Green Ultra-High-Performance Glass Concrete

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Abstract:

This paper presents research work on the development of a green type of ultra-high-performance concrete at the University of Sherbrooke using ground glass powders with different degrees of fineness (UHPGC). In UHPGC, glass is used to replace quartz sand, cement, quartz powder, and silica-fume particles. UHPGC design is based on particle packing density, mechanical properties, and specific rheology. Mixes are designed to suit the rheology and mechanical performances of different concrete applications. Depending on composition and curing conditions, UHPGC can provide improved rheology (mini-slump spread of 260 mm), higher mechanical properties (compressive strength greater than 200 MPa, flexural strength more than 25 MPa). A case study of using this UHPGC is presented through the design and construction of a footbridge.

Keywords: Ultra-high-performance concrete, Sustainability, Waste-glass materials, Glass powder, Footbridge.

1. Introduction

A typical UHPC mix contains portland cement, silica fume (SF), quartz powder (QP), quartz sand (QS) with a maximum size of 600 µm (1/42″), and possibly steel fiber (Richard and Cheyrezy, 1994 and 1995; de Larrard and Sedran, 1994; Roux et al., 1996; Schmidt and Fehling, 2005; Lee et al., 2005). Such typical mixes have a very low water-to-binder ratio (*w/b*) and high superplasticizer contents. Depending on composition and curing temperature, this material can exhibit compressive strength (f_c) of up to 150 MPa (21756 psi), flexural strength in excess of 15 MPa (2176 psi), and elastic modulus above 50 GPa (7252 ksi) (Matte et al., 2000; Schmidt and Fehling, 2005). It can also resist freeze–thaw and scaling cycles without any damage, and it is nearly impermeable to chloride-ion penetration (Richard and Cheyrezy, 1994). These outstanding characteristics of UHPC are achieved by enhancing homogeneity, eliminating coarse aggregate, enhancing the packing density by optimizing the granular mixture through a wide distribution of powder size classes, improving matrix properties, incorporating pozzolanic materials, reducing the *w/b*, improving the microstructure, applying post-set heat treatment, and enhancing ductility by including small steel fibers (Matte et al., 2000).

When producing cement-based materials, consideration must be given not only to good mechanical and durability characteristics, but also to the environmentally friendly, ecological, and socioeconomic benefits (Aïtcin, 2000). A typical UHPC design has a cement content of 800 to 1000 kg/m^3 (0.6 to 0.75 t/yd^3) (Richard and Cheyrezy, 1994 and 1995). This high cement content not only affects production costs and consumes natural sources; it also negatively affects the environment through CO_2 emissions and greenhouse effect (Aïtcin, 2000). The QP has an immediate and long-term harmful effect on the human health because it is human carcinogen. Because of the large difference in grain-size distributions between portland cement and ultrafine SF, high amount of ultrafine SF (25% to 30% by cement weight) have to be used to fill the pores between the cement particles. This significantly decreases the workability of UHPC and increases concrete cost. All these drawbacks are considered as impediments to the wide use of UHPC in the concrete market.

Despite that the post-consumption glass can be recycled in many countries several times without significantly altering of its physical and chemical properties, large quantities of glass cannot be recycled because of high breaking potential, color mixing, or expensive recycling cost (Shi et al., 2005). Most waste glass is dumped into landfills, which is undesirable because it is not biodegradable and not very environmentally friendly (Roz-Ud-Din and Parviz, 2012). Attempts in recent years have been made to use waste-glass powder (GP) as an alternative supplementary cementitious material (ASCM) or ultrafine filler in concrete, depending on its chemical composition and particle-size distribution (PSD) (Shao et al., 2000; Roz-Ud-Din and Parviz, 2012). GP with a mean-particle size (d_{50}) finer than 75 µm (0.003″) exhibits pozzolanic behavior, which contributes to concrete strength and durability (Idir et al., 2011; Cong and Feng, 2012; Vaitkeviciuset et al., 2014). GP can be used to partially replace cement in different types of concrete (Juengera and Ostertag, 2004; Andrea and Chiara, 2010; Zerbino et al., 2012; Soliman et al., 2014), which significantly decreases the adverse effects caused by alkali–silica reaction (de Larrard, 1999). Based on this research, incorporating waste GP in concrete provides high value and feasibility because of the economic and technical advantages.

This article presents the development of an innovative, low-cost, and sustainable UHPGC through the use of glass with various degrees of fineness to replace cement, QP, QS, and SF particles. This research highlights the UHPGC design method used to produce various mixtures to suit different concrete applications in terms of rheology and strength requirements. Erection of footbridge at University of Sherbrooke Campus using UHPGC is also presented as a full-scale application.

2. UHPGC Description

UHPGC is a new type of UHPC that is a sustainable concrete incorporating granulated post-consumer waste glass ground to a specific fineness (Tagnit-Hamou and Soliman, 2014). Glass sand (GS) can replace QS; GP can partially replace cement and completely replace QP; and fine glass powder (FGP) can partially replace SF.

UHPGC mix designs were developed by optimizing (1) the packing density of the granular materials using the compressible packing model (de Larrard, 1999), (2) *w/b* and high-range-water-reducing admixture (HRWRA) dosage using a full-factorial design approach, and (3) fiber content (Tagnit-Hamou and Soliman, 2014). Figure 1 presents the continuous particle-size distributions (PSDs) of the combination of the all ingredients to produce UHPGC. The *w/b* and HRWRA dosage used in UHPGC are optimized to produce concrete with certain rheological characteristics and strength requirements. The fiber content is optimized without significant alteration of the rheological properties of the fresh mixture. The fiber optimization depends mainly on the fiber type and content.

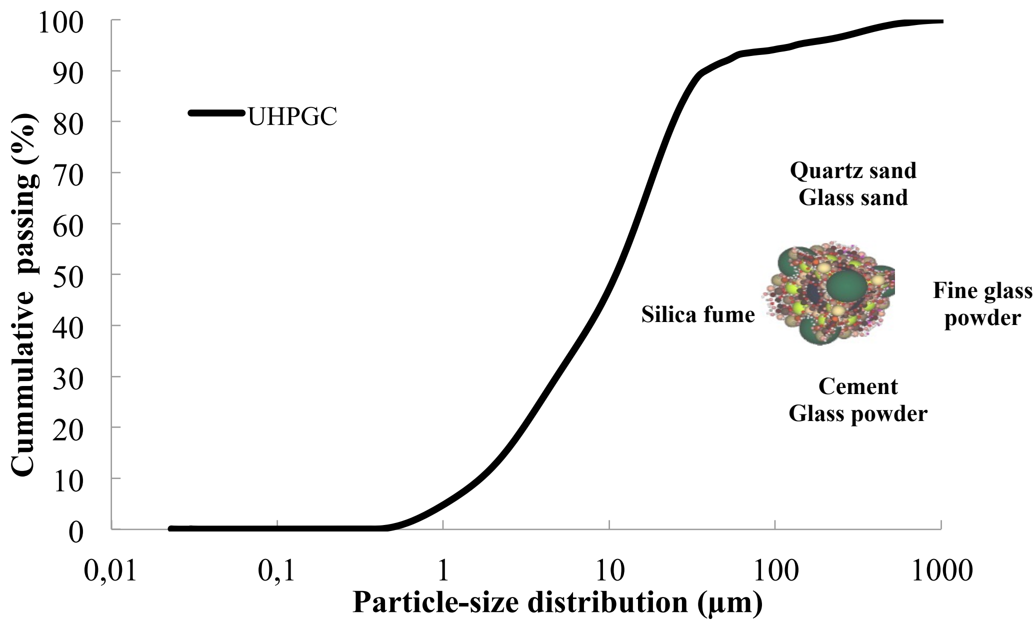

Figure 1. Particle-Size Distribution of UHPGC (1000 µm = 0.039″)

UHPGC can be produced with a lower water-to-binder ratio (*w/b*) due to the glass particles with zero absorption. UHPGC has enhanced rheological properties, so that it is practically self-placing without the need for internal vibration. UHPGC has enhanced rheological properties and workability due to the glass particles' zero adsorption. Depending on composition and curing temperature, UHPGC's f_c can range from 130 to 260 MPa (18855 to 37710 psi), while it's flexural strength (f_{fl}) can exceed 15 MPa (2176 psi), tensile strength (f_{sp}) exceed 10 MPa (1450 psi), and elastic modulus (E_c) exceed 45 GPa (6527 ksi). UHPGC is characterized by excellent durability due to high packing density and lack of interconnected pores. This concrete has negligible chloride-ion penetration, low mechanical abrasion, and very high resistance to freeze–thaw cycles and deicing chemicals (Tagnit-Hamou and Soliman, 2014). UHPGC can be considered an innovative low-cost, sustainable, and green UHPC.

3. UHPGC Mix Designs for Various Construction Applications

3.1. UHPGC Classes

Based on the research conducted to develop UHPGC using waste-glass materials (Tagnit-Hamou and Soliman, 2014), four different UHPGC mixture types can be delimited in responding to various construction demands (Table 1). The UHPC mixtures in Class A are characterized by low flowability of less than 200 mm (7.87″) but with 2-day f'_c under hot curing conditions (HC) of more than 200 MPa (29008 psi). Concrete mixes in Class A have a *w/b* between 0.150 and 0.190. Highly flowable UHPC can be obtained, as in Class C, with higher *w/b* between 0.225 and 0.250. The UHPC mixtures in Class C are characterized by 2-day f'_c under HC between 160 and 175 MPa (23206 to 25382 psi). The concrete mixes in Class B blend the characteristics of those in Classes A and C. All UHPGC mixtures in Classes A, B, and C are designed with steel fiber. The mixtures in Class D are designed for architectural applications, with the steel fiber being replaced with polyvinyl alcohol (PVA) fiber. The concretes in this Class are characterized by higher flowability (260 mm or 10.24″) and moderate strength [91-day f'_c of more than 120 MPa (17405 psi) under normal curing conditions (NC)].

Table 1. UHPC with Local Materials for Various Construction Applications

Characteristics	Class A	Class B	Class C	Class D (architecture)
Flowability	Semi-flowable	Flowable	Highly flowable	Highly flowable
Mini-slump flow diameter, mm (in.)	200 (7.87)	230 (9.06)	260 (10.24)	260 (10.24)
w/b	0.150–0.190	0.190-0.225	0.225-0.250	0.225-0.250
Solids in superplasticizer/cement wt., %	1-3	1-3	1-3	0.225-0.25
Steel fiber, %	2	2	2	--
PVA fiber, %	--	--	--	2.5
2-day-HC $f'c$, MPa (psi)	> 200 (29008)	175-200 (25382-29008)	160-175 (23206-25382)	--
28-day-NC $f'c$, MPa (psi)	> 160 (23206)	> 140 (20305)	> 30 (4351)	> 100 (14504)
91-day-NC $f'c$, MPa (psi)	> 180 (26107)	> 150 (21756)	> 140 (20305)	> 120 (17405)
Flexural strength, MPa (psi)	> 25 (3626)	> 20 (2901)	> 15 (2176)	> 10 (1450)
Modulus of elasticity, GPa (ksi)	> 50 (7252)	> 45 (6527)	> 40 (5802)	> 40 (5802)
Chloride-ion penetration	Negligible	Negligible	Negligible	Negligible
Relative dynamic modulus of elasticity after 1000 freeze–thaw cycles, %	100	100	100	100

3.2. Examples of Various UHPGC Classes

3.2.1. Material Properties and Mixture Proportioning

High-sulfate resistant cement (Type HS) formulated with a low C_3A content was selected to provide high sulfate-resistance. SF compliant with CAN/CSA A3000-13 “Cementitious materials compendium” specifications, QS, and GP with Na_2O content of 13% were used in the UHPGC mixture. Table 2 provides the properties of these materials. This mixture had more than 400 kg/m^3 (0.3 t/yd^3) of GP as cement replacement. A polycarboxylate-based HRWRA with a specific gravity of 1.09 and solids content of 40% was used. The polyvinyl alcohol (PVA) fibers used were 13 mm (0.51″) in length and 0.2 mm (0.01″) in diameter, and had a specific gravity of 1.3 and tensile strength of 400 MPa (58015 psi). The corresponding values for the steel fibers are 13 mm (0.51″), 0.2 mm (0.01″), 7.85, and 1104 MPa (160122 psi).

Table 2. Material Properties

Property	HS Cement	Silica fume	Glass powder	Fine glass powder	Glass sand	Quartz sand
Silica (%)	--	99.8	73	73	73	99.8
Specific gravity	3.21	2.20	2.60	2.60	2.60	2.70
d_{max}, µm (1/in.)	< 100 (254)	< 1 (25400)	< 100 (254)	< 10 (2540)	< 800 (32)	< 600 (42)

Table 3 presents the mixture proportions for seven UHPGC mixtures covering the various concrete Classes described in Table 2. As shown in the table, the design allowed using GP in all mixes in contents varying between 222 and 403 kg/m^3 (0.17 and 0.30 t/yd^3). FGP contents ranging from 53 to 113 kg/m^3 (0.04 and 0.09 t/yd^3) were used to partially replace the ultrafine SF in UHPGC-1 to 4. GS was also used as a 25% replacement of QS in UHPGC-3 and 50% in both UHPGC-4 and 6. A 2% volume fraction of steel fiber was used for UHPGC-1 to 6, while 2.5% PVA fiber was used for UHPGC-7.

Table 3. UHPGC Mixture Compositions for Various Construction Applications in kg/m^3 (t/yd^3)

	Class A		Class B		Class C		Class D
Materials	UHPGC-1	UHPGC-2	UHPGC-3	UHPGC-4	UHPGC-5	UHPGC-6	UHPGC-7
Water	196 (0.15)	193 (0.15)	211 (0.16)	186 (0.14)	215 (0.16)	236 (0.18)	224 (0.17)
Cement	812 (0.61)	640 (0.48)	608 (0.46)	790 (0.59)	561 (0.42)	739 (0.56)	544 (0.41)
Silica fume	113 (0.09)	142 (0.11)	158 (0.12)	109 (0.08)	208 (0.16))	205 (0.15)	204 (0.15)
Fine glass powder	113 (0.09)	80 (0.06)	53 (0.04)	109 (0.08)	--	--	--
Glass powder	244 (0.18)	382 (0.29)	380 (0.29)	237 (0.18)	411 (0.31)	222 (0.17)	403 (0.30)
Quartz sand	974 (0.73)	960 (0.72)	684 (0.51)	474 (0.36)	896 (0.67)	443 (0.33)	888 (0.67)
Glass sand	--	--	228 (0.17)	474 (0.36)	--	443 (0.33)	--
Superplasticizer*	13 (0.010)	13 (0.010)	10 (0.008)	17 (0.013)	16 (0.012)	10 (0.008)	16 (0.012)
PVA fiber	--	--	--	--	--	--	32.5 (0.02)
Steel fiber	158 (0.12)	158 (0.12)	158 (0.12)	158 (0.12)	158 (0.12)	158 (0.12)	--

*Solids content

3.2.2. UHPGC Performance

Table 4 provides the workability and *f'c* after 2 days of HC (*f'c-2d-HC*), 28 days of NC (*f'c-28d-NC*), and 91 days of NC (*f'c-91d-NC*) of the seven UHPGC mixtures. A mini-slump spread of more than 230 mm (9.06″) indicates higher concrete workability. Strength results satisfy the requirements given in Table 1. As shown in the table, the mechanical strength for the samples subjected to 2 days of HC was greater than those obtained under the normal curing conditions, even after 91 days of curing. The concrete mixtures in Class A showed the highest strength results (*f'c-2d-HC* of 210 and 205 MPa (30458 and 29733 psi) for UHPGC-1 and 2, respectively), while those in Class C were the lowest (*f'c-2d-HC* of 169 and 175 MPa, or 24511 and 25382 psi, for UHPGC-5 and 6, respectively). The concrete in Class B exhibited moderate strength (*f'c-2d-HC* of 200 and 190 MPa, or 29008 and 27557 psi, for UHPGC-3 and 4, respectively). UHPGC-7 (Class D) tested at 135 MPa for the *f'c-2d-HC* due to the inclusion of the PVA fiber.

Table 4. Performance Characteristics of UHPGC Mixtures Used for Various Construction Applications

	Class A		Class B		Class C		Class C
Materials	UHPGC-1	UHPGC-2	UHPGC-3	UHPGC-4	UHPGC-5	UHPGC-6	UHPGC-7
Mini-slump, mm (in.)	240 (9.4)	230 (9.1)	260 (10.2)	250 (9.8)	270 (10.6)	290 (11.4)	270 (10.6)

f'c-2d-HC, MPa (psi)	210 (30458)	205 (29733)	200 (29008)	190 (27557)	169 (24511)	175 (25382)	135 (19580)
f'*c*-28d-NC, MPa (psi)	177 (25672)	170 (24656)	158 (22916)	150 (21756)	130 (18855)	138 (20015)	100 (14504)
f'c-91d-NC, MPa (psi)	191 (27702)	185 (26832)	175 (25382)	165 (23931)	155 (22481)	162 (23496)	127 (18420)

4. Field Applications

4.1. Footbridge Design

Once successfully developed in the laboratory, the UHPGC was used to fabricate two identical footbridges to replace the deteriorated wooden structures on the University of Sherbrooke's campus (Figure 2). UHPGC-7 (Table 3) was used to cast the bridge. UHPGC-7 was produced at the University of Sherbrooke's laboratory in a 500 L (132 gallons) capacity pilot-scale automatic concrete plant with a paddle-type stationary pan mixer. All powder materials were mixed for 10 minutes. About one-half of the HRWRA diluted in half of the mixing water was added over 3 to 5 minutes of mixing. The PVA fibers and remaining water and HRWRA were added during 3 to 5 additional minutes of mixing.

The two footbridges were designed to meet the university's architectural and structural requirements for pedestrian use as well as to comply with the university's regulation on sustainable development. The UHPGC's mechanical properties made it possible to fabricate the spans with relatively small cross sections; each bridge's total weight was around 4000 kg. The structure is expected to be durable with high abrasion and impact resistance. The structural system consisted of an arch slab 4.91 m (16.1′) in length, 2.5 m (8.2′) in width, and 0.075 m (2.95″) in thickness supported by longitudinal ribs of variable height and a constant width of 0.13 m (Tagnit-Hamou et al., 2015). The arch slab was reinforced with welded-wire reinforcement (M10 at 300 mm, or 11.8″, in both directions) placed at slab mid-height. Each rib was reinforced with a single M20 reinforcing bar located near the bottom of the rib.

The bridge mold was built by a specialist UHPC precaster, and then transported to the university's laboratory for casting. The mold was made of urethane-rubber facing with specific shore hardness. The mold was designed so that the bridges were cast upside down, allowing the relatively complex shape to be formed with integral non-slip areas on the deck, very smooth surfaces elsewhere, and no joints. Handrails were attached to the bridges before they were transported to the installation site. The bridges were mounted on conventional concrete abutments with neoprene bearing pads.

Figure 2. UHPGC Footbridge Built at the University of Sherbrooke

4.2. Concrete Performance

Fresh properties: The fresh concrete slump was about 280 mm (11″) without tamping, 2231 kg/m^3 (1.68 t/yd^3) unit weight, 3.5% air content, and 22°C (72°F) for the fresh concrete temperature.

Mechanical properties: The f_c tests were carried at 1, 7, 28, and 91 days after NC (ASTM C39). The 28 and 91-day f_c values of this UHPGC were 96 and 127 MPa (13924 and 18420 psi), respectively (Table 5). The f_c gain of about 33% from 28 days to 91 days indicates the effect of the pozzolanic reactivity of glass powder. Other mechanical tests—including indirect splitting tensile strength (ASTM C496), flexural strength (ASTM C78), and modulus of elasticity (ASTM C469)—were also performed (Table 5).

Durability properties: The mechanical abrasion test (ASTM C779) shows an average relative volume-loss index of 1.35 mm (0.05″). The mass loss after 56 freeze–thaw cycles with deicing salts was very low (12 g/m^2 or 1.11 g/ft^2) (BNQ NQ 2621-900). The 28- and 91-day specimens subjected to the chloride-ion penetration (ASTM C1202) test yielded a negligible value of 10 Coulombs. The relative dynamic modulus of elasticity (ASTM C666) was 100% after 1000 freeze–thaw cycles.

Table 5. Mechanical Properties of the UHPGC

Properties	Concrete age, days			
	1	7	28	91
Compressive strength, MPa (psi)	12 (1740)	52 (7542)	96 (13924)	127 (17420)
Splitting tensile strength, MPa (psi)	--	--	10 (1450)	11 (1595)
Flexure strength, MPa (psi)	--	--	10 (1450)	12 (1740)
Modulus of elasticity, GPa (ksi)	--	--	41 (5947)	45 (6527)

5. Conclusions

A new type of UHPC has been developed using waste-glass materials, resulting in UHPGC. The new material exhibited excellent workability and rheological properties due to the zero absorption of the glass particles as well as the material's optimized packing density. The UHPGC evidenced an improved microstructure with higher mechanical properties and superior durability properties comparable to conventional UHPC. The UHPGC can be developed with different mix designs for various construction applications. The mechanical properties of the UHPGC made it possible to design two footbridges with reduced cross sections (about a 60% reduction in concrete volume compared to normal concrete). The UHPGC's improved durability performance can reduce maintenance costs. The construction of footbridge at the University of Sherbrooke with the UHPGC demonstrates the material's potential for large-scale production. The UHPGC can be used to build highly energy-efficient, environmentally friendly, affordable, and resilient structures. It can save the money spent for the treatment of glass cullets and their disposal in landfills.

6. References

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7. Acknowledgements

This research was funded by the SAQ Industrial Chair on Valorization of Glass in Materials, and the authors gratefully acknowledge this support.