with a diameter of 2 μm and 98% SiO_2 were included to improve the homogeneity of the mix. For all test series, a W/B of 0.2 was adopted, and to improve the tensile strength and ductility, 2% (by volume) of micro steel fibers having a length of 13 mm and a diameter of 0.2 mm were blended. The properties of the steel fibers used are given in Table 3. To provide adequate workability and viscosity, a high performance water-reducing agent, polycarboxylate superplasticizer (SP) with a density of 1.06 g/cm^3, was also added.

In fabricating specimens, two Hobart type laboratory mixers with 1200 L capacity each were used. Firstly, cement, SF, silica flour, and sand were dry-mixed for about 10 min. Then, water and SP were added, and mixed for another 10 min. When the state of the mortar matrix showed appropriate flowability, the steel fibers were dispersed and were then mixed for an additional 5 min. When an adequate flowability and viscosity to prevent the fiber gravitation was achieved, UHPFRC was then cast in the forms of slabs at one end and allowed it to flow, as shown in Fig. 1. All prismatic specimens were similarly fabricated by placing UHPFRC at one end of the specimen and allowing the mixture to flow. Since UHPFRC has self-consolidating properties, no vibration was applied, and all test specimens were fabricated on the same day. After concrete casting, all test specimens were immediately covered with a plastic sheet to prevent the evaporation of moisture until demolding of the specimens (after 24 h from concrete casting) and tested in the field with an average temperature of 9.4 °C (ranging from 2.2 °C to 20.6 °C) and an average relative humidity of 52.4% (ranging from 21.5% to 77.8%), as shown in Fig. 2.

Table 2
Chemical and physical properties of cementitious materials and admixture.

Composition % (mass)	Cement (CEM 1)	Silica fume	Expansive admixture
CaO	61.33	0.38	13.55
Al_2O_3	6.40	0.25	18.66
SiO_2	21.01	96.00	3.80
Fe_2O_3	3.12	0.12	–
MgO	3.02	0.10	–
SO_3	2.30	–	51.35
K_2O	–	–	0.56
F-CaO	–	–	16.02
Specific surface (cm^2/g)	3413	200,000	3117
Density (g/cm^3)	3.15	2.10	2.98

Where, Cement (CEM 1) = Type 1 Portland cement.

3.2. Test setup and procedure

3.2.1. Mechanical tests

In order to investigate the strength development with age, the compressive, flexural, and tensile strengths were measured at 1, 3, and 7 days. All test data were obtained by averaging the results from the three specimens. For the compression test, cylindrical specimens with a dimension of φ 100 × 200 mm were used, and the uniaxial load was applied from a universal testing machine (UTM) with a maximum load capacity of 3000 kN, according to ASTM C 39 [18]. In the case of flexure test, a four-point bending test according to ASTM C 1609 [19] was adopted. The dimensions of the prismatic specimen used was 100 × 100 × 400 mm with the clear span length of 300 mm. Bending load was applied by using a UTM with a maximum load capacity of 250 kN. Finally, the direct tensile test was carried out using a dog-bone shaped specimen with a section of 50 × 100 mm at the mid-length, according to a previous study [20]. Uniaxial tensile load was provided using the same UTM as that of the flexure test, and to minimize the secondary flexural stress, the test setup was designed with pin-fixed ends [21].

Table 1
Mix proportions.

	Relative weight ratios to cement								Steel fiber (V_f, %)
	Cement	Water	Silica fume	Sand	Silica flour	SP	SRA	EA	
UH-N UH-A	0.2	1	0.25	0.30	1.10	0.2	– 0.01	– 0.075	2%

Where, UH = ultra-high-performance fiber-reinforced concrete, N = without SRA and EA, A = with 1% SRA and 7.5% EA, SP = superplasticizer, SRA = shrinkage-reducing admixture, and EA = expansive admixture.