UHPC Precast Concrete under Severe Freeze-Thaw Conditions

Ming-Ju Lee, Ming-Gin Lee, Yishuo Huang, and Kun-Long Lee

***Abstract*—In this study, ultra high performance concrete (UHPC) was used to investigate the effect of UHPC and its precast product by the severe freeze-thaw testing. The UHPC to be used as a precast product material contains a large amount of cement and cementitious materials, a large amount of superplasticizer, and a very small amount of water. The UHPC mixes with eight different volumes of steel fibres were tested and evaluated to find the optimum quality of precast production. The results show that the mechanical properties of UHPC possess high strength, ductility, and bond stress. The results also indicate that most of UHPC specimens presented a steady decrease in compressive and flexural strength after freeze-thaw testing. The 2.5, 3.0 and 3.5% steel fibres by volume were chosen and used in UHPC precast products, after UHPC specimens were tested and finished on their performance evaluations. The results show that the loading capacity of UHPC precast products increased significantly after 600 free-thaw cycles. As a result of freeze-thaw resistance, the appropriate mixes of UHPC applied in the precast products have been obtained; it would provide a reference manufacturing for the UHPC products.**

***Index Terms*—UHPC, freeze-thaw, precast product, ultra high performance concrete.**

I. Introduction

Many severe circumstances are the result of extreme climate conditions such as low temperature, freeze–thaw action, fire attack, and exposure to deicing salts. Because of this, the environmental durability of both the construction materials and methods used in severe conditions and applications are of utmost importance. For example, a small fire can reach 250°C, while a common blaze can easily produce temperatures of around 800°C. In major conflagrations the temperature can even reach 1100°C. At this level, the heat affects most materials, provoking the spontaneous combustion of some of them and affecting the resistance of others. However, very little research has been performed in evaluating the environmental durability of construction materials for UHPC members. Very little work has been done on the effects of freeze–thaw cycling on UHPC materials and UHPC precast products too.

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The process of degradation of concrete due to freeze-thaw cycling is known as occurring due to the expansion of pore water in the cement paste as it freezes to ice. The expansion of water into ice is approximately 9%. This results in the ice pushing water to take up the extra volume and in turn creates hydraulic pressure inside the concrete matrix when it has no more room to expand. Micro-crack or local crack is caused if the expansive forces exceed the tensile strength in the concrete during the freeze-thaw cycling. The effect of freeze-thaw cycling has a significant effect on cement concrete and it causes cracking and scaling and ultimately failure [1].

There are three categories of freezes: 1) dry freeze and hard dry freeze, 2) wet freeze, and 3) hard wet freeze. Freeze-thaw rresistance of concrete depends on the permeability, the degree of saturation, the amount of freezable water, the rate of freezing, and the average maximum distance from any point in the paste to a free surface where ice can form safely. If the pressure developed exceeds the tensile strength of the concrete, the cavity will expand and split. The accumulative effect of continuous freeze-thaw cycles and interruption of paste and aggregate can ultimately cause expansion and cracking, scaling, and collapsing of the concrete [1].

The UHPC was originally developed by Bouygues construction group and is currently being marketed by Lafarge Inc. This particular UHPC is the only one currently widely available in the United States; however, other companies also have similar materials available in other markets. A new class of concrete that exhibits greatly improved strength and durability properties has recently been developed. The Federal Highway Administration (FHWA) at its Turner-Fairbank Highway Research Center (TFHRC) is currently evaluating UHPC for use in the transportation industry [2], [3].

Selecting new materials for concrete structures requires an understanding of how the material behaves in both the uncured and cured states, given the anticipated service and exposure conditions. One of the greatest challenges for the successful performance of new materials is to control their dimensional behavior relative to the substrate. Relative dimensional changes can cause internal stress within the material as well as within the substrate. High internal stress may result in tension cracking, which can lead to loss of load-carrying capability and deterioration. Particular attention must be paid to select materials that properly address relative dimensional behavior so as to minimize these stresses [4], [5].

UHPC has remarkable flexural strength and very high ductility: the ductility is 250 times greater than that of conventional concrete [5]-[7]. The material's extremely low porosity gives its low permeability and high durability, making it potentially suitable for retrofitting reinforced concrete structures or for use as a new construction material and precast product [8].

The Atrium is setting a new stage for UHPC precast solutions. The Atrium is a unique, seven-story, mixed-use building located in the vibrant downtown core of Victoria, British Columbia. Aptly named for the large, free-form atrium space at its core, the building's exterior is clad with UHPC, a material at the cutting edge of innovation for new architectural applications. Thanks to its combination of superior properties, UHPC makes it possible to design and produce thin, complex shapes, curvatures and customized textures; concepts that were previously difficult or impossible to achieve with traditional reinforced precast concrete elements [9].

In recent times, a TechBrief was published by the Federal Highway Administration (FHWA) providing a final design for a full depth UHPC waffle deck system. This TechBrief highlights the results of a study aimed at evaluating the inelastic tensile response of UHPC subjected to simultaneous structural and environmental loading. Practical application of concrete in the highway infrastructure frequently subjects cracked sections to simultaneous mechanical and environmental stressors. This experimental investigation focused on the response of a UHPC beam subjected to concurrent inelastic flexural loading and 15 percent sodium chloride (NaCl) solution application. The results provided insight into the sustained robustness of UHPC structural members loaded beyond their tensile cracking strength [10].

Test results from Lee *et al.* [11] revealed that UHPC specimen (5 cm × 10 cm cylinder) was still in good condition after 600 cycles of freezing and thawing in accordance with ASTM C 666-97. After freezing and thawing test, the non-shrinkage high strength mortar showed a reduction in compressive strength, slant shear strength, steel pull out strength, and dynamic modulus by 17, 21, 24, and 25 %, compared with the corresponding values of 6, 7, 5, and 10 %, respectively, for UHPC. Specimens of normal strength concrete were used as reference specimens. For the normal strength concrete, the average value of relative dynamic modulus of elasticity based on resonant frequencies after 600 freeze-thaw cycles was 55%, compared with the corresponding value of 92% for UHPC.

The goal of this paper is to describe the research done toward the realization of UHPC as an option for precast concrete products. Special concern will be given to the steel fibres by volume were chosen and used in UHPC precast products in severe freeze-thaw conditions. In addition to the above, this experimental study also focuses on evaluating the the optimum steel fibre of UHPC precast products.

II. Experiments

A. Materials and Mix Design

The cement used in this study was type II Portland cement conforming to ASTM C 150 which was manufactured by the Taiwan cement company. Table I displays its chemical composition and physical properties. The silica fume used was supplied by Sun-Li Trade Company in Taiwan. The specific gravity of the silica fume is 2.25. The physical and chemical properties of silica fume are displayed in Table II. The UHPC to be used as a precast product material contains a large amount of cement (type II Portland cement), silica fume, silica sand, quartz powder, steel fiber, superplasticizer, and a very small amount of water. The superplasticizer (SP) to be used as a high range water reducer which was from the Takemoto Fat & Oil Co. Ltd, Japan as Chupol SSP-104 could reduce water requirements by 25 - 40%. The specific gravity and solid contain of Chupol SSP-104 are 1.10 and 30%, respectively. The UHPC mixes with eight different volumes of steel fibres and their price are shown in Table III, were designed, tested and evaluated to find the optimum quality of precast production. The price of the UHPC mixes increase as the percent of steel fiber increase.

TABLE I: Chemical Composition and Physical Properties of Portland Cement II

Chemical composition (%)				
C_3S	C_2S	C_3A	C_4AF	CSH_2
50	24	4.9	12.2	5

Physical properties		
1-day hydration heat	Blaine	1-day strength
250 J/G	250 cm^2/g	60 kgf/cm^2

TABLE II: Chemical Composition and Physical Properties of Silica Fume

Chemical composition (%)				
SiO_2	Al_2O_3	K_2O	CaO	MgO
97.2	0.32	0.32	0.05	0.1

Physical properties		
Loss on Ignition	Blaine	Specific Gravity
2.12%	25.69 m^2/g	2.25

TABLE III: Mix Design and Price of UHPC Concretes (kg/m^3)

Mix	Cement + Silica fume + Quartz	Silica sand	Steel fiber	Water + SP	Price (US)
UHPC0	720 + 256 + 252	900	0	133.7 + 71.3	690
UHPC0.5	720 + 256 + 252	860	40	133.7 + 71.3	800
UHPC1.0	720 + 256 + 252	820	80	133.7 + 71.3	910
UHPC1.5	720 + 256 + 252	780	120	133.7 + 71.3	1020
UHPC2.0	720 + 256 + 252	740	160	133.7 + 71.3	1130
UHPC2.5	720 + 256 + 252	700	200	133.7 + 71.3	1240
UHPC3.0	720 + 256 + 252	660	240	133.7 + 71.3	1350
UHPC3.5	720 + 256 + 252	620	280	133.7 + 71.3	1460

Note: SP means Super-plasticizer.

B. Test Specimens

The UHPC flexural specimens are flexural prism concretes, with two specimens for flexural tests. The UHPC flexural specimens, small-scale concrete prisms had dimensions of 160 mm × 40 mm ×40 mm, were made according to ASTM C 1018 Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using a Beam with Third-Point Loading) was one test used to determine the flexural and tensile properties of UHPC at a specific steel fiber dosage of 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and

3.5 percent by volume. The flexural test was conducted to investigate the effects of steel fiber dosage and curing conditions on UHPC flexural specimens [2].

The UHPC precast concrete specimens had dimensions of 600 mm × 350 mm ×40 mm with eight opening holes as shown in Fig. 1. The fibers included in the UHPC were always Dramix steel fibers that were 13 mm long and had two 0.2-mm and 0.25-mm diameter. These fibers were included in the mix at a specific percent by volume. The demolding of the UHPC precast specimens occurred approximately 48 hours after casting. The normal curing and heat curing treatments were used in this study. The heat curing treatment used heat water to cure the UHPC at 90 ºC for three days. In practice, this procedure included 2 hours of increasing temperature and 2 hours of decreasing temperature, leaving 68 total hours of constant heat water at 90 ºC. This treatment was initiated within 4 hours after demolding. This curing condition will henceforth be referred to as heat water treatment.

C. Freeze-Thaw Tests

One accelerated deterioration environment, namely the freeze-thaw cycle test, was selected for the evaluation of UHPC precast products. Freeze-thaw cycling of all specimens was conducted using the cold climate testing facilities at Chaoyang University of Technology in Taiwan. Freeze-thaw cycles were applied to the blocks at a rate of one cycle/185 min, in accordance with ASTM C 666-97, Test Method for Resistance of Concrete to Rapid Freeze and Thawing, with 1.5 hours of freezing in cold air at – 18°C followed by 1.5 hours of thawing in cool air at + 4.4°C. Specimens that were not subjected to freeze-thaw cycling were stored in the material testing laboratory by immersing in saturated lime water for 24 hours prior to testing, for more detail see Lee et al [12]. The specimens were divided into groups of three, with groups subjected to 0, 200, 400, and 600 freeze-thaw cycles. Before and after freeze-thaw cycling, the samples were tested for their drop-off test and loading test.

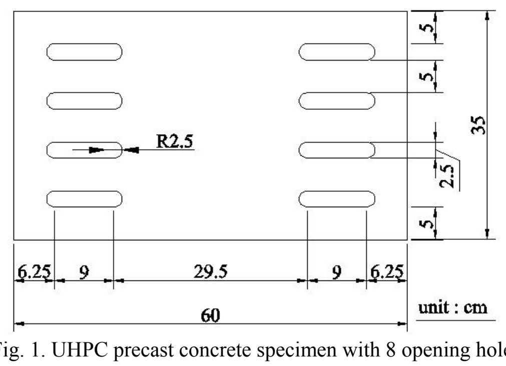

Fig. 1. UHPC precast concrete specimen with 8 opening holes

III. Results and Discussion

A. Flexural Strength

The ASTM C 1018 Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using a Beam with Third-Point Loading) was one test used to determine the flexural and tensile properties of UHPC at a specific steel fiber dosage of 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 percent by volume. The small-scale concrete prisms had dimensions of 160 mm × 40 mm ×40 mm were used in this test. During the test, the load on and the deflection of the prism are monitored. These data are then used to determine the cracking failure and flexural strength response of the UHPC concretes. The flexural strength test was performed on prisms from all two curing regimes. Table IV shows flexural strength of UHPCs in comparison with different steel fiber concentration at normal curing and heat water curing. The result of the entire UHPC heat water curing treatment comparison is that UHPC exhibits significantly enhanced flexural strength compared with standard normal curing of UHPCs. The application of the heat water or steam treatment is clearly beneficial; however, this procedure is also not always necessary as long as the user is willing to accept its strength and durability in loss. The influence of the fibre dosage was very significant. Compared with the flexural strength of UHPCs in Table IV, the experimental result shows the UHPC containing up to 2.5% steel fiber content is reached the predetermined effect at particular load level of 30 MPa. flexural strength. Final tensile failure of UHPC generally occurs when the steel fiber reinforcement begins to debond from and to pull out of the UHPC matrix. Steel fiber has a tremendous effect on flexural strength of UHPC concretes. Test results from Table IV showed that the effect of steel fiber on the flexural strength was apparent. All the UHPC concretes with 2.5%, 3.0% and 3.5% by volume steel fiber replacement showed significantly higher flexural strength than those of the control one (UHPC0) with the same curing condition at all ages. Fig. 2 displays the photo of prism UHPC2.5 with crack extension and failure after flexural test. The UHPC containing up to 2.5% steel fiber content is reached the predetermined effect at flexural strength of 30 MPa, therefore, the 2.5%, 3.0% and 3.5% steel fibres by volume were chosen and used in UHPC precast concrete specimens on their performance evaluations and cost effective in this study.

TABLE IV: Flexural Strength of UHPCs in Comparison with Different Steel Fiber Dosage (MPa)

Mix	Normal curing 14 day	28 day	Ieat curing 14 day	28 day
UHPC0	18.83	20.54	18.81	21.53
UHPC0.5	19.44	21.31	23.35	23.52
UHPC1.0	21.65	24.15	24.65	25.09
UHPC1.5	22.89	24.51	24.76	29.17
UHPC2.0	22.94	24.82	25.15	31.68
UHPC2.5	23.82	31.21	29.70	34.66
UHPC3.0	26.47	32.48	33.56	34.83
UHPC3.5	28.95	32.73	34.88	38.44

Fig. 2. Photo prism UHPC2.5 after flexural test of crack extension and failure

B. Free Falling Test

Fig. 3 displays the photo of UHPC2.5 precast concrete specimen in the free falling test setup for 6-meter high. After the 6-meter high free falling test, the UHPC2.5 precast concrete specimen appeared three micro-cracks as shown in Fig. 4. Table V indicates the surface cracks of UHPC2.5 precast concrete specimen after the free falling test at three different heights. It was found from the free falling test result that UHPC2.5 specimen shows non-crack and remains good condition on the surface at 2-meter height, but several micro-cracks appeared at 4-meter and 6-meter heights. It can be concluded that the surface micro-cracks of UHPC2.5 precast concrete specimen increases substantially as height of the free falling test increases. The safety height of free falling test for UHPC2.5 precast concrete specimen is 2 meters.

C. Loading Capacity Test

Table VI shows ultimate loading strength of UHPC precast concrete specimens in comparison with different steel fiber concentration at 90 °C water curing. The result of the diameter of steel fiber comparison is that UHPC precast concrete specimens exhibits non-significantly enhanced ultimate loading strength compared at 90 °C water curing. For the ranges of steel fiber contents investigated in the study, both flexural strength and ultimate loading strength of the UHPC specimens increase as the percent steel fiber increase. The 2.5, 3.0 and 3.5% steel fibres by volume were chosen and used in UHPC precast products, after UHPC specimens were tested and finished on their performance evaluations. Compared with the ultimate loading strength of UHPCs in Table VI, the experimental result shows the UHPC containing up to 2.5% steel fiber content reached the predetermined effect at particular load level of 12-ton ultimate loading strength. Table VII displays ultimate loading strength of UHPC2.5 precast specimens after freeze-thaw cycling test. The results show that the loading capacity of UHPC precast concrete specimens steadily increased in failure load after 600 free-thaw cycles. As a result of freeze-thaw resistance, the appropriate mixes of UHPC applied in the precast products have been obtained; it would provide a reference manufacturing for the UHPC products [12].

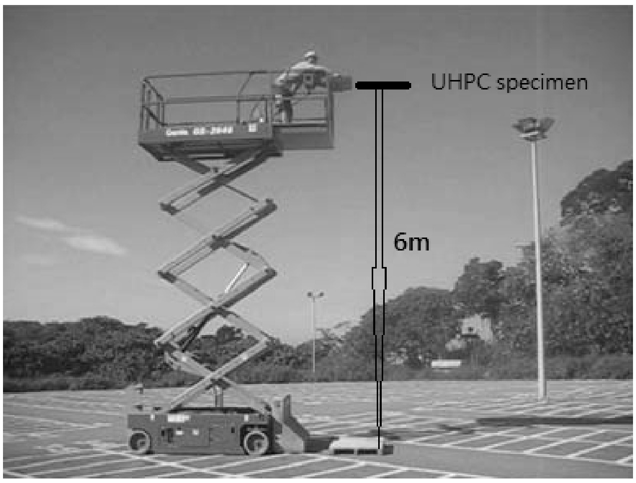

Fig. 3. Photo UHPC2.5 specimen free falling test setup for 6-meter high

Fig. 4. Photo UHPC2.5 specimen cracks after 6-meter high free falling test

TABLE V: UHPC2.5 SPECIMENS CRACKS AFTER FREE FALLING TEST AT THREE DIFFERENT HEIGHTS

Free falling height	2 meter	4 meter	6 meter
Surface crack (mm)	0*	0.35	1.40

0*: non-crack

TABLE VI: ULTIMATE LOADING STRENGTH OF UHPC PRECAST SPECIMENS AFTER LOADING CAPACITY TEST

	Diameter of steel fiber	Ultimate loading strength
UHPC2.5	0.20 mm	13738 kg
UHPC2.5	0.25 mm	12293 kg
UHPC3.0	0.20 mm	13835 kg
UHPC3.0	0.25 mm	14369 kg
UHPC3.5	0.20 mm	13301 kg
UHPC3.5	0.25 mm	14733 kg

TABLE VII: ULTIMATE LOADING STRENGTH OF UHPC2.5 PRECAST SPECIMENS AFTER FREEZE-THAW CYCLING TEST

Freeze-thaw cycle	0 cy.	200 cy.	400 cy.	600 cy.
Ultimate loading strength (kg)	12293	12864	13349	14344
Increase in loading strength	0.0 %	4.4 %	8.1 %	15.8 %

IV. SUMMARY

For the ranges of steel fiber contents investigated in the study, both flexural strength and ultimate loading strength of the UHPC specimens increase as the percent of steel fiber increase. The application of the heat water curing or steam treatment is clearly beneficial to UHPC precast specimens. The 2.5% steel fibres by volume were chosen and used in UHPC precast products, after UHPC specimens were tested and finished on their performance evaluations and cost effective.

Two diameters of steel fiber used in UHPC precast specimens exhibit non-significantly enhanced ultimate loading strength at 90 °C water curing. UHPC precast specimens containing up to 2.5% steel fiber content reached the predetermined effect at particular load level of 12-ton ultimate loading strength. The UHPC2.5 precast concrete specimens displayed a continuous increase in ultimate loading capacity after the free-thaw cycling.

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