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Influence of reinforcing bar type on autogenous shrinkage stress and bond behavior of ultra high performance fiber reinforced concrete

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ABSTRACT

This study investigated the effects of reinforcing bar type and reinforcement ratio on the restrained shrinkage behaviors of ultra high performance fiber reinforced concrete (UHPFRC), including autogenous shrinkage stress, degree of restraint, and cracking potential. In addition, the influence of the type and embedment length of reinforcing bars on the bond behavior of UHPFRC was evaluated by performing pullout test. Three different reinforcing bars (deformed steel bar, round steel bar, and GFRP bar) were investigated in the restrained shrinkage and pullout tests. The GFRP bar exhibited the best performance in relation to the autogenous shrinkage stress, degree of restraint, and cracking potential because of its low stiffness. The highest bond strength was obtained for the deformed steel bar, and the bar yielding was observed when the bar embedment length of $l_b = 2d_b$ was used. The round steel bar exhibited the poorest behaviors for both of the restrained shrinkage and pullout.

1. Introduction

Ultra high performance fiber reinforced concrete (UHPFRC) that was recently developed exhibits superior compressive and tensile strengths, toughness, and bond performance, as well as exceptional durability. Thus, UHPFRC is an attractive alternative to use in numerous structures such as bridge decks, prestressed girders and segmental joints, and results in achievement of low maintenance and durable structures [1–3]. Even though UHPFRC presents excellent tensile strength and ductility by itself, the structures made of UHPFRC generally include reinforcing bars and tendons in tensile zone to improve the structural performance. Accordingly, investigation of the fundamental properties such as bond properties and restrained shrinkage properties between the UHPFRC and the reinforcing bar is essential before using it.

In contrast to normal concrete, UHPFRC is susceptible to a very high ultimate autogenous shrinkage of about 800 $\mu\varepsilon$ because of its low water-to-binder ratio (W/B) [4]. If this high autogenous shrinkage is restrained by the internal reinforcing bars, tendons, forms, and contiguous structural members, a significant residual tensile stress and shrinkage crack would be generated in the concrete without any external load. For this reason, research on the restrained shrinkage behavior of UHPFRC under both sealed and unsealed conditions has recently been carried out [5–10]. In these studies, the restrained shrinkage and cracking behaviors of UHPFRC were evaluated using ring-test (ASTM C 1581 [11]), drying shrinkage crack test (KS F 2595 [12]), and a developed restrained shrinkage device [10]. Since these test methods provide a restraining force using an external steel frame and ring, it seems to be more appropriate to simulate the shrinkage behavior restrained by forms and contiguous structural members rather than that restrained by reinforcing bars. On the other hand, unfortunately, no published study exists on the shrinkage behavior of UHPFRC restrained by reinforcing bars up to date, even though reinforcing bars are usually used in UHPFRC structures, as mentioned above. According to Tanimura et al. [13], the prediction accuracy for crack width and deformation of high strength RC members can be improved by taking into account the strain change in the reinforcing bars and the curvature change from the concrete shrinkage and expansion. Thus, the shrinkage behaviors of UHPFRC restrained by reinforcing bars should be investigated to precisely predict its structural behavior.

Meanwhile, many studies have been conducted to decrease shrinkage stress in concrete [5,7,14–16]. In particular, using GFRP bars to reduce restrained shrinkage and thermal stresses in concrete was recently considered [14,16]. Chen and Choi [14] reported that due to the lower elastic modulus of GFRP bar, the shrinkage

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stress level in concrete with GFRP bar is about one-fifth that with steel bar. The tensile stress that results from the shrinkage restraint and thermal variation in concrete is a major cause of the cracking and residual stress generation that occurs before an external load is applied. Thus, the use of GFRP bars is thought to have a beneficial effect on the restrained shrinkage stress.

Bond performance between concrete and reinforcing bars is of paramount importance because it is positively necessary for designing concrete structure with reinforcing bars. The bond performance is influenced by various parameters such as reinforcing bar surface shape and roughness, bar geometry, concrete cover, and concrete properties. Thus, even if there is a reinforcing bar having good mechanical properties and a beneficial effect on the restrained shrinkage stress, it is essential to ensure that the reinforcing bar exhibits adequate bond performance for use in concrete structures.

Therefore, in this study, the effect of reinforcing bar type on both of the restrained shrinkage and bond behaviors of UHPFRC was investigated using three different reinforcing bars: deformed steel bar, round steel bar, and GFRP bar. Because the main driving force in the internal deformation of UHPFRC is autogenous shrinkage [10], the restrained shrinkage test was carried out under sealed condition, according to the Japan Concrete Institute (JCI) recommendation [17]. The specific objectives included evaluating the effect of reinforcing bar type on (1) autogenous shrinkage stress, degree of restraint and cracking potential; and (2) bond properties such as bond strength and slip at peak load.

2. Experimental program

2.1. Materials and mix proportions

The details of mix proportions investigated in this study are presented in Table 1. Type 1 Portland cement and silica fume (SF) were used as cementitious materials. The chemical compositions and physical properties of the cementitious materials used are listed in Table 2. Fine aggregate (sand) with grain size smaller than 0.5 mm and silica flour with a diameter of 2 μm, including 98% SiO_2, were also included in the mixture. For all of the test specimens, a *W*/*B* of 0.2 was used, and to improve the tensile strength and ductility, 2% of the volume consisted of high strength steel fibers. The detailed properties and geometry of the fiber used are given in Table 3. In addition, to improve workability, a high performance water-reducing agent, polycarboxylate superplasticizer (SP) with a density of 1.06 g/cm^3, was added.

2.2. Test setup and procedure

2.2.1. Flow and direct tensile tests

To investigate the workability of UHPFRC required for construction usage, a flow table test was performed according to ASTM C 1437 [18]. The average flow was measured by averaging the maximum flow diameter and the perpendicular diameter for the maximum diameter.

The geometry and test setup for direct tensile test used are shown in Fig. 1. A dog-bone shaped specimen was fabricated with a cross section of 50 × 100 mm in the middle. The elongation along with the tensile load was estimated by averaging the measured strains from two 175 mm long LVDTs that were installed. To avoid secondary flexural stress and ensure a centric loading condition, the test setup was designed with so-called pin-fixed ends [6]. In addition, before testing, the alignment of the test specimen was carefully checked using a plumb. At least three dog-bone shaped specimens were used at each age. A universal testing machine (UTM) with maximum load capacity of 250 kN was used and loading was applied through displacement control. The rate of displacement increase was 0.4 mm/min, and the applied load was measured using a load cell attached to the bottom of the crosshead.

Table 2
Chemical compositions and physical properties of cementitious materials.

Composition% (mass)	Cement	Silica fume
SiO_2	21.01	96.00
CaO	61.33	0.38
Al_2O_3	6.4	0.25
Fe_2O_3	3.12	0.12
MgO	3.02	0.1
SO_3	2.3	–
Specific surface (cm^2/g)	3413	200,000
Density (g/cm^3)	3.15	2.1

2.2.2. Test method for autogenous shrinkage stress

An experimental test was carried out to determine the autogenous shrinkage stress of UHPFRC caused by the restraint of reinforcing bars. Based on previous research [19,20], the bond length of 300 mm between concrete and reinforcing bar with a diameter of 32 mm is sufficient to transfer the shrinkage stress in concrete having a cross section of 100 × 100 mm and a *W*/*B* of 0.24. Thus, since UHPFRC exhibits superior bond strength compared to previous high strength concrete [21], the bond length of 350 mm at both ends was conservatively selected to provide sufficient bonding in this study, as shown in Fig. 2.

Prismatic 100 × 100 × 1000 mm specimens containing two types of embedded steel bars (deformed and round steel bars) with diameters of 32, 19, and 13 mm, as well as GFRP bars with diameters of 19, 16, and 13 mm at the center of the cross section, were used. The detailed properties of the reinforcing bars used are summarized in Table 4. Reinforcement ratios of 8.04%, 2.84%, 2.01%, and 1.33% were obtained for the specimens including reinforcing bars with diameters of 32 mm, 19 mm, 16 mm, and 13 mm, respectively. In accordance with the technical committee on autogenous shrinkage at JCI [17], the ribbed edges of the reinforcing bars were lathed to within 150 mm from the center and covered with a Teflon sheet to prevent bonding between concrete and reinforcing bar, as shown in Fig. 2. Thus, in this region, the maximum shrinkage stress could uniformly occur. A strain gage and thermocouple were attached to the center of the reinforcing bar before covering it with a Teflon sheet to measure the strain and temperature. In addition, to minimize the restraint of concrete from the frictional force between the mold and the concrete, a Teflon sheet and polyester film were placed inside the mold.

To measure autogenous shrinkage strain, prismatic specimens having an identical size with the test for autogenous shrinkage stress were prepared. Before the concrete casting, a Teflon sheet and polyester film were placed between the concrete and the mold to reduce friction. In addition, a strain gage, which had nearly zero

Table 1
Mix proportions (relative weight ratios to cement).

	Cement	Water	Silica fume	Sand	Silica flour	Superplasticizer	Steel fiber
UHPFRC	1.00	0.25	0.25	1.10	0.30	0.018	$V_f = 2\%$

Where, V_f = volume fraction of fiber.