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Effects of fiber geometry and cryogenic condition on mechanical properties of ultra-high-performance fiber-reinforced concrete

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ABSTRACT

This study examined the effect of steel fiber geometry on the mechanical properties of ultra-high-performance fiber-reinforced concrete (UHPFRC) under cryogenic conditions (approximately −162 °C). For this, compressive and tensile tests were performed using UHPFRCs containing three types of straight steel fibers and one type of twisted steel fiber. To investigate the mechanical properties of UHPFRCs under various temperatures, mechanical tests were performed in three different conditions: ambient temperature, cryogenic temperature, and recovered ambient temperature. The test results demonstrated considerable increases in both the compressive strength and tensile performance, including strength and fracture energy, for UHPFRCs with straight fibers at the cryogenic temperature, whereas that containing the twisted fibers demonstrated the poorest energy absorption capacity at the cryogenic temperature, due to the fiber fracturing. Finally UHPFRCs containing longer straight fibers most effectively achieved excellent mechanical properties at the cryogenic temperature, compared to those with short straight and twisted fibers.

1. Introduction

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a cement-based construction material, which was first introduced by Richard and Cheyrezy [1]. However, unlike normal concrete (NC), it has no coarse aggregate, but includes a large amount of finer components, has a low water-to-binder (W/B) ratio of 0.2, and generally requires a process of heat curing to accelerate its strength development. Following their research, numerous studies [2–7] have been conducted thus far to investigate and improve the mechanical properties of UHPFRC, which has a compressive strength > 150 MPa, high durability, and excellent tensile performance and ductility [7]. Given these excellent mechanical properties, in recent years, researchers in South Korea have been attracted to its potential use for liquefied natural gas (LNG) storage tanks. Unfortunately, very limited studies [8] have been conducted to investigate the material properties of UHPFRC in cryogenic environments.

Many studies have examined the mechanical properties and microstructural changes of NC at cryogenic temperatures [9–20]. According to several studies [11,12,15,19,20], the compressive strength of NC significantly and proportionally increases as the temperature decreases to the cryogenic temperature. This is because the water in the capillary pores freezes at the cryogenic temperature and provides additional resistance to external loads [11,21]. However, it was also reported by some researchers [11,21] that after several freeze-thaw cycles, the mechanical performance of NC deteriorated because when the pore water freezes, it causes critical stresses, cracks, and residual strains in the NC. For this reason, it was reported that higher water contents could cause more detrimental effects on the mechanical performance of NC [22] after several numbers of freeze-thaw cycles. In addition, Hanaor [23] noted that the micro-cracks were formed due to the incompatibilities of the physical and thermal properties of the coarse aggregate and the cement matrix. Following this, Yang et al. [24] reported the formation of micro-cracks in the matrix, which were generated at the interfaces between the coarse aggregate and cement matrix. Richard and Cheyrezy [1] also reported that crack width of the cement-based composite generated under compression is in proportion to the sizes of coarse aggregates. In the meantime, Hanaor [23] found that the liquid nitrogen (LN2) permeability of the matrix was clearly related to the crack width. Thus, in cryogenic conditions, UHPFRC can be expected to have better resistance to freeze-thaw cycles and micro-crack formation than NC because it has no coarse aggregate, includes only very fine components, and has a low W/B ratio.

Recently, Kim et al. [8] investigated the compressive and tensile behaviors of NC and UHPFRC that was commercially available in North America, reinforced with 2% (by volume) 13-mm long straight steel

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fibers to evaluate the feasibility of using UHPFRC for LNG storage tanks. They [8] found that the UHPFRC demonstrated much better mechanical performance and durability under both ambient and cryogenic temperatures, compared with NC. However, they did not examine the effect of fiber geometry on the mechanical properties of the UHPFRC at the cryogenic temperature. Since the 1960s, for the purpose of improving the fiber-matrix bonding, several deformed fibers, such as crimped, hooked, and twisted fibers, have been developed to enhance their mechanical anchorage effect. Subsequently, several studies [25–29] were conducted to investigate the influence of fiber geometry on the mechanical behaviors of UHPFRC. Regarding compressive strength, Nguyen and Kim [74] reported that the twisted fiber and long straight fiber reinforced specimens showed 11% and 18% higher compressive strengths, respectively, than the specimen reinforced with the same amount of hooked fibers when the fibers had all the same length of 30 mm. However, this compressive strength benefit was insignificant compared to the improvements in the tensile properties, according to Hassan et al. [25]. They [25] reported that the fiber reinforcement had relatively minor influences on the compressive strength and elastic modulus. In contrast, there were significant improvements and differences in the tensile and flexural behaviors of the UHPFRC due to the fiber geometries. Although some studies [30,31] have reported that the excellent bonding properties of the deformed fibers are caused by the mechanical anchorage effect, there have also been competing studies [26–28] reporting that the mechanical anchorage effect has a detrimental influence. Wille et al. [27] reported that the high mechanical bond of the deformed fiber causes severely concentrated stress and damages to the matrix around the fiber, thus degrading the bond strength. Flanders et al. [28] also explained the detrimental effect of the mechanical anchorage by observing that the matrix split at the end of the hooked fiber, causing deterioration in the mechanical performance of the UHPFRC. This was confirmed in a study by Yoo et al. [26], which found that the unstraightened end hooks after the pull-out of the hooked fiber, resulting in the significantly lower flexural performance of the material than one with the same amount of straight fibers having the same length. They [26] also reported the detrimental effect of the un-twisting action during the pull-out of the twisted fiber, which caused the matrix to split near the twisted fiber and demonstrated a flexural performance below that of a specimen reinforced with the same amount of straight fibers. However, in addition to the previously mentioned studies, further study is required to examine the precise effects of the fiber geometry on the mechanical properties of UHPFRC at the cryogenic temperature and to determine whether it can be practically used for LNG storage tanks. Finally, Xu and Wille [32] asserted the irrelevance of the mechanical anchorage for improving the fiber-matrix bonding because the ultra-high-performance concrete (UHPC) matrix already achieved sufficient bonding strength with straight steel fibers.

Accordingly, in this study, the mechanical properties of UHPFRCs with various steel fibers were evaluated under ambient (A), cryogenic (C), and recovered ambient (RA) temperatures. For this, four different types of steel fibers: short straight (SS), mid-length straight (MS), long straight (LS), and twisted (T) steel fibers, were initially considered at the identical volume fraction of 2%. Furthermore, the compressive strengths and tensile performances of UHPFRCs, including strengths and fracture energies, were evaluated, and the surface conditions and the failure modes of the steel fibers after a complete pullout were examined using scanning electron microscopy (SEM) images.

2. Experimental program

2.1. Mixture proportions of the UHPFRCs

In this study, one basic mixture proportion of UHPC was used to examine the mechanical properties of four types of UHPFRCs, each containing one of four different types of steel fibers, SS-, MS-, LS-, and T-fibers, at the cryogenic temperature. The mixture proportions are shown in Table 1. Type I Portland cement and Zirconium (Zr) silica fume (SF) were first included in the mixture as a binder. The chemical and physical properties of these cementitious constituents are described in Table 2. Next, silica sand and flour, having diameters of 0.2–0.3 mm and 10 μm, respectively, were used as the fine aggregate and filler, respectively. Their sizes were determined from preliminary rheological and mechanical test results and packing density theory [33]. In contrast with the NC, coarse aggregates were not used in the UHPFRC mixture for several reasons. Based on several previous studies [34,35], there are some benefits of including coarse aggregates, in terms of strength, cost-efficiency, and amount of shrinkage. However, the shrinkage restraint action of the coarse aggregate causes deterioration of the tensile and flexural performance and durability of UHPFRC [36]. In accordance with Richard and Cheyrezy [1], the inclusion of coarse aggregates restrains the shrinkage of the cement paste, thus increasing the porosity of the material. Moreover, the coarse aggregates caused micro-cracks which the sizes were directly proportional to the diameter of the coarse aggregate under compressive force as introduced earlier. With reduced aggregate size, they [1] also found considerably improved crack resistance of UHPFRC under external loads. Following this, Stang [37] also reported a significant proportional relationship between the matrix shrinkage and the fiber clamping effect that might enhance the fiber-matrix bond strength by increasing the frictional resistance at the interface. Based on these previous studies [1,36,37], the coarse aggregates were eliminated from the mixture for better crack resistance and mechanical properties at cryogenic temperatures, considering both durability and safety against LNG leakage that might cause a massive explosion.

As shown in Table 1, a low W/B ratio of 0.2 was used for the UHPFRCs which was expected to mitigate the detrimental influence of the cryogenic temperature on the durability. According to Rostasy and Wiedemann [22], a higher water-to-cement (W/C) ratio leads to residual strain in the matrix after experiencing several freeze-thaw cycles. Since UHPFRC has a low W/B ratio and contains a large amount of fine admixtures, a polycarboxylate superplasticizer (SP) was added to provide excellent fluidity, ranging from 240 to 250 mm without fiber segregation, per ASTM C1437 [38]. To this point, the mixture

Table 1
Mixture proportions of UHPFRC.

W/B[b]	Mix design (kg/m^3)					
	Water	Cement	Zr SF	Silica sand	Silica flour	SP[a]
0.2[a]	160.3	788.5	197.1	867.4	236.6	52.6

[Note] W/B = water-to-binder ratio, Zr SF = zirconium silica fume, and SP = superplasticizer.

[a] Superplasticizer consists of 30% solid (= 15.8 kg/m^3) and 70% water (= 36.8 kg/m^3).

[b] W/B is calculated by dividing total water content (160.3 kg/m^3 + 36.8 kg/m^3) by total amount of binder (788.5 kg/m^3 + 197.1 kg/m^3).

Table 2
Chemical compositions and physical properties of cementitious materials.

Composition % (mass)	Cement[a]	Zr SF
CaO	61.33	0.04
Al_2O_3	6.40	0.43
SiO_2	21.01	94.3
Fe_2O_3	3.12	0.01
MgO	3.02	–
SO_3	2.30	–
K_2O	–	–
Specific surface area (cm^2/g)	3413	15,064
Density (g/cm^3)	3.15	2.50

[Note]

[a] Type 1 Portland cement.

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