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SUSTAINABLE ULTRA-HIGH-PERFORMANCE GLASS CONCRETE FOR INFRASTRUCTURES

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This paper presents research work on the development of a green type of ultra-high-performance concrete using ground glass powders with different degrees of fineness (UHPGC). This article presents the development of an innovative, low-cost, and sustainable UHPGC through the use of glass powder to replace cement, and quartz powder particles. An UHPGC with a compressive strength (f_c) of up to 220 MPa was prepared and its fresh, and mechanical properties were investigated. The test results indicate that the fresh UHPGC properties were improved when the cement and quartz powder were replaced with non-absorptive glass powder particles. The strength improvement can be attributed to the glass powder's pozzolanicity and to its mechanical performance (very high strength and elastic modulus of glass). A case study of using this UHPGC is presented through the design and construction of a footbridge. Erection of footbridge at University of Sherbrooke Campus using UHPGC is also presented as a full-scale application.

Keywords: Waste-glass materials, Green, Fiber, Footbridge, Pozzolanic behavior, Eco-efficient, UHPC.

1 INTRODUCTION

A typical UHPC mix contains Portland cement, silica fume (SF), quartz sand (QS) having a maximum size of 600 µm, quartz powder (QP), and, possibly, very fine steel fiber (Richard and Cheyrezy 1995). Such a mix has very low water-to-binder ratio (w/b) and contains a high amount of superplasticizer (SP). Depending on its composition and curing temperature, the resultant material can exhibit compressive strength higher than 150 MPa, flexural strength greater than 15 MPa, and elastic modulus above 50 GPa (Richard and Cheyrezy 1994, Graybeal 2006, Schmidt and Fehling 2005). It can also resist freeze-thaw and scaling cycles without visible damage, and it is nearly impermeable to chloride ions penetration (Roux *et al.* 1996). UHPCs are designed with high cement contents ranging from 800 to 1,000 kg/m^3 (Richard and Cheyrezy 1995). This huge amount of cement not only affects production costs and consumes natural sources, but it negatively impacts the environment through CO2 emissions and the greenhouse effect (Aïtcin 2000). Moreover, the use of quartz powder (QP) in UHPC with small-diameter crystalline quartz particles raises concerns about respiratory health concerns (World Health Organization 2000).

Most waste glass is dumped into landfills, which is undesirable because it is not biodegradable and not very environmentally friendly (Shi *et al.* 2005). Attempts in recent years have been made to use waste-glass powder (GP) as an alternative cementitious material or ultrafine filler in concrete, depending on its chemical composition and particle-size distribution (PSD) (Roz-Ud-Din *et al.* 2012). GP with a mean-particle size (d_{50}) finer than 75 µm exhibits pozzolanic behavior, which contributes to concrete strength and durability (Shayan and Xu 2006, Idir *et al.* 2011). GP can be used to partially replace cement in different types of concrete (Soliman and Tagnit-Hamou 2016).

This article presents the development of an innovative, low-cost, and sustainable UHPGC through the use of glass powder to replace cement, and QP particles. Erection of footbridge at University of Sherbrooke Campus using UHPGC is also presented as a full-scale application.

2 EXPERIMENTAL PROGRAM

2.1 Materials

A high-sulphate-resistant cement (Type HS cement), which is formulated specifically with low C_3A content, was selected. The HS cement contains 50% C_3S, 25% C_2S, 2% C_3A, and 14% C_4AF. It has a specific gravity of 3.21, Blaine fineness of 370 m^2/kg, and mean particle diameter (d_{50}) of 11 µm. The SF used in this study has silica content of 99.8%, specific gravity of 2.20, specific surface area of 20,000 m^2/kg, and d_{50} of 0.15 µm. The QP used in this study has silica content of 99.8%, and d_{50} of 13 µm. QS with a maximum particle-size diameter (d_{max}) of 600 µm was used as granular materials. It has a d_{50} of 250 µm, silica content of 99.8%, and specific gravity of 2.70. GP with a d_{max} of 100 µm, silica content of 73%, Na_20 content of 13%, and specific gravity of 2.60 was used. A polycarboxylate-based (PCE) high-range water-reducing admixture (HRWRA) was used as superplasticizer. To enhance ductility, steel and Polyvinyl Alcohol (PVA) fibers 13 mm in length and 0.2 mm in diameter were incorporated in fiber reinforced mixture.

2.2 Mixture Proportioning

A total of eight mixtures were designed to study the effect of GP on the fresh, and mechanical, properties of the UHPC: one traditional mixture without GP; three mixtures containing different percentages of GP as partial cement replacement (series I), two mixtures with 50% and 100% QP replacement with GP (series II), and two mixtures to study the synergetic effect of GP as replacement for both cement and QP (series III). The conventional UHPC prepared with cement, SF, QP, and, QS was considered as the reference. The mixture labels (Table 1) are a combination of two parts: cement or QP, and GP replacement ratios.

Table 1. Mixture proportioning (kg/m^3).

Material	Reference	Series I (cement replacement)			Series II (QP replacement)		Series III (synergetic effect)	
		90C/10GP	80C/20GP	70C/30GP	50QP/50GP	0QP/100GP	UHPGC-A	UHPGC-S
Type HS cement	807	724	639	556	807	807	544	623
Silica fume	225	224	222	221	224	224	204	216
Water	195	195	193	192	195	195	224	188
Water-to-binder ratio *(w/b)*	0.189	0.189	0.189	0.189	0.189	0.189	0.24	0.189
Quartz sand	972	966	960	953	967	967	888	935
Quartz powder	243	241	240	238	121	--	--	--
Glass powder	--	81	160	238	121	242	403	390
Solids content of SP	13	13	13	13	13	13	16	13
Steel fiber	--	--	--	--	--	--	--	158
PVA fiber	--	--	--	--	--	--	32.5	--

For example, 90C/10GP contained 90% cement and 10% GP. In series III, the UHPC mixture was prepared with GP to replace 20% of cement and 100% of QP. A 2% volume fraction of steel fiber was used for UHPGC-S, while 2.5% PVA fiber was used for UHPGC-A. The UHPGC-S present the mix design for structure application while UHPGC-A present the mix design for architecture applications.

2.3 Specimen Preparation and Test Methods

All of the powder materials were mixed for 10 minutes. The half amount of the HRWRA diluted in half of the mixing water was added after 5 minutes of mixing time. The rest water and HRWRA were added during an additional 5 minutes of mixing then fiber was added for extra 2 minutes. The fresh properties of the mixtures were measured. The tests included concrete temperature, unit weight, and air content (ASTM C 185). Concrete flow was measured according to ASTM C 1437. The f_c measurements for the UHPC were determined according to ASTM C 109. The flexural strength was determined according to ASTM C 1018. The modulus of elasticity was measured according to ASTM C 469. The samples were tightly covered with plastic sheets and stored at 23°C and 50% RH for 24 h before the molds were removed. The samples were then cured under two different curing regimes: normal curing (NC) and Hot curing (HC). Under NC, the samples were stored in a fog room at a temperature of 23°C and 100% RH until the day of testing. The HC mode cured the samples at 90ºC and 100% RH for 48 h.

3 RESULTS AND DISCUSSION

3.1 Parametric and Synergetic Effect of Cement and QP Replacement with GP

3.1.1 *Fresh properties*

Table 2 presents the flowability, air content and unit weight values for the UHPC containing various contents of GP as a cement replacement. The flowability increased slightly when the GP content increased. This slight improvement was due to the replacement of cement particles by GP particles, which have low water absorption and smoother surfaces. Another explanation for workability increasing with increasing GP content is cement dilution, which tends to reduce the formation of cement hydration products in the first few minutes of mixing. Therefore, there are insufficient products to bridge various particles together. The greater the GP replacement of cement, the lower the unit weight due to the low specific gravity of the GP compared to the cement (2.6 vs. 3.2, respectively). All of the mixtures had air-content values lower than 4%. The PCE-based HRWRA used in these concrete mixtures resulted in high amounts of entrapped air.

Table 2. Fresh properties of UHPC mixtures containing GP as a replacement for cement and QP.

Property	Reference	Series I (cement replacement)			Series II (QP-replacement)		Series III (synergetic effect)	
		90C/10GP	80C/20GP	70C/30GP	50QP/50GP	0QP/100GP	UHPGC-A	UHPGC-S
Slump-flow (mm)	190	195	205	210	200	210	275	220
Air void, %	3.8	3.8	4.2	4.1	4.1	4.0	3.3	4.3
Unit weight, kg/m^3	2458	2446	2426	2410	2450	2446	2231	2524
Concrete temperature, °C	34	31	28	26	31	29	25	27

The incorporation of the GP as a QP replacement significantly increased the slump flow. For example, the slump flow increased from 190 to 200 mm and to 210 mm when the GP replacement increased from 0% to 50% and 100% (reference, 50QP/50GP, 0QP/100GP, respectively). The unit-weight and air-content values were similar for the reference (0% GP) and the concrete containing GP, as seen in Table 2.

The fresh properties of the combination of cement and quartz powder replacement by glass powder are presented in Table 2. The slump flow for the UHPGC-S mixture was 220 mm compared to 190 mm for the reference. Incorporating steel fibers did not affect the fresh properties of the UHPGC. The UHPGC-A fabricated with PVA fiber additions of 2.5 required higher dosages of HRWRA as well as increase the w/b percentage to secure acceptable range of concrete workability for architecture application purpose.

3.1.2 *Compressive strength*

Figure 1 presents the compressive strengths of all the mixtures at different ages and under different curing conditions (NC and HC). The replacement of cement with 10% and 20% GP yielded to higher f_c values after NC (at different ages) and after HC (Fig. 1-A). The f_c values for the reference mixture at 91 days of NC and 2 days of HC were 179 and 204 MPa, respectively, while the f_c of 90C/10GP and 80C/20GP were 213 and 216 MPa at 2 days of HC and 198 and 201 MPa at 91 days of NC, respectively.

The inclusion of GP as a QP replacement increased the compressive strength of the UHPC mixtures compared to the reference, as shown in Fig. 1-B. For NC at 7 and 28 days, the f_c values of 50QP/50GP and 0QP/100GP were approximately similar to the reference mixture. At 56 and 91 days, the strength of the UHPC containing GP was higher than the reference. When the QP was totally replaced with GP (0QP/100GP), the concrete exhibited a higher increase in f_c of about 12% and 17% at 56 and 91 days under NC, respectively, compared to reference mixture. The concrete mixtures with GP exhibited higher mechanical properties at both 56 and 91 days of NC as well as at 2 days of HC due to the pozzolanic reaction of the GP with the hydrated cement product, which took place at a later age. Strength was also improved by the glass particles acting as inclusions with very high elastic modulus (70 GPa).

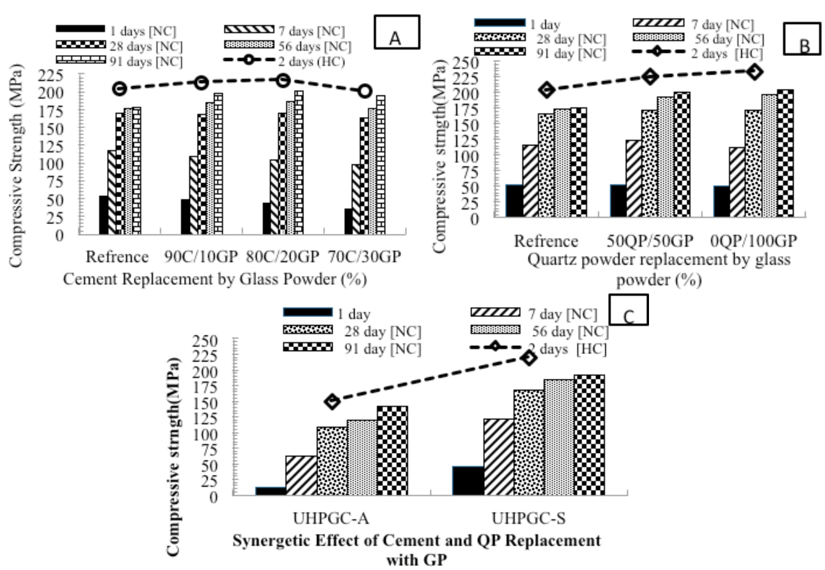

Figure 1. Compressive strength of UHPC: (A) cement replacement by glass powder (B) quartz powder replacement by glass powder, and (C) cement and quartz powder by glass powder.

Based on our results, it can be summarized that the strength of the mixture with 20% GP replacement (80C/20GP) exhibited a greater increase in f_c of 8% and 13% at 56 and 91 days of NC, respectively, and 20% after 2 days of HC, compared to the reference mixture. Also, it can be concluded that the total replacement of QP with GP gives the optimal composition of UHPC in terms of high strength and slump flow.

Figure 1-C shows the compressive-strength results of the UHPGC-A and UHPGC-S after NC for 1, 7, 28, 56, and 91 days and after HC for 2 days. Adding steel fibers (accounting for 2% of the UPHC by volume) only slightly increased the concrete's compressive strength. For example, after HC, the f_c results for UHOGC-S was 217 MPa. The UHPGC-A mixture designed with PVA fiber exhibited lower f_c values compared to the corresponding mixture without fiber.

3.2 Field Applications

3.2.1 *Footbridge design*

Once successfully developed in the laboratory, the UHPGC-A was used to fabricate a footbridge to replace the deteriorated wooden structure on the University of Sherbrooke's (US) campus (Figure 2). UHPGC-A was produced at the US laboratory in a 500 L capacity pilot-scale automatic concrete plant with a paddle-type stationary pan mixer. The footbridge was 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 (Soliman *et al.* 2015).

Figure 2. UHPGC Footbridge built at the University of Sherbrooke.

3.2.2 *Concrete performance*

Fresh properties: The fresh concrete slump was about 280 mm without tamping, 2,231 kg/m^3 unit weight, 3.5% air content, and 22°C for the fresh concrete temperature.

Mechanical properties: The f_c tests were carried at 1, 7, 28, and 91 days after NC. The 28 and 91-day f_c values of this UHPGC were 96 and 127 MPa, respectively (Table 3). 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, flexural strength, and modulus of elasticity—were also performed (see Table 3).

Table 3. Mechanical properties of the 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

Durability properties: All the durability tests were conducted according to ASTM test methods. The mechanical abrasion test shows an average relative volume-loss index of 1.35 mm. The mass loss after 56 freeze–thaw cycles with deicing salts was very low (12 g/m^2). The 28- and 91-day specimens subjected to the chloride-ion penetration test yielded a negligible value of 10 Coulombs. The relative dynamic modulus of elasticity was 100% after 1,000 freeze–thaw cycles.

4 CONCLUSIONS

Sustainable ultra-high-performance glass concrete (UHPGC) has been developed through the use of glass powder. The glass powder was used to replace cement and quartz powder in conventional UHPC. Concrete mixes presented good workability; this is due to the non-absorptive glass particles. Mechanical performances were excellent and comparable to conventional ultra-high performance concrete (UHPC). UHPGC provides several advantages through: usage of waste glass, reduce the production cost of ultra-high performance concrete UHPC and decrease of the carbon footprint of typical UHPC. The construction of two footbridges at the University of Sherbrooke using the UHPGC shows the potential for the material to be used in future projects. The UHPGC will produce highly energy efficient, environmentally friendly, affordable, and resilient structures. The use of UHPGC provides several advantages, such as using waste glass, reducing UHPC production costs, and decreasing the environmental footprint of conventional UHPC.

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