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Novel Ultra-High-Performance Glass Concrete

New material used to fabricate pedestrian bridges on the University of Sherbrooke campus

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Ultra-high-performance concrete (UHPC) is defined worldwide as concrete with superior mechanical, ductility, and durability properties. A typical UHPC is composed of cement, quartz powder (QP), silica fume (SF), quartz sand (QS), and steel fibers.[1] UHPC achieves compressive strengths of at least 150 MPa (22,000 psi), flexural strengths up to 15 MPa (2200 psi), elastic moduli of up to 45 GPa (6500 ksi), and minimal long-term creep or shrinkage.[2] It can also resist freezing-and-thawing cycles and scaling conditions without visible damage, and it is nearly impermeable to chloride ions.[3] UHPC is thus a promising material for special prestressed and precast concrete elements (decks and abutments for lightweight bridges and marine platforms; urban furniture; and precast walls), concrete repair, and architectural façade elements.[4]

Although UHPC is relatively expensive to produce, it presents some economic advantages because its enhanced properties allow:

- Reduction or elimination of passive reinforcement in structural elements;
- Reductions in the thickness and self-weight of concrete elements; and
- Increases in service life accompanied with reductions in maintenance costs.[5]

UHPC is designed with a very high cement content ranging between 800 and 1000 kg/m^3 (1350 and 1690 lb/yd^3), which leads to high production costs, consumes natural sources, and increases CO_2 emissions. These factors and others such as a relatively high SF content (25 to 35% by weight of cement) are considered impediments to UHPC use in the concrete market.

Ultra-high-performance glass concrete (UHPGC) is a new type of UHPC that constitutes a breakthrough in sustainable concrete technology,[6] as it comprises granulated post-consumer glass with a specific particle-size distribution (PSD) developed using glass sand, high amounts of glass powder, and moderate contents of fine glass powder. UHPGC technology can provide ecological benefits by valorization of post-consumer glass and reducing the CO_2 footprint of UHPC. It can also provide economical benefits by reducing the volume of land-filled materials and lowering the cost of UHPC. While UHPGC can be designed with less cement, SF, QP, and QS than typical UHPC, it still contains fibers and a high-range water-reducing admixture (HRWRA).

UHPGC can be produced with low water binder ratio (*w*/*b*), yet because the glass particles have zero absorption, its rheological properties allow it to be practically self-placing. Depending on UHPGC composition and curing temperature, the concrete's compressive strength can range from 130 to 260 MPa (20,000 to 40,000 psi), while flexural strength can exceed 15 MPa (2200 psi), tensile strength can exceed 10 MPa (1500 psi), and elastic modulus can exceed 45 GPa (6500 ksi). UHPGC is characterized by excellent durability due to negligible chloride-ion penetration, low mechanical abrasion, and very high freezing-and-thawing resistance.

Pedestrian Bridges

Developing UHPGC was one of the main goals of the University of Sherbrooke's SAQ Industrial Chair on the Valorization of Glass in Materials. After a major research program, this newly developed concrete was used to fabricate new footbridges to replace deteriorated wooden structures on the University of Sherbrooke campus, Sherbrooke, QC, Canada. The technology enabled the designer to create thin sections that are light, graceful, and innovative in geometry and form at a relatively low cost. In addition, the structure is expected to be durable with high abrasion and impact resistance.

Materials

As with any concrete or mortar, UHPC rheology is strongly affected by cement fineness as well as the two most reactive components in portland cement—C_3A and C_3S. The cement characteristics are even more critical in the case of UHPGC, as the very low *w/b* results in close packing of the cement particles. It is particularly important to select cement with the lowest contents of C_3A and C_3S. The cement selected for the UHPGC footbridges was formulated with a low C_3A amount to provide high sulfate resistance. The cement properties included: Bogue composition of 50% C_3S, 25% C_2S, 14% C_3A, and 11% C_4AF; specific gravity of 3.21; Blaine fineness of 370 m^2/kg; and D_{50} of 11 µm.

Other materials used in the UHPGC mixture included:

- SF compliant with CAN/CSA-A3000-13 "Cementitious materials compendium" specifications with silica content of 99.8%, specific gravity of 2.20, D_{50} of 0.15 µm, and specific surface area of 20,000 m^2/kg;
- QS with silica content of 99.8%, specific gravity of 2.70, D_{50} of 250 µm, and maximum particle size of 600 µm;
- Glass powder (GP) with silica content of 73%, specific gravity of 2.60, maximum particle size of 100 µm, and Na20 content of 13%;
- Polycarboxylate-based HRWRA, marketed as ViscoCrete-6100 (Sika); and
- Polyvinyl alcohol (PVA) fibers with 13 mm (0.5 in.) length and 0.2 mm (0.008 in.) diameter.

Concrete mixture

The mixture design was developed in three steps. In the first step, the packing density of the granular composition (QS, GP, cement, and SF) was optimized to 0.78% using the compressible packing model.[7] The resulting mixture comprised 410 kg/m^3 (690 lb/yd^3) of GP. In the second step, the optimum HRWRA dosage was determined for a range of *w/b* values, yielding the rheological characteristics needed to obtain a self-consolidating matrix as well as adequate strength. In the third step, the fiber content was optimized as needed to improve the UHPGC ductility without significantly altering the rheological properties of the fresh mixture.

Table 1 provides the compositions for the UHPGC mixtures with *w/b* of 0.24 used in this project.

Design

The footbridges were designed to meet the university's architectural and structural requirements for pedestrian use as well as to be in compliance with the university's regulation on sustainable development. Because the mechanical properties of the UHPGC allowed the spans to be constructed with relatively small cross sections, each bridge had a total weight of around 4000 kg (8800 lb).

The structural system consisted of an arch slab 4910 mm (193 in.) in length, 2500 mm (98 in.) in width, and 75 mm (3 in.) in thickness supported by longitudinal ribs of variable height and a constant width of 130 mm (5 in.). Using the mechanical properties determined during the testing program, the section was designed to meet strength and serviceability limits as per the university's requirements. The arch slab was reinforced with welded wire reinforcement (M10 at 300 mm [12 in.] in both directions) placed at the midheight of the slab. Each rib was reinforced with a single M20 reinforcing bar located near the bottom of the rib. Figure 1(a) shows the footbridge reinforcement arrangement and Fig. 1(b) provides the concrete dimensions. One footbridge was instrumented with thermocouples and vibrating wire strain gauges so that temperature and deformation could be monitored over time.

Formwork

The mold for the bridges was built at the Bétons Génial, Inc., plant and then transported to the university's integrated laboratory for innovative and sustainable materials and structural valorization research. Bétons Génial, Inc., designed and built a reusable wooden mold integrating a urethane-rubber facing with specific shore hardness. The facing was designed to produce a textured, non-slip walking surface on the decks and very smooth, joint-free surfaces on other surfaces of the bridges (Fig. 2). Although UHPGC shrinkage is very low, the liner material was selected to accommodate concrete shrinkage and minimize the risk of creating micro-cracks during concrete curing. The mold was designed so that the bridge could be cast upside down, allowing the relatively complex shape to be formed with the integral non-slip areas on the deck.

Table 1:
UHPGC mixture design

Materials	kg/m^3
Type HS cement	555
Silica fume (SF)	205
Glass powder (GP)	410
Water	226
Syntactic fiber	32.5
Quartz sand (QS)	888
HRWRA (solid content)	17

Note: 1 kg/m^3 = 1.69 lb/yd^3

Production

The UHPGC was produced at the University of Sherbrooke laboratory using a pilot-scale automatic concrete plant with a paddle-type stationary pan mixer with a 500 L (18 ft^3) capacity. To achieve a homogeneous mixture and avoid particle agglomeration, all powder materials were dry mixed for 10 minutes before the water and HRWRA additions. About half of the HRWRA was diluted in half of the mixing water, and this was gradually added over the next 3 to 5 minutes of mixing time. The remaining water and HRWRA as well as the fibers were then added over the following 3 to 5 minutes of mixing time. The total mixing time was 20 minutes.

Four batches of concrete were produced for a total of 2.0 m^3 (3 yd^3) for each footbridge. Concrete production and placement took 2 hours. Once the four batches had been loaded into the hopper, the UHPGC's fluidity and self-placing properties allowed for placing the concrete into the mold in fewer than 12 minutes without external

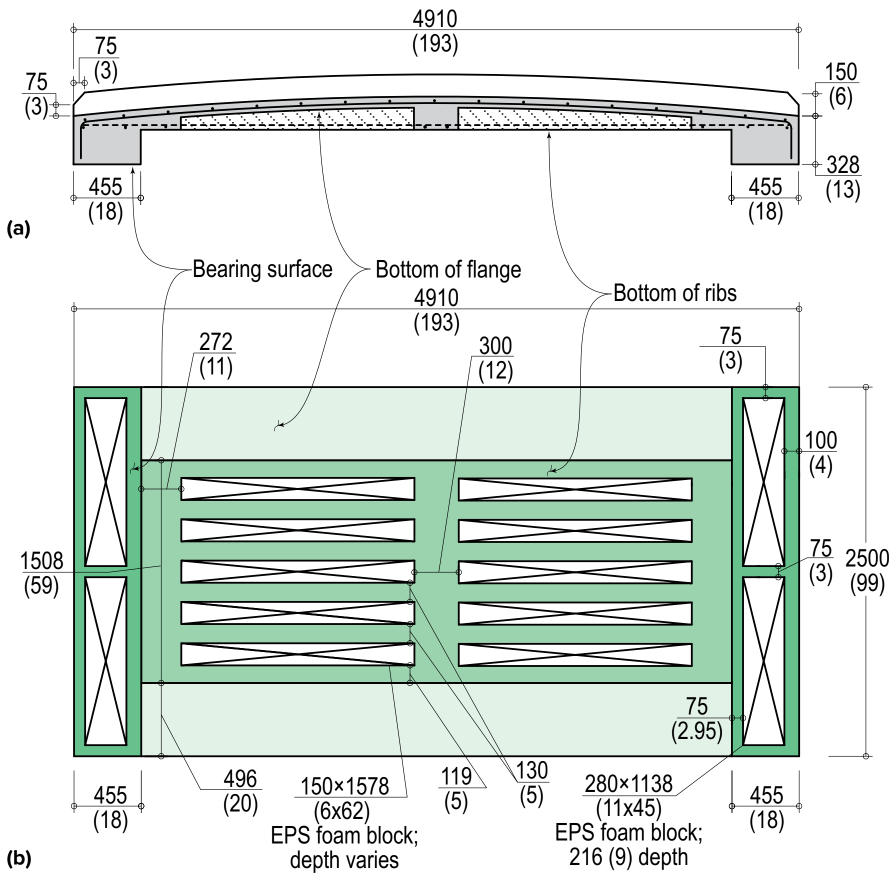

Fig. 1: Bridge schematic: (a) longitudinal section at centerline; and (b) bottom view showing concrete dimensions. Dimensions are in mm (nearest in.)

Fig. 2: The footbridge mold was designed to provide formed surfaces on all exposed faces: (a) a wooden insert was fabricated in the shape of the deck wearing surface and curbs; and (b) the insert was used as the master to cast the urethane rubber liner used for production of the footbridges

vibration. While the UHPGC couldn't be described as self-consolidating, it flowed extremely well. Only 1 minute of internal vibration was required to ensure good compaction. After casting, exposed concrete was covered with plastic sheeting until the mold was removed. For each bridge, the mold was removed 24 hours after placement. First, an overhead crane was used to open the mold by separating its two parts with straps and anchors (Fig. 3(a)). The bridge was then lifted and rotated (Fig. 3(b)). After form removal, plastic sheeting was placed over each footbridge to allow continued curing.

The UHPGC's fresh and rheological properties were measured after mixing. Specimens needed for compressive, tensile, and flexural strength tests as well as modulus of elasticity, resistance to mechanical abrasion, scaling, freezing-and-thawing resistance, chloride-ion penetration, and resistivity tests were then fabricated. Tests were performed according to ASTM International standards. The samples were stored at 23°C (73°F) and 100% relative humidity (RH) for 24 hours before mold removal, after which they were stored in a fog room at 23°C (73°F) and 100% RH until testing.


(a)


(b)

Fig. 3: The footbridge was cast upside down. The mold base held the urethane rubber liner shown in Fig. 2, and the mold was closed with a separate wooden insert that formed the curved and ribbed bottom surfaces of the footbridge: (a) the insert is removed from the mold base, exposing the bottom concrete surfaces and the expanded polystyrene blocks indicated in Fig. 1; and (b) the footbridge was pulled from the mold using straps and anchors, and a steel frame was attached in preparation for flipping the completed structure

Installation

Before the bridges were transported to their installation sites, wooden and steel railings were attached (Fig. 4). A simple flatbed truck was used for transportation to the site (Fig. 5), and a truck-mounted crane and straps were used to lift and install the bridges on conventional concrete abutments with neoprene bearing pads. Lifting and placing took a little less than an hour.

Concrete Performance

Fresh properties

Tests were performed to obtain basic fresh concrete properties including slump flow (ASTM C1437, "Standard Test Method for Flow of Hydraulic Cement Mortar"), unit weight, air content, and temperature (ASTM C185, "Standard Test Method for Air Content of Hydraulic Cement Mortar")—values were 280 mm (11 in.) without tamping, 2231 kg/m^3 (140 lb/ft^3), 3.5%, and 22°C (72°F), respectively.

To examine the concrete's ability for self-placement without consolidation or segregation issues, various tests normally carried out for self-consolidating concrete were performed. The slump-flow diameter with the Abrams cone (ASTM C143/C143M, "Standard Test Method for Slump of Hydraulic-Cement Concrete") was 780 mm (31 in.). The time to reach a 500 mm (20 in.) spread diameter (T500) was 6.8 seconds, which explains the relatively high viscosity. The visual stability index (VSI) was 0, which means no evidence of segregation.

To ensure the concrete flows adequately around the reinforcement bars, the difference between the slump-flow diameter and the J-Ring spread diameter should not exceed

Fig. 4: As final preparation before shipping to the jobsite, wooden and steel railings were attached to the UHPGC curbs

Fig. 5: The completed footbridges were transported on a flatbed truck and installed with a truck-mounted crane

50 mm (2 in.) according to the German SCC guideline[8] or 10 mm (0.4 in.) according to EFNARC.[9] This value was only 5 mm (0.2 in.) for the UHPGC, indicating excellent passing ability. The blockage ratio for the J-Ring test was 0.83. The self-leveling index for the L-Box test with two steel rods was 1.0 (the limit accepted under the EFNARC 2002 guideline[9] is between 0.80 and 1.0). The time for the leading edge of the concrete to reach the end of the 600 mm (24 in.) long horizontal section was 9.8 seconds. This mixture's enhanced fresh properties derive from the large incorporation of glass powder with zero absorption.

Mechanical properties

Compressive-strength tests were carried out according to ASTM C39/C39M, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," on 100 x 200 mm (4 x 8 in.) cylindrical specimens at 1, 7, 28, and 91 days after normal curing. The 28- and 91-day compressive strengths of this UHPGC were 96 and 127 MPa (14,000 and 18,500 psi), respectively. The increase in compressive strength of about 33% from 28 days to 91 days indicates the glass powder's pozzolanic reactivity.

Other test conducted at 28 and 91 days included: indirect splitting tensile strength according to ASTM C496/C496M, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," on 100 x 200 mm (4 x 8 in.) cylindrical specimens; flexural strength according to ASTM C78/C78M, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)," on 100 x 100 x 400 mm (4 x 4 x 16 in.) prisms; and modulus of elasticity according to ASTM C469/C469M, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," on 100 x 200 mm (4 x 8 in.) cylinders. Table 2 lists the concrete's mechanical properties.

Durability properties

Concrete abrasion was measured according to ASTM C944/C944M, "Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method." The average value of the relative volume loss index was 1.35 mm (0.05 in.). For a typical UHPC, the relative volume loss index ranges from 1.1 to 1.7 mm (0.04 to 0.07 in.),[10] which itself is small relative to that for HPC (2.8 mm [0.11 in.]) and normal concrete (4.0 mm [0.16 in.]).[3]

Scaling resistance was measured according to ASTM C672/C672M, "Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals." After 50 freezing-and-thawing cycles, the scaled mass was 12 g/m^2 (0.04 oz/ft^2). The scaled mass reported for UHPC in the literature, varies from about 8 to 60 g/m^2 (0.20 oz/ft^2) for samples subjected to

Table 2:
Mechanical properties of UHPGC

Properties	Concrete age, days			
	1	7	28	91
Compressive strength, MPa	12	52	96	127
Splitting tensile strength, MPa	—	—	10	11
Flexure strength, MPa	—	—	10	12
Modulus of elasticity, GPa	—	—	41	45

Notes: 1 MPa = 145 psi; 1 GPa = 145 ksi

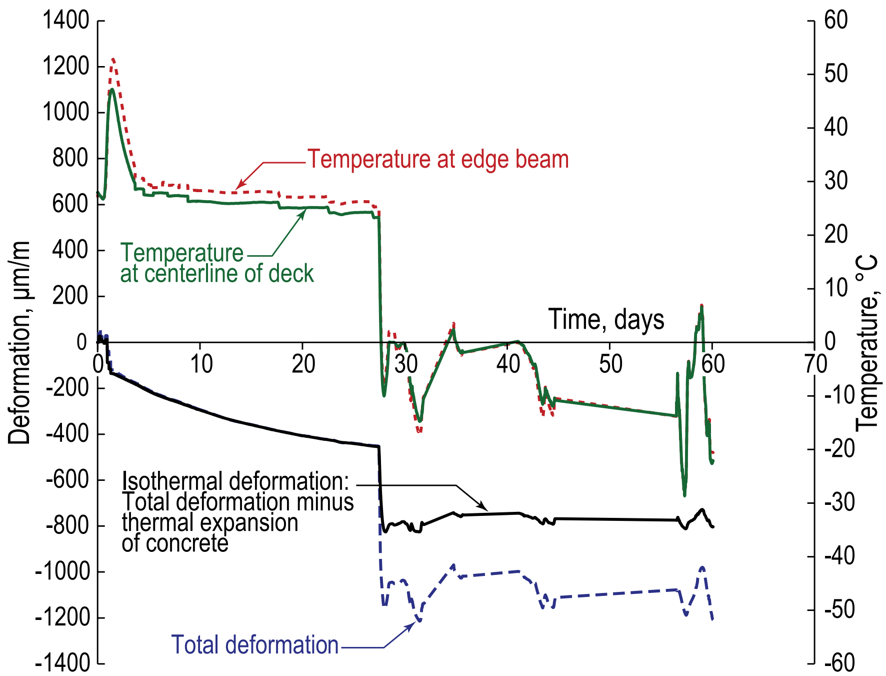

Fig. 6: Variations of deformation and temperature with time obtained from instrumented bridge (Note: °F = 1.8 x °C + 32°)

28 to 50 freezing-and-thawing cycles.[11]

Resistance to chloride-ion penetration was evaluated per ASTM C1202, "Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration." The 28- and 91-day specimens exhibited values below 10 coulombs, indicating "negligible" chloride-ion permeability.

Resistance to freezing-and-thawing was measured according to ASTM C666/C666M, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing." Relative dynamic modulus was 100% after 700 freezing-and-thawing cycles.

The resistivity test was carried out on 100 x 200 mm (4 x 8 in.) cylindrical sample after 91 days of curing. An extremely high value of 3466 kΩ•cm was obtained. For comparison, the resistivity is 1130 kΩ•cm for traditional UHPC without fibers, 96 kΩ•cm for HPC, and 16 kΩ•cm for normal concrete.[3]

Bridge instrumentation

The temperature changes in one footbridge were monitored with two thermocouples: one inserted in the center of the deck and another in the center of the supporting (edge) beam. Figure 6 provides the results from the two thermocouples. The temperature reached approximately 53°C (127°F) in the first days after casting, followed by a gradual drop to laboratory temperature. After curing at laboratory temperature (around 23°C [73°F]) for 28 days, the footbridges were transferred to the field sites, where the temperature dropped below zero, as shown by the sudden drop in the temperature curve. Some nights, the temperature fell to –30°C (–22°F).

A vibrating wire gauge was inserted at the center of the instrumented bridge deck to measure deformation due to shrinkage (Fig. 6). A strain of about 430 µm/m was measured at the end of laboratory curing, followed by a sudden increase in the deformation at the field site due to the temperature changes and removal of the plastic sheeting (the strains resulted from temperature change and additional drying shrinkage). The total strain was as much as 1200 µm/m on some days. After deducting thermal expansion, the isothermal strain was about 800 µm/m.

Summary

A new type of UHPC has been developed using recycled glass, creating UHPGC. The new material exhibited excellent workability and rheological properties due to the zero absorption of the glass particles and optimized packing density for the entire material matrix. The mechanical properties were found to be excellent and comparable to conventional UHPC.

The construction of two UHPGC footbridges at the University of Sherbrooke shows the potential for the material to be used in future projects. UHPGC will produce highly energy efficient, environmentally friendly, affordable, and resilient structures.

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Note: Additional information on the ASTM and CSA standards discussed in this article can be found at **www.astm.org** and **www.csagroup.org**, respectively.

Selected for reader interest by the editors.

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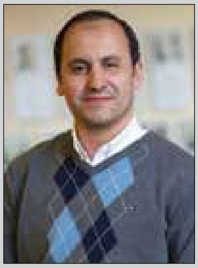

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