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Effect of shrinkage-reducing admixture on biaxial flexural behavior of ultra-high-performance fiber-reinforced concrete

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HIGHLIGHTS

- Lower autogenous shrinkage of UHPFRC is obtained by including SRA.
- The use of SRA deteriorates compressive strength and fiber pullout resistance.
- The use of SRA decreases load carrying capacity and toughness of UHPFRC panel.
- First cracking point of UHPFRC under biaxial flexure is suggested.
- Deflection-hardening ratio and crack pattern are seldom influenced by SRA content.

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ABSTRACT

This study aims to investigate the effect of shrinkage-reducing admixture (SRA) on the mechanical properties of ultra-high-performance fiber-reinforced concrete (UHPFRC). Three different SRA to cement weight ratios (0%, 1%, and 2%) were considered using the UHPFRC including 2% of smooth steel fibers by volume. The specimen without SRA exhibited the best performance in almost all aspects of the mechanical behaviors in compression, fiber pullout, and biaxial flexure including load carrying capacity, strain capacity, and energy absorption capacity (pullout energy and toughness). The mechanical performances deteriorated with the increase in the amount of SRA up to 2%. Finally, a suggestion was made to define the first cracking point of deflection-hardening UHPFRC under biaxial flexure stress.

1. Introduction

Due to its superb performances including compressive strength, tensile strength, ductility, and durability, ultra-high-performance fiber-reinforced concrete (UHPFRC) is considered to be useful in structural applications where bending prevails. These advantages mean that the self-weight of the structural member made of UHPFRC is substantially reduced by decreasing the cross sectional area [1], and thus UHPFRC can be applied to the thin plate structures such as long span bridge decks, roofs, and thin walls [2–4].

UHPFRC develops a compressive strength exceeding 150 MPa with improved toughness and exhibits strain-hardening behavior, which exhibits a higher load carrying capacity after first cracking, by decreasing water-to-cementitious ratio (w/cm) and by adding high volume contents of steel fibers [5–7]. However, due to the low w/cm, UHPFRC is highly prone to early age shrinkage cracking and shows high ultimate autogenous shrinkage by approximately 800 $\mu\varepsilon$ [8]. Therefore, research to prevent early age cracking in the manufacturing stage of UHPFRC structural members and to reduce the shrinkage strain has been conducted [6,8–13]. Due to its efficiency, many researchers have considered using a shrinkage-reducing admixture (SRA) to reduce drying and autogenous shrinkage of UHPFRC [8,9–12]. In addition, to mitigate the shrinkage cracking potential of concrete and mortar, using a combination of SRA and fibers has also been considered by several researchers [14,15]. These studies have shown that SRA degrades the surface tension of water in capillary pores, thus decreasing the magnitude of capillary stress, shrinkage, evaporation rate, and compressive strength. However, research related to the effect of SRA on the

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Table 1
Mix proportion.

	Relative weight ratios to cement							Steel fiber (V_f, %)
	Cement	Water	Silica fume	Fine aggregate	Silica flour	Superplasticizer	Shrinkage-reducing admixture	
UH-S0	1.00	0.25	0.25	1.10	0.30	0.018	0.00	2%
UH-S1							0.01	
UH-S2							0.02	

Where, UH = ultra-high-performance fiber-reinforced concrete, Sn = *n*% of shrinkage reducing admixture, V_f = volume fraction of fiber.

Table 2
Chemical compositions and physical properties of cementitious materials.

Composition% (mass)	Cement	Silica fume
CaO	61.33	0.38
Al_2O_3	6.40	0.25
SiO_2	21.01	96.00
Fe_2O_3	3.12	0.12
MgO	3.02	0.10
SO_3	2.30	–
Specific surface (cm^2/g)	3413	200,000
Density (g/cm^3)	3.15	2.10

tensile and flexural behaviors of fiber-reinforced concrete (FRC) is very limited [16]. According to Wang et al. [16], the flexural behavior of high-strength FRC containing SRA is inferior to that of high-strength FRC without SRA due to the undernourished transition zone between the fiber and the matrix. It is well known that the superb tensile properties including strength and ductility are the major reasons for using UHPFRC in the structures, and thereby the effect of SRA on the tensile and flexural properties of UHPFRC should be investigated before using it.

Meanwhile, because of the excellent tensile performances of UHPFRC, research and practical applications of UHPFRC have focused on the thin plate structures [2–4]. Thin plate structures are subjected to a multi-axial stress state, rather than a uniaxial tensile stress, owing to the geometry and complex loading form [17]. However, for practical reasons, the uniaxial strength value was decided as a reference in many applications, and the most previous studies only evaluated the uniaxial tensile and flexural behaviors using dog-bone test and three- or four-point bending test [6,9,16,18–20]. The strength is not a constant parameter, but depends on the stress state [21]. Therefore, from these test methods, the structural behavior of thin plate structures cannot be directly evaluated, and it needs to assess the flexural behavior of UHPFRC under biaxial stress state.

There are two different test methods available for the investigation of the biaxial flexural behavior of concrete; the flexural toughness test (ASTM C 1550) [22] and the biaxial flexure test (BFT) [17,21]. A circular plate is tested in both methods. The stress field is three-fold symmetric, and equi-biaxial only at the center, in the ASTM C 1550 test in which the specimen is supported by three pivots and loaded at its top point of the center [17]. Due to the stress distribution, specimens are fractured by three axisymmetric cracks initiating from the center of the specimen because the stress is maximum, also equi-biaxial, at the center. Unlike the ASTM C 1550 test, the stress in the BFT is equi-biaxial in the finite region enclosed by the loading ring. This feature allows taking into account the stochastic variation of the biaxial tensile strength of concrete. By the same reason that the four-point bending test is preferred over the three-point bending test in the uniaxial stress condition, the BFT is adopted in this study.

Accordingly, this study investigates the effect of SRA on the mechanical behaviors of UHPFRC including compressive, fiber pullout, and biaxial flexural behaviors. The specific objectives were to investigate the effect of SRA on; (1) the compressive strength, elastic modulus, strain capacity and Poisson's ratio, (2) the bond strength and pullout energy of the fiber embedded in the matrix, and (3) the biaxial flexural strength, toughness and crack patterns.

Table 3
Properties of steel fiber.

Type of fiber	Diameter (mm)	Length (mm)	Aspect ratio	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)
Smooth fiber	0.2	13	65	7.8	2500	200

Where, aspect ratio = length of fiber/diameter of fiber (13/0.2 = 65).

2. Research significance

Very few investigations of the effect of SRA on the tensile and flexural behaviors of UHPFRC have been conducted, although SRA has been used for decreasing shrinkage and evaporation. In addition, even though UHPFRC is mostly applied to thin plate structures subjected to multi-axial stress, uniaxial tensile and flexural behaviors have been generally evaluated. This study therefore examines the influence of SRA on the interfacial bond properties of fiber and matrix (which profoundly influence in tensile behavior), and on the flexural properties of UHPFRC under biaxial stress state.

3. Experimental program

3.1. Materials and mix proportion

The details of the mix proportion investigated in this study are given in Table 1. This optimized mix proportion was determined based on the packing density theory and the results from rheological and mechanical tests [23]. Type 1 Portland cement and silica fume (SF) were used as cementitious materials, the chemical compositions of which are listed in Table 2. Fine aggregate (silica sand) with grain size below 0.5 mm and 2 μm diameter silica flour including 98% SiO_2 were also included in the mixture without coarse aggregate. In order to evaluate the effect of SRA on mechanical properties, glycol based SRA produced in Germany was applied for the tests. For all test specimens, 2 vol.% of smooth and high strength steel fibers was added, and the properties of the fibers used are given in Table 3. A high performance water-reducing agent, polycarboxylate superplasticizer (SP) with a density of 1.06 g/cm^3, was also added to achieve workability. Test specimens were covered with plastic sheets immediately after concrete casting and were cured

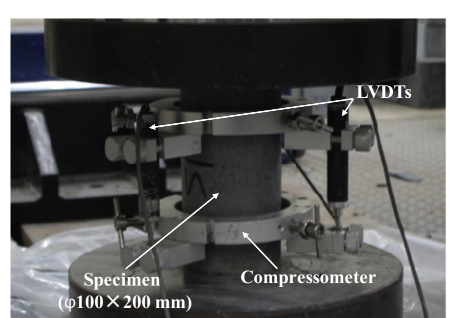

Fig. 1. Uniaxial compression test.