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Mechanical properties of ultra-high-performance fiber-reinforced concrete at cryogenic temperatures

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HIGHLIGHTS

- The compressive strengths of NC and UHPFRC increase at cryogenic temperature.
- Tensile strength of NC does not increase at cryogenic temperature but rather is deteriorated after exposure to cryogenic temperature.
- Tensile strength, post-cracking stiffness, and energy absorption capacity of UHPFRC are improved at cryogenic temperature.
- Application of UHPFRC for liquefied natural gas storage tank is appropriate.

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ABSTRACT

This paper aims to investigate the influence of exposure to cryogenic temperatures using liquid nitrogen on the mechanical properties of normal concrete (NC) and ultra-high-performance fiber-reinforced concrete (UHPFRC), which is commercially available. This research was carried out to examine the feasibility of using UHPFRC for a liquefied natural gas storage tank. For this, both compressive and direct tensile tests were performed at three different testing conditions: ambient temperature, cryogenic temperature (−170 °C), and recovered ambient temperature after experiencing the cryogenic temperature. The test results showed that the compressive strengths of both NC and UHPFRC were noticeably increased at the cryogenic temperature compared with those at ambient temperature. However, there was no improvement in the tensile strength of NC at the cryogenic temperature, and its tensile strength was deteriorated after exposure to the cryogenic temperature. In contrast with NC, the tensile performance of UHPFRC significantly increased, including improvements in strength, post-cracking stiffness, and energy absorption capacity. Given the superior mechanical properties, it was concluded that UHPFRC is suitable for liquefied natural gas storage tanks.

1. Introduction

Many researchers have worked to improve the mechanical properties of concrete since it is considered to be one of the most cost-efficient construction materials that can be used in various circumstances. One advantage of concrete is that it contains a number of constituents, so substituting some substances with other admixtures can lead to excellent functional improvement under various circumstances. Cryogenic temperatures are possibly one of the most severe environmental conditions for concrete to maintain serviceability and safety. To construct a storage tank for liquefied natural gas (LNG), adequate resistance to cryogenic conditions is required. Since the 1970's, pre-stressed concrete has been used for secondary or even primary LNG storage tanks, which have a temperature of approximately −172 °C. Due to the economic benefits regarding both production and construction costs compared with conventional LNG storage tanks using 9% nickel steel, some researchers [1] have recently insisted on using concrete for primary storage tanks. Although using pre-stressed concrete as primary LNG storage tanks has these benefits and a few studies have been carried out recently, the challenge still remains to prevent leakage of LNG through cracks in the concrete tank. Because a small leakage of LNG at high pressure through small cracks may cause a massive explosion, there is a pressing need to enhance the mechanical properties and crack resistance of concrete.

Since the 1970's, a number of studies have been performed on the mechanical properties of concrete at very low temperatures [2–19]. First, Lee et al. [2] examined the various fundamental properties of concrete at very low temperatures down to −170 °C.

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According to their research, compressive strength, elastic modulus, splitting tensile strength, bond strength, and Poisson's ratio were improved as much as 101%, 56%, 42%, 107%, 128%, and 47%, respectively, at a very low temperature (−170 °C) compared with ambient temperature. In addition, Miura [3] found that the compressive strength of concrete linearly increases with decreasing temperature until it reaches −120 °C, and no additional improvement in the compressive strength was observed below this temperature. Researchers consistently reported that the increase of the mechanical strength of concrete is proportional to the water-to-cement (W/C) ratio and relative humidity [5,6,7,12,16]. However, the concrete with high W/C ratio showed more residual strain after experiencing freeze–thaw cycles [4], and this can cause the decrease in dynamic modulus of elasticity [13]. It might be caused by nucleation of water in the matrix which the amount is probably proportional to W/C ratio [14,18] and difference in thermal expansion coefficients of the cement paste and the aggregates causing stresses and micro-cracks at their interfaces [9].

Numerous studies have been performed to develop ultra-high-performance fiber-reinforced concrete (UHPFRC) showing significantly enhanced mechanical performance compared with NC. Richard and Cheyrezy [19] first introduced UHPFRC with a high volume fraction of micro-steel fibers and elimination of the coarse aggregate. They [19] reported that UHPFRC is a novel construction material having a much higher mechanical strength and more homogeneous micro-structure than NC. Based on their mixture proportion, many researchers [20–25] have developed new types of UHPFRCs showing a minimum compressive strength of 150 MPa, excellent durability, and certain levels of tensile properties [25]. However, despite these efforts, to the best of the authors' knowledge, there is no published study investigating the mechanical properties of UHPFRC at cryogenic temperatures. Additionally, variation in the compressive strength of UHPFRC at various aspect ratios has not been examined by researchers yet, although structural elements made of UHPFRC may have different aspect ratios.

Accordingly, in this study, the compressive and tensile behaviors of UHPFRC under a cryogenic temperature of approximately −170 °C were examined. NC, which is used for making LNG storage tanks in South Korea, was also considered for comparison. To precisely evaluate the compressive strength at cryogenic temperatures, the confinement effect on the compressive strength of UHPFRC was investigated according to the aspect ratio. Furthermore, in order to thoroughly understand the mechanical properties of UHPFRC at the cryogenic temperature, its micro-structure at both the ambient and cryogenic temperatures was examined.

2. Experimental program

2.1. Mixture proportions

In order to investigate the variation in mechanical properties for NC and UHPFRC at the cryogenic temperature condition, two mixture proportions were used, as summarized in Table 1. For NC, the water-to-binder (W/B) ratio and sand to total aggregate weight (s/a) ratio were 0.4 and 0.445, respectively. As cementitious materials, type I Portland cement and fly ash (FA) were included, and their chemical and physical properties are given in Table 2. Crushed sand and coarse aggregate (gravel) were also included, along with a superplasticizer (SP) and an air entraining (AE) agent. This mixture proportion has been used by the Korea Gas Corporation (KOGAS) to build the outside pre-stressed concrete wall for an LNG storage tank.

For UHPFRC, the coarse aggregate was excluded from the mixture. The coarse aggregate has a number of benefits for a cement matrix regarding shrinkage restraint, fluidity, and mixing time without any significant change in compressive strength [26,27]. However, it was eliminated from the mixture for the following two reasons. First, when a compressive load is applied, the coarse aggregate can cause micro-cracks to form at the interface between the cement matrix and aggregates, and those cracks become more severe as the size of the coarse aggregates increase. Richard and Cheyrezy [19] found that, under compressive loads, if the shape of the coarse aggregate is spherical, the sizes of the micro-cracks are directly associated with the diameter of the coarse aggregate. Therefore, granular cementitious materials with smaller diameters of constituents have more homogeneous and denser micro-structure, and better compressive behavior than those including coarse aggregates. The second reason is related to the porosity of the material and bond strength of the steel fibers in the matrix caused by the shrinkage restraint action of the coarse aggregate. According to Richard and Cheyrezy [19], coarse aggregate resists shrinkage of cement paste increasing porosity of the material. Following this, Collepardi et al. [28] found that the presence of coarse aggregates led to a deteriorated flexural strength compared to UHPFRC including only fine sand, which was caused by the restrained matrix shrinkage and the decreased homogeneity. This resulted in deterioration of the fiber bond strength because the bond strength is closely related to the amount of matrix shrinkage. Finally, Rostasy and Wiedemann [4] found that the higher W/C ratio, the more the matrix has residual strains after exposure to the cryogenic temperature which can cause a deterioration of the mechanical properties and air/water tightness. For these reasons, UHPFRC which consist of granular constituents with a low W/B ratio of 0.2 was used in this study.

When the W/C is low as 0.2, to achieve an adequate fluidity of 240–250 mm as per ASTM C1437 [29] inducing no fiber segregation, a polycarboxylate SP was added into the mixture. In this study, silica sand and silica flour with diameters of 0.2–0.3 mm and 10 μm, respectively, were included into the mixture as a fine aggregate and filler, respectively, according to the preliminary rheological and mechanical test results and packing density theory [30]. The mixture proportion and constituents are the same as the commercially available UHPFRC in North America [31], except for the chemical composition of the silica fume (SF). In this study, to improve the fluidity of UHPFRC with only a small amount of SP, zirconium (Zr) SF was used. The chemical compositions and physical properties of the cementitious materials are summarized in Table 2. The specific surface areas of cement and Zr SF were 3,413 cm^2/g and 15,064 cm^2/g, respectively, and their densities were 3.15 g/cm^3 and 2.50 g/cm^3, respectively. In addition, to obtain

Table 1
Mixture proportions for NC and UHPFRC.

Nomenclature	W/B	S/a	Mix design (kg/m^3)									
			Water	Cement	FA	Zr SF	Sand	Silica sand	Silica flour	Gravel	AE	SP*
NC	0.4	0.445	162.0	345.0	61.0	–	763.0	–	–	958.0	0.07	3.25
UHPFRC	0.2†	–	160.3	788.5	–	197.1	–	867.4	236.6	–	–	52.6

[Note] W/B = water-to-binder ratio, S/a = sand to aggregate weight ratio, FA = fly ash, Zr SF = zirconium silica fume, AE = air entraining agent, and SP = superplasticizer.

* Superplasticizer includes 30% solid (=15.8 kg/m^3) and 70% water (=36.8 kg/m^3).

† 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).