



Development of ultra-high-performance concrete using glass powder – Towards ecofriendly concrete



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HIGHLIGHTS

- UHPC is a concrete with high mechanical, ductility, and durability properties.
- UHPC with glass decrease the UHPC cost and greenhouse gas emission.
- UHPGC provides technological, economical, and environmental advantages.
- Glass in UHPGC enhance the concrete rheology and mechanical properties.

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ABSTRACT

A green ultra-high-performance glass concrete (UHPGC) with a compressive strength (f_c) of up to 220 MPa was prepared and its fresh, mechanical, and microstructural properties were investigated. The test results indicate that the fresh UHPGC properties were improved when the cement and quartz powder were replaced with nonabsorptive glass-powder (GP) particles. The strength improvement can be attributed to the GP's pozzolanicity and to its mechanical performance (very high strength and elastic modulus of glass). The microscope investigation revealed the formation of a hydration rim around cement and GP particles. UHPGC provides technological, economical, and environmental advantages compared to traditional ultra-high-performance concrete (UHPC).

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1. Introduction

The recent enormous developments in concrete technology are yielding new generations of concrete such as ultra-high-performance concrete (UHPC). UHPC has been defined worldwide as a concrete with high mechanical, ductility, and durability properties [1]. A typical UHPC mix design is composed of very high cement content, silica fume (SF), quartz powder (QP), quartz sand (QS), and steel fibers [2]. The fiber inclusion improves in the UHPC's ductility and flexural capacity. UHPC can achieve compressive strength (f_c) higher than 150 MPa, flexural strength (f_{fl}) of up to 15 MPa, an elastic modulus (E_c) of 45 GPa, and minimal long-term creep [2,3]. UHPC can also resist freeze–thaw cycles and deicing-salt scaling with no visible damage, and it is nearly impermeable to chloride-ion penetration [4–6]. These outstanding characteristics of UHPC result from enhancing homogeneity, eliminating the coarse aggregate,

enhancing packing density, improving microstructure, and incorporating fibers [1,2]. Currently, UHPC is used in constructing special prestressed and precast concrete elements, such as decks and abutments for lightweight bridges, marine platforms, precast walls, concrete repairs, as well as urban furniture and other architectural applications [7–10].

Cement-based materials must not only have good mechanical and durability characteristics, but they must also be environmental friendly (ecological) and provide socioeconomic benefits [11]. UHPC is usually designed with a higher cement content ranging between 800 and 1000 kg/m³ [1,2]. The huge amount of cement not only affects production costs and consumes natural sources, but it also negatively affects the environment through the release of carbon dioxide (CO₂) emissions, which can contribute to the greenhouse effect. Furthermore, estimates put the final hydration percentage of the cement from 31% to 60% due to UHPC's very low water-to-cementitious material ratio (w/cm) [12,13]. Unhydrated cement particles in UHPC act as microaggregates and lead rapid hydration reaction, high heat of hydration, and shrinkage cracking.

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Based on an Environment Canada report [14], QP—the main component in UHPC—causes immediate and long-term environmental harm because its biological diversity makes it an environmental hazard. Additionally, the International Agency for Research on Cancer (IARC) has classified respirable quartz due to occupational exposure as a Group 1 carcinogen (carcinogenic to humans). The U.S. National Toxicology Program has classified crystalline silica of respirable size as a human carcinogen. The basis for these classifications is sufficient evidence from human studies indicating a causal relationship between exposure to respirable crystalline silica in the workplace and increased lung-cancer rates in workers [15]. Based on this information, an intensive effort to replace QP with other safe, nonharmful materials should be undertaken.

In achieving the “sustainable” concrete concept, cement and QP can be replaced with mineral admixtures such as fly ash (FA), silica fume (SF), and ground granulated blast-furnace slag (GGBFS). Recently, various studies have been carried out to develop UHPC that is more ecologically and economically feasible. Soutsos et al. [16] found that up to 36% of cement could be replaced with GGBFS without decreasing f_c . Yazici [17] also reported that cement replacement of up to 40% with either FA or GGBFS had no detrimental effects on f_c . Van Tuan et al. [18] investigated the possibility of using rice-husk ash (RHA) to produce UHPC. They achieved f_c over 150 MPa by incorporating RHA in UHPC. The degree of cement replacement with FA and GGBFS in UHPC mixtures was also studied by Puntke [19] based on the concept of particle-packing density.

Recently, FA production has been reduced in North America because most of the coal-fired power plants are being refitted as gas-fired plants. In addition, shipping FA and GGBFS over long distances can increase the greenhouse-emission effect, as illustrated by the fact that transportation is responsible for more than 28% of Canada’s total greenhouse-gas emissions [20]. So, using alternative materials available locally should be more beneficial for UHPC production.

Post-consumption glass can be recycled several times in many countries without significantly altering its physical and chemical properties. Large quantities of glass cannot be recycled because of the high breaking potential, color mixing, or high recycling costs [21]. Most of waste glass goes into landfill sites, which is undesirable since it is not biodegradable and less environmentally friendly [22]. In recent years, attempts have been made to use waste glass as an alternative supplementary cementitious material (ASCM) or ultra-fine filler in concrete, depending on its chemical

composition and particle-size distribution (PSD) [23,24]. Glass ground to a particle size finer than 38 μm exhibits pozzolanic behavior, which contributes to concrete strength and durability [25–27]. The ground glass powder (GP) (with a particle size of 30 μm or smaller) can be used as an ASCM to partially replace cement in certain concrete types [28–31], thereby significantly decreasing the adverse effects caused by the alkali–silica reaction [32]. This research indicates that incorporating waste GP in concrete holds high value and feasibility considering its economic and technical advantages.

According to Leadership in Energy and Environmental Design (LEED) certification, using glass in concrete can double the points earned from using other by-products such as SF, FA, and BFS. GP is regarded as a post-consumption material, while the others are considered post-production materials. Using GP as a cement replacement has very little environmental impact. The Recyc-Quebec analysis (2015) showed that valorizing glass bottles as GP in concrete can allow for its transportation within a radius of 8950 km without environmental impacts compared to landfilling.

The research program described herein aimed at developing an innovative low-cost, sustainable, and green UHPC by using GP. In this program, cement and QP were replaced with GP at different proportions, while keeping QS and SF quantities constant in all mixtures. The UHPC mixtures were optimized based on the packing-density theory. The effect of GP on fresh properties, hydration kinetics, f_c , and microstructure of UHPC was investigated. The effect of two different curing conditions on the f_c and microstructure properties of UHPC mixtures were also studied: normal curing (NC) at a temperature of 20 °C \pm 2 °C and relative humidity (RH) of 100%, and standard steam hot curing (HC) at a temperature of 90 °C and 100% RH for 48 h.

2. Research significance

In order to produce concrete “greener” than conventional UHPC, both the cement and QP were replaced with GP. This strategy reduces CO₂ emissions. Moreover, the glass is being reused, which cuts down on landfilled materials and saves more natural resources. This can reduce the carbon footprint of a typical UHPC. Replacing QP and cement with GP can also dramatically reduce the cost of conventional UHPC. For example, QP costs three times more than GP. Moreover, the transportation cost of materials can also be reduced by using locally available GP to produce UHPC.

Table 1
Chemical composition (%) of the type HS cement, quartz sand, quartz powder, glass powder, and silica fume.

	Identification	Quartz Sand	Quartz Powder	Glass Powder	HS Cement	Silica Fume
Chemical Composition (%)	Silicon dioxide (SiO ₂)	99.80	99.80	73.00	22.00	99.80
	Iron oxide (Fe ₂ O ₃)	0.04	0.09	0.40	4.30	0.09
	Aluminum oxide (Al ₂ O ₃)	0.14	0.11	1.50	3.50	0.11
	Calcium oxide (CaO)	0.17	0.38	11.30	65.6	0.40
	Titanium dioxide (TiO ₂)	0.02	0.25	0.04	0.20	–
	Sulfur trioxide (SO ₃)	–	0.53	–	2.30	–
	Magnesium oxide (MgO)	0.01	0.20	1.20	1.90	0.20
	Sodium oxide (Na ₂ O)	–	0.25	13.00	0.07	0.20
	Potassium Oxide (K ₂ O)	0.05	3.50	0.50	0.80	0.50
	Equivalent alkali (Na ₂ O _{eq})	–	–	–	0.90	–
	Zinc oxide (ZnO)	–	–	–	0.09	0.25
	Loss on ignition (LOI)	0.20	0.32	0.60	1.00	3.50
	Bogue Components	C ₃ S	–	–	–	50.00
C ₂ S		–	–	–	25.00	–
C ₃ A		–	–	–	2.00	–
C ₄ AF		–	–	–	14.00	–
Physical Properties	Specific gravity	2.70	2.73	2.60	3.21	2.20
	Blaine surface area (m ² /kg)	–	–	380	430	20,000
	Mean particle size, d_{50} , (μm)	250	13	12	11	0.15
	Maximum-particle size, d_{max} , (μm)	600	–	100	–	–
	Cost (\$/ton)	235	560	150	220	450

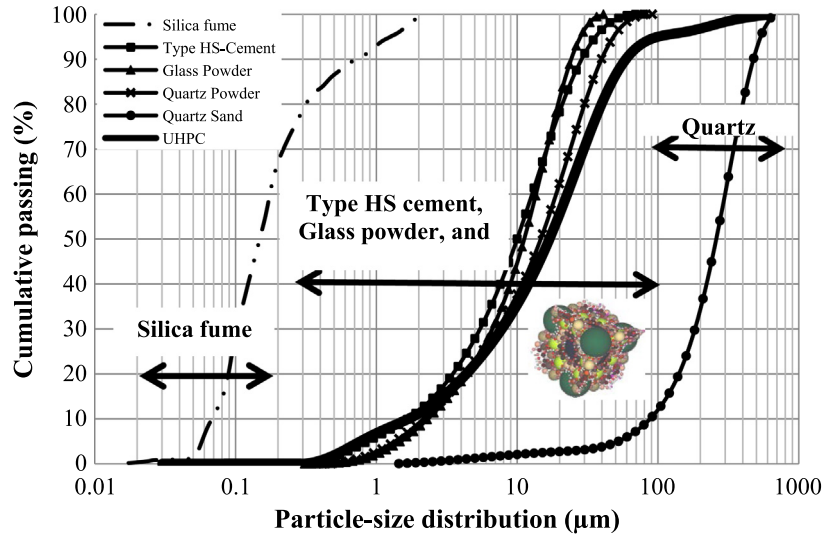


Fig. 1. Particle-size distributions of individual materials and combined granular materials used in the UHPGC mix design.

In addition, UHPC has a very high cement content and very low w/cm , which results in rapid hydration, high heat of hydration, and shrinkage. Controlling this early-age shrinkage by replacing cement with GP is essential to ensure enhanced long-term performance and longer service life.

3. Experimental program

The following section describes the material characteristics, mixture proportions, mix-design optimization, and specimen preparation.

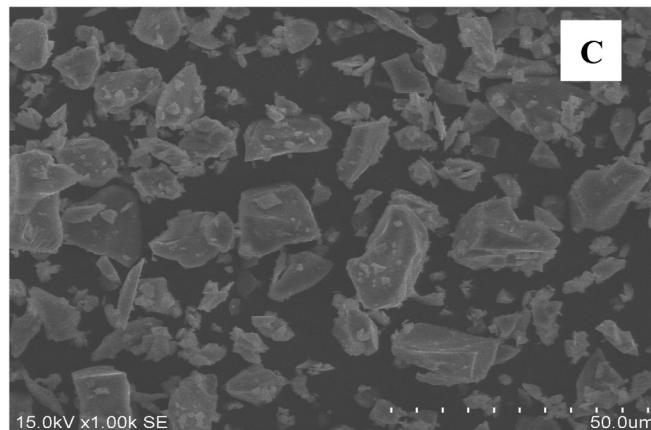
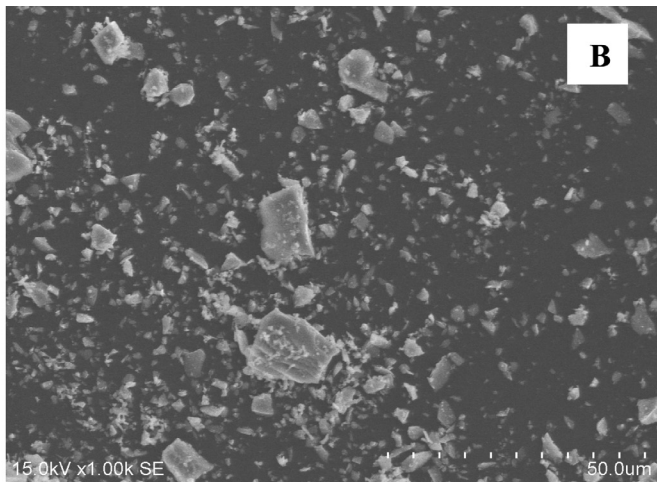
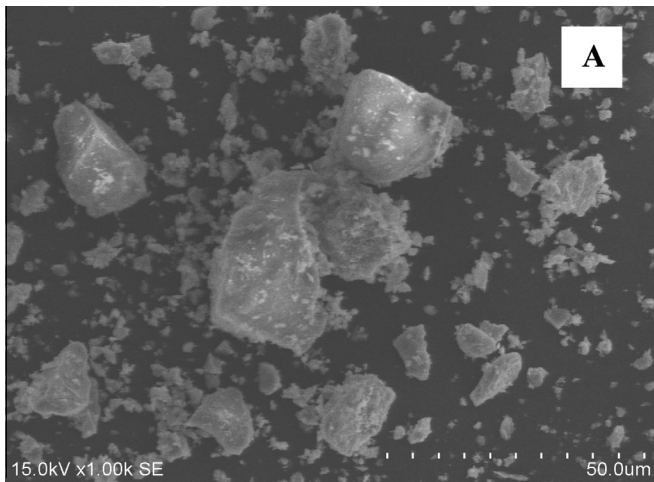


Fig. 2. Photomicrographs of (A) type HS cement (B) quartz powder, and (C) glass powder.

3.1. Materials

In general, the cement C_3A and C_3S contents and cement fineness are critical for controlling concrete rheology [11]. This is more pronounced in case of UHPC, which is designed with higher cement content. Therefore, high sulfate-resistance cement (Type HS cement) with low C_3A and C_3S contents was selected for designing the UHPC mixtures used herein. The SF complies with CAN/CSA A3000 specifications. The UHPC was also designed with QS with a specific gravity (SG) of 2.70 and a maximum particle size (d_{max}) of 600 μm . A QP with a SG of 2.73 and d_{50} of 13 μm was used as a filler material. A GP with a SG of 2.6 and d_{50} of 12 μm was used to replace cement and QP in traditional UHPC. Table 1 gives the chemical and physical properties of the Type HS cement, SF, QS, QP, and GP. The physical properties include specific gravity, Blain surface fineness, mean particle-size diameter (d_{50}), and maximum particle diameter (d_{90}). Fig. 1 provides the particle-size distribution (PSD) of the Type HS cement, QP, SF, and QS. The micrographs in Fig. 2 show the morphology and size of the cement, QP, and GP particles. Obviously, the cement powder consists of multi-size, multi-phase, irregularly shaped particles generally ranging in size from less than 1 μm to about 100 μm . the QP and GP have multi-size and irregular shaped particles. XRD analysis was performed to determine the nature of each material, as shown in Fig. 3. XRD analysis of the cement and QP indicate that they were crystallized, while the GP was amorphous.

The costs for each UHPC constituent is listed in Table 1. The materials are obtained from reputable suppliers and the costs spec-

ified are valid for 2014 when the bulk of the research was conducted.

A polycarboxylate (PCE)-based high-range water-reducing admixture (HRWRA) with a specific gravity of 1.09 and solids content of 40% was used in all the concrete mixtures.

Steel fibers measuring 13 mm in length and 0.2 mm in diameter were incorporated into the optimized mixtures.

3.2. Mix design optimization

UHPC development starts with designing the granular structure of all the granular components. The key factor for enhancing UHPC performance is optimizing the particle-size distribution and packing density. The granular structure strongly affects the balance between the UHPC rheological behavior and mechanical performances as well as the chemical reactivity of the constituents. The design of the granular structure of the UHPC used in our study was made according to the compressible packing model (CPM) developed by de Larrard et al. [33].

Fig. 2 shows the PSD of all the materials and the optimized UHPC. The water-to-binder ratio (w/b) of 0.189 and the dosage of HRWRA (expressed as percentage of solids content in the HRWRA relative to cement weight, %*SolidHRWRA*) of 1.5% were obtained by optimizing the different mixtures designed with various w/b and HRWRA concentrations to yield concrete with certain rheological characteristics and strength requirements [31]. The GP, which had a PSD close to that of the cement and QP was used to replace the cement and QP by weight.

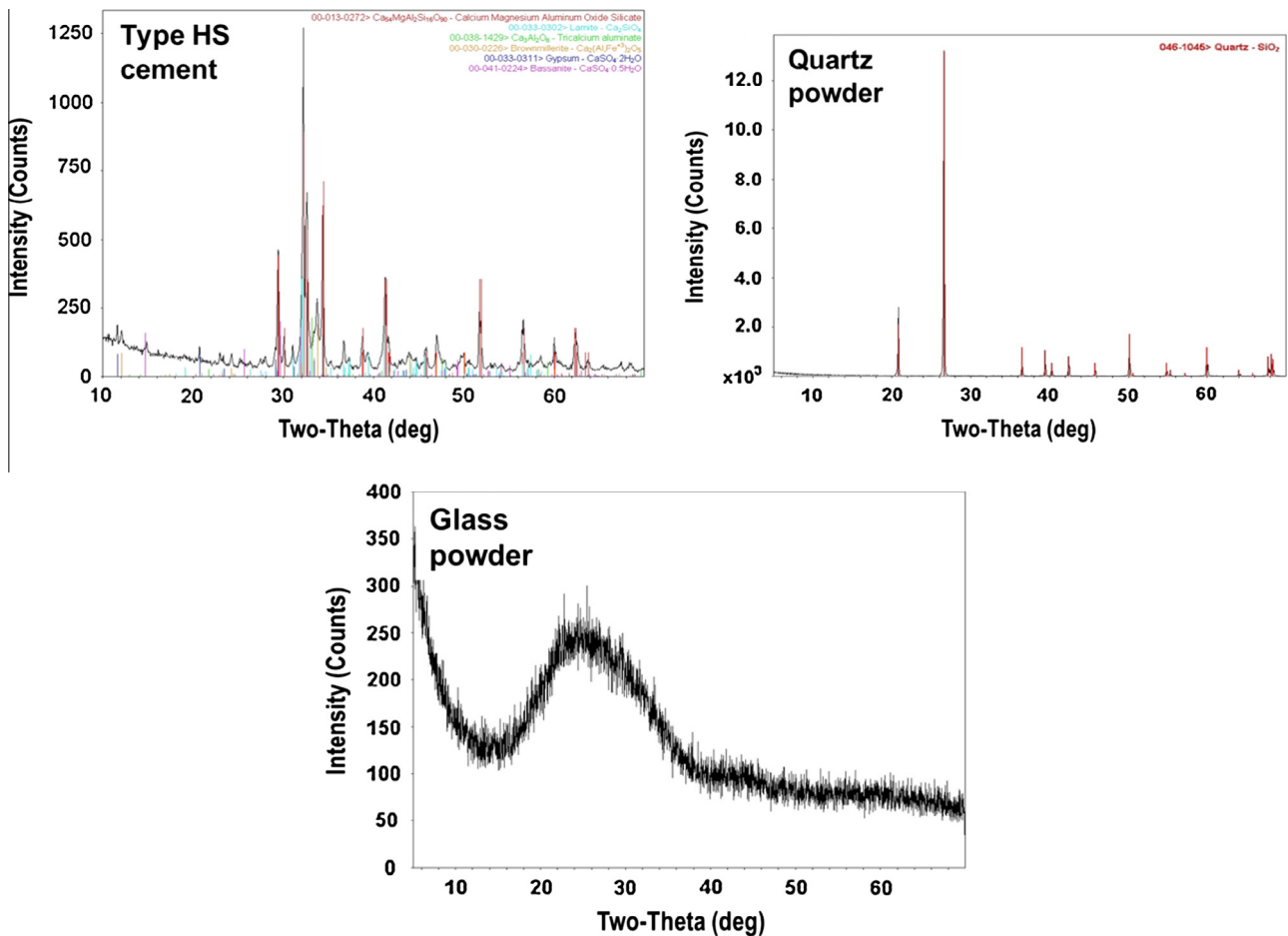


Fig. 3. X-ray diffraction patterns for type HS cement, quartz powder, and glass powder.

Table 2
Mixture proportioning (kg/m³).

Material	Reference	Series I (cement replacement)					Series II (QP replacement)		Series III (synergetic effect)	
		90C/ 10GP	80C/ 20GP	70C/ 30GP	60C/ 40GP	50C/ 50GP	50QP/ 50GP	0QP/ 100GP	80C20GP/ 0QP100GP	80C20GP/ 0QP100GP-F
Type HS cement	807	724	639	556	473	392	807	807	636	623
Silica fume	225	224	222	221	219	217	224	224	221	216
Water	195	195	193	192	191	190	195	195	193	188
Water-to-binder ratio (<i>w/b</i>)	0.189	0.189	0.189	0.189	0.189	0.189	0.189	0.189	0.189	0.189
Quartz sand	972	966	960	953	947	941	967	967	955	935
Quartz powder	243	241	240	238	237	235	121	–	–	–
Glass powder	–	81	160	238	316	392	121	242	398	390
Solids content in PCE-based HRWRA	13	13	13	13	13	13	13	13	13	13
Steel fiber	–	–	–	–	–	–	–	–	–	158
Cost index (\$/\$ Refinance)	1	0.99	0.98	0.97	0.96	0.94	0.93	0.87	0.83	0.83

3.3. Mixture proportioning

A total of 10 mixtures were designed to study the effect of GP on the fresh, hydration, mechanical, and microstructural properties of the UHPC: one traditional mixture without GP; five 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. In series I, the cement was replaced by 10%, 20%, 30%, 40%, and 50% of GP by weight. In series III, the UHPC mixture was prepared with GP to replace 20% of cement and 100% of QP. A similar mixture was designed with 2% steel fiber addition. The SF, QS, *w/b*, and HRWRA were kept constant in all the mixtures. The 10 concrete mixtures were designed with a *w/b* of 0.189 and % SolidHRWRA of 1.5%, as given in Table 2. The mixture labels (Table 2) are a combination of two parts: cement or QP, and GP replacement ratios. For example, 90C/10GP contained 90% cement and 10% GP, while 50QP/50GP contained 50% GP and 50% GP.

The Table 2 lists the mix proportions and associated costs (without fibers) for all of the mixes considered in this work. Cost is listed as a cost index in order to simplify the discussion later on. The cost index is simply the ratio of the mix's cost compared to the starting mixture published in [5], based on current prices in Canada. The index is a relative indicator of cost, since actual costs will vary in time and by location.

3.4. Specimen preparation and test methods

All the concrete mixtures were batched using high-energy shear mixer with a capacity of 10 L. To achieve a homogeneous mixture and avoid particle agglomeration, all of the powder materials were mixed for 10 min before the water and HRWRA were added. Approximately half of the HRWRA diluted in half of the mixing water was gradually added over 5 min of mixing time. The

remaining water and HRWRA were gradually added during an additional 5 min of mixing. At the end of mixing, the fresh properties of the UHPC mixtures were measured. The tests included concrete temperature, unit weight, and air content (ASTM C 185). Concrete flow was measured with the flow-table test (ASTM C 1437).

The heat flow was measured with a thermometric TAM air-conduction calorimeter, containing eight separate measuring cells. About 20 g of freshly mixed paste was weighed in a glass vial with a 24.5 mm inside diameter. The glass vial was sealed and placed in the calorimeter, and the heat flow was measured for about 52 h. During the test, isothermal conditions of 20 °C ± 0.02 °C were maintained in the measuring cells. The initial heat peak, occurring right after the addition of the water to the cement, could not be measured because of the very low *w/b* needed to produce the UHPC required external mixing of the paste ingredients before placement in the calorimeter.

The f_c measurements for the UHPC were determined using 50 × 50 × 50 mm cubes, according to ASTM C 109. The flexural strength was determined on 100 × 100 × 400 mm prisms according to ASTM C 1018. The modulus of elasticity was measured on 100 × 200 mm cylinders 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: NC and 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 consisted of curing the samples at 90 °C and 100% RH for 48 h before testing.

The microstructure of the UHPC samples subjected to HC regime for 48 h. was observed with scanning electron microscopy (SEM: Hitachi S-3400N) coupled with energy dispersive spectroscopy (EDS: Oxford Inca). The SEM was operated at a pressure of 50 Pa, a voltage of 20 kV, and tungsten filament current of 80 μA. The SEM observations were performed on polished surfaces, from which a chunk of the concrete was removed and cast in resin. The cast samples was cut perpendicularly to its cross section and

Table 3
Fresh properties of UHPC mixtures containing glass powder as a replacement for cement and quartz powder.

Property	Reference	Series I (cement replacement)					Series II (QP-replacement)		Series III (synergetic effect)	
		90C/ 10GP	80C/ 20GP	70C/ 30GP	60C/ 40GP	50C/ 50GP	50QP/ 50GP	0QP/ 100GP	80C20GP/ 0QP100GP	80C20GP/ 0QP100GP-F
Slump-flow diameter, mm	190	195	205	210	215	220	200	210	220	217
Air void, %	3.8	3.8	4.2	4.1	4.2	4.7	4.1	4.0	4.0	4.3
Unit weight, kg/m ³	2458	2446	2426	2410	2394	2380	2450	2446	2414	2524
Concrete temperature, °C	34	31	28	26	25	23	31	29	28	27

polished with a 1.0- μm roughness polishing pad. In this paper, each site of interest is presented with two SEM micrographs: a low-magnification micrograph shot 250 times and higher magnification micrographs shot 2.0 k times, respectively.

4. Results and discussion

4.1. Cement replacement with GP

Different GP contents (0%, 10%, 20%, 40%, and 50%) were used to replace cement in the conventional UHPC, and their relevant effects on workability, hydration kinetics, microstructure, and mechanical properties were investigated, as detailed below.

4.1.1. Fresh properties

Table 3 presents the fresh concrete properties. The flowability increased slightly when the GP content increased. This slight improvement was due replacing cement particles with GP particles, which have low water absorption and smoother surfaces. Previous studies also indicate that cement paste and glass interaction was significantly decreased due to the surface smoothness of GP [34,35]. 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.

In addition, the cement used in this study had a specific surface area of 430 m^2/kg , which is greater than that of the GP (380 m^2/kg). Therefore, the total surface area of the cement and GP blend

decreased when using GP as cement replacement. Consequently, the water demand to lubricate particle surfaces decreased due to the drop in the net particle surface area, and hence the slump flow for the same w/b .

It is worth noting that the GP replacement of cement was by weight. As the specific gravity of GP is lower than that of cement, the solid particles-to-water ratio, by volume, is then higher in case of cement and GP blends compared to pure cement. This increased the friction between the solids in the paste in the case of the cement and GP blend, thereby resulting in a slight improvement in workability. This inverse effect of higher solid-to-water volume ratio was less effective on workability compared to the dilution of cement, smooth glass surface, and nonabsorptive nature of GP mentioned earlier. The higher GP content ended up yielding better workability.

As described in [36], superplasticizer efficiency largely depends on the zeta potential on the entire surface of the tested binder particles. In most cases, cement needs more superplasticizer to reach a certain slump flow compared to the common mineral admixtures. On the contrary, the mixture containing cement and GP required less superplasticizer than the mixture designed with cement alone.

Table 3 presents the air content and unit weight values for the UHPC containing various contents of GP. 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. A defoaming agent was not used to reduce entrapped air.

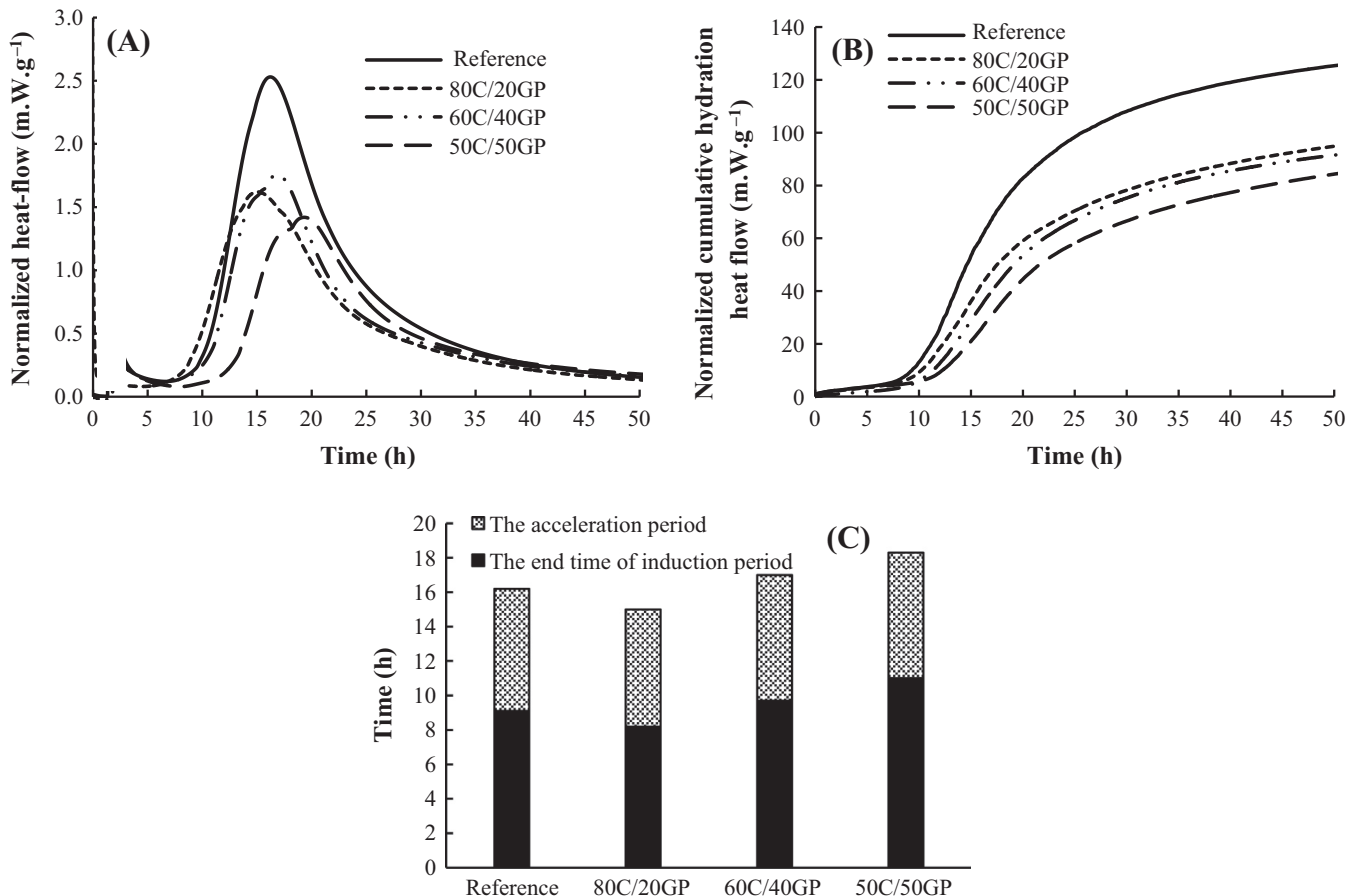


Fig. 4. Hydration process of cement with various glass-powder replacement levels: (A) evolution of normalized hydration heat flow, (B) normalized cumulative hydration heat flow, and (C) acceleration and induction periods.

4.1.2. Hydration kinetics

Isothermal calorimetry was performed to investigate the pozzolanic reaction of the GP on cement hydration at an early age. The rate of hydration heat emission and the cumulative hydration heat curves of the UHPC with 0%, 20%, 40%, and 50% GP replacements within the first 48 h after contact between the water and cementitious materials contact, normalized to the total binder weight in the mixture, are shown in Fig. 4. It is clear that the maximum heat flow and the total heat were reduced as the cement replacement with GP increased. Figs. 5 A and B show that the maximum value of the second exothermic peak of 80C/20GP, 60C/40GP and 50C/50GP were 35%, 32% and 50% lower, respectively, compared to the reference mixture. These reductions in the rate of heat evolution and the total heat generated were due to the dilution of the cement (reduction in overall volume of the cementitious materials) and, consequently, the hydration products. Also, the cement used in this study had a specific surface area of 430 m²/kg, which is greater than that of the GP (380 m²/kg). The pozzolanic reaction of GP generates less heat than ordinary portland cement because the reaction is similar to a C₂S reaction. The results of this study are consistent with previous findings [37,38]. The lower heat of hydration helps minimize the cracking resulting from increased temperature.

When the GP replacement of cement was 20%, the time of the end of the induction period (calculated as the time between the lower point of the heat flow curve and the first inflection point in the main peak) and the acceleration period (calculated as the time between the first and the second inflection points in the heat flow curve) relative to the main peak were shorter, as shown in Fig. 5 A and C. The ends of the induction period of the reference and 80C/20GP were 9.1 and 8.2 h, while the acceleration periods were about 7.1 and 6.8 h, respectively. This can be attributed to the fact that fine glass powders can accelerate the cement hydration through the adsorption of calcium ions from the liquid phase and serve as nucleation and growth sites for C–S–H and other hydrates. At the same time, the high alkali (Na₂O) content in GP can act as catalyst in the formation of calcium silica hydrate at an early age [39,40].

When the GP replacement of cement was higher than 20%, the ends of the induction and the acceleration periods relative to the main peak were delayed, as shown in Fig. 5A and C. For example,

the end of the induction period for reference, 60C/40GP, and 50C/50GP mixtures are about 9.1, 9.7 and 11.2 h, respectively. The acceleration period for the reference, 60C/40GP, and 50C/50GP mixtures are about 7.1, 7.3, and 7.5 h, respectively. The increased level of cement replacement with GP (less cement content) increased both the w/c and superplasticizer solids content in the mix. This is more significant in UHPC production as a high superplasticizer dosage is used. This restricts Ca²⁺ diffusion and dilutes of the pozzolanic reaction of the GP. According to Jansen [41], complexation of Ca²⁺ ions from the pore solution by the superplasticizer can affect the polymer absorbed on the nuclei or the anhydrous grain surfaces, which, in turn, might prevent nuclei growth or lead to dissolution of the anhydrous grains. This significantly retards early hydration of the cement and restricts Ca(OH)₂ generation. The pozzolanic reaction is delayed due to the inadequate amount of portlandite in the mixtures.

4.1.3. Microstructure

SEM was used to study the morphology and microstructure of the reference sample and the samples containing GP. Fig. 6 shows the back-scattered electrons (BSE) images of the selected UHPC mixtures (reference and 80C/20GP) with HC. The figure clearly shows that the interfacial transition zone (ITZ) of the reference mixture without GP was very thin (Fig. 6A); adding GP did not affect the ITZ (Fig. 6 C and E). Because of the low w/b, a large amount of unreacted cement, QP, and GP particles can be seen in the image. No visible capillary pores and cracks can be found. In addition, no portlandite [Ca(OH)₂] was noticed in the matrix because it was consumed by the pozzolanic reaction of SF + GP. The UHPC was designed with close packing density and the use of pozzolanic mineral admixtures. Therefore, the UHPC matrix was significantly more dense and homogeneous than the normal concrete; this indicates very low porosity, in accordance with the literature [12,42,43]. Entrained or entrapped spherical air pores were also observed in the UHPC matrix. Most of these pores were formed as a side effect of the high amount of superplasticizer used. Some of the black points in (Fig. 6A, B, C, D, E, D) are probably the fingerprints of QS or any each particles when the concrete is crushed.

In addition, no portlandite [Ca(OH)₂] was noticed in the matrix because it was consumed by the pozzolanic reaction of SF + GP.

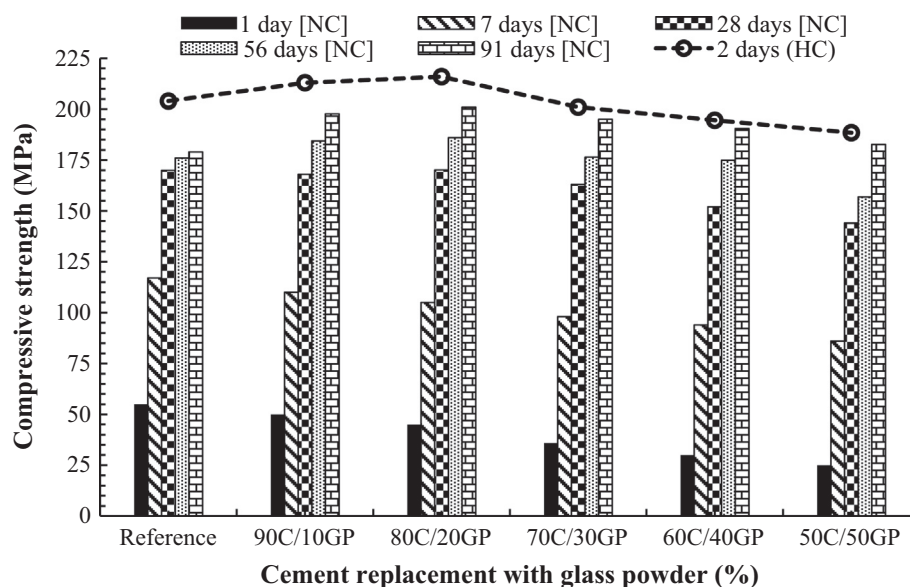


Fig. 5. Effect of cement replacement by glass powder on compressive strength at different ages after normal curing (NC) and hot curing (HC).

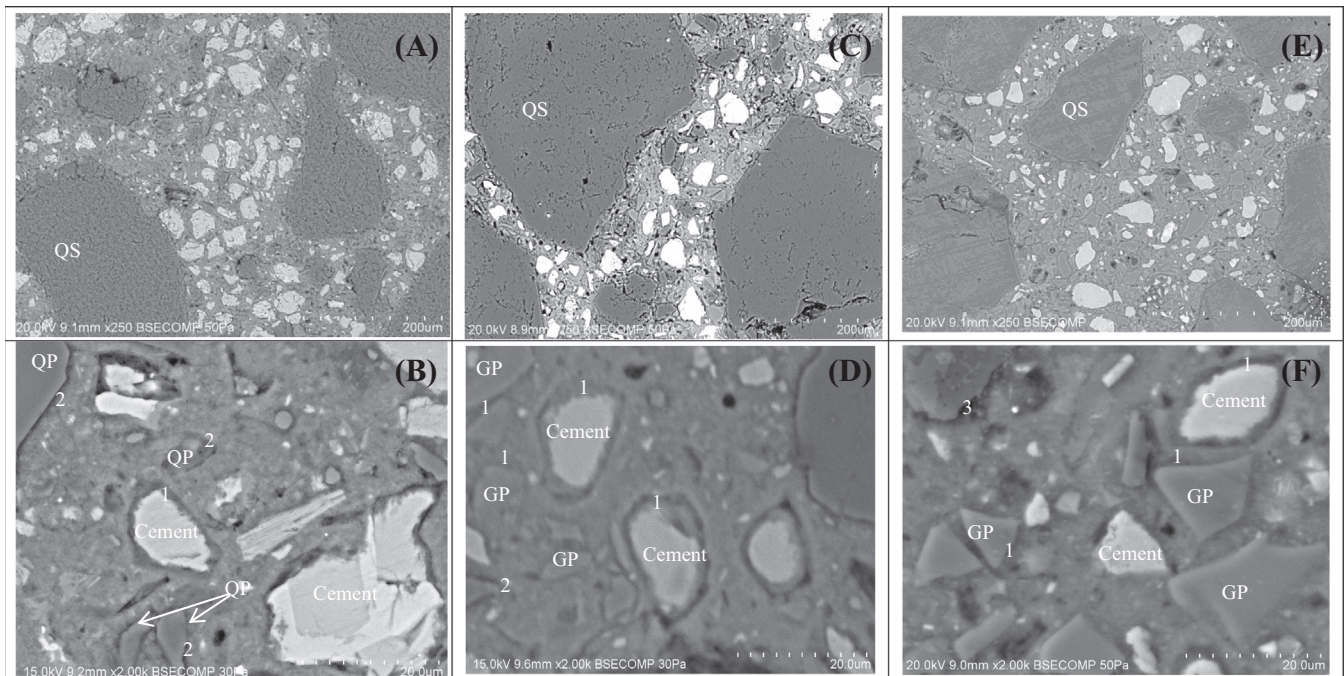


Fig. 6. BSE/SEM image of specimens (A,B) reference, (C,D) 80C/20GP, and (E,F) 0QP/100GP; (A,C,E) 250 times magnification (B,D,F) and 2.0 K magnification, (1) hydration rim, (2) separation between unreacted QP particles and C–S–H phase.

The BSC images (Fig. 6B and D) of the reference and 80C/20GP subjected to heat treatment for 48 h showed a C–S–H hydration rim forming around cement and GP particles. The GP exhibited pozzolanic reaction and produced more C–S–H and enhanced the microstructure, as shown in Fig. 6D. In addition, no ASR microcracking ring was found around the large glass-powder particle due to the adequate fineness of the glass powder and dense matrix, in accordance with the literature [44].

4.1.4. Compressive strength (f_c)

Fig. 4 presents the compressive strengths of the mixtures at different ages and under different curing conditions (NC and HC). The replacement of cement with 10% and 20% GP yielded higher f_c values after NC (at different ages) and after HC (Fig. 4). 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 f_c of the UHPC with 30%, 40%, and 50% GP replacement (70C/30GP, 60C/40GP, and 50C/50GP, respectively) decreased by 10–20% at early ages (1, 7, and 28 days) of NC compared to the reference mixture. The results were different at later ages (56 and 91 days) of NC and also after HC. The f_c values at 2 days of HC and 56 and 91 days of NC for 70C/30GP, 60C/40GP, and 50C/50GP were close to the strength of the reference mixture (Fig. 4).

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. Nevertheless, this pozzolanic reaction was slower than cement hydration [45,46,37]. A C–S–H gel can be generated, causing the microstructure of the concrete to densify. The newly generated C–S–H fills the pore structure in the concrete. Thus, the mechanical properties of the concrete are significantly improved at a later age of NC or with accelerated HC. Moreover, when the GP content increased in the concrete mixture, the w/c increased, which accelerated cement hydration. More portlandite can be generated, and more GP pozzolanic reaction developed, which yielded the successive strength

improvement. Strength and rigidity were also improved by the glass particles acting as inclusions having very high strength and elastic modulus (70 GPa) [31].

Fig. 4 compares the f_c obtained after NC at 91 days and HC. The results indicate that the f_c of UHPC specimens under HC were about 7–10% higher than that of those under NC, regardless of the cement replacement ratio. This was due to the higher pozzolanic reaction resulting from both SF and GP in the UHPC mixture that was activated by the high temperature. Such pozzolanic reaction led to a denser microstructure of C–S–H, resulting in faster strength development.

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.

4.2. Effect of QP replacement with GP

4.2.1. Fresh properties

Table 3 presents fresh concrete temperature, unit weight, air content, and slump flow of the UHPC. The incorporation of the GP 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 particle packing density of concrete was observed to improve when more GP was incorporated in the mixture. For example, the packing density values obtained from the CPM for the reference (0% GP), 50QP/50GP, and 0QP/100GP were 0.79, 0.80, and 0.80, respectively. This was attributed to the GP have a finer particle size than the QP, which also enhanced concrete workability. The unit-weight and air-content values were similar for the reference (0% GP) and the concrete containing GP, as seen in Table 3.

4.2.2. Hydration kinetics

Fig. 8 presents the normalized rate of heat evolution and normalized cumulative amount of heat, relative to the total binder

content, by weight, for the pastes with varying GP contents as QP replacement. The maximum rate of heat evolution and the total heat generated by the different pastes were similar, as shown in Figs. A and B, because of the slower rate of pozzolanic reaction of GP.

The presence of GP shortens the time to reach the peak hydration rate because fine glass powders can accelerate the cement hydration via adsorption of calcium ions from the liquid phase and serve as nucleation and growth sites for C–S–H and other hydrates. At the same time, the high alkali content (Na_2O) in GP may act as a catalyst in the formation of calcium silica hydrate at an early age [39,40]. The ends of the induction period for the reference, 50QP/50GP, and 0QP/100GP was about 9.1, 8.1 and 6.2 h, respectively. The acceleration period of the reference, 50QP/50GP, and 0QP/100GP were about 7.1, 7.5, and 8.3 h, respectively.

Consequently, according to the results obtained in this section, it can be concluded that the GP, as a QP replacement, accelerated the hydration kinetics of the UHPC at an early age.

4.2.3. Microstructure

Fig. 6E and F show the microstructure of 0QP/100GP after HC, for example. The BSE of 0QP/100GP showed no separation between GP particles from the surrounding C–S–H phase, which could indicate the formation of a thin hydration rim due to the pozzolanic reactivity of the GP. In the reference mixture, partial separation of the QP particles from the surrounding C–S–H phase was observed, as shown in Fig. 6B. In this case, because the concrete was heated at a low temperature ($90\text{ }^\circ\text{C}$), the QP is considered as a filler material. The QP only reacts when subjected to heat

temperature in range of $150\text{--}200\text{ }^\circ\text{C}$. QP by altering the calcium oxide (CaO)/silicon dioxide (SiO_2) ratio and favor the formation of tobermorite and xonotlite when UHPC is subjected to heat treatment or setting pressure [12]. The improvement in the f_c due to the QP replacement with GP was confirmed by microstructural observation in the following (Section 4.2.4).

As mentioned in the case of cement replacement with GP (Section 4.1.3), the figure reveals the existence of a dense microstructure and hydration rims around the cement particles.

4.2.4. Compressive strength

The inclusion of GP as a QP replacement increased the compressive strength of the UHPC mixtures compared to the reference, as shown in Fig. 7. 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. Furthermore, at all GP replacement levels, the f_c of 2-day HC specimens was greater than those subjected to NC at all tested ages. After 2 days of HC, the f_c of the reference was 204 MPa, while the f_c values for 50QP/50GP and 0QP/100GP were 222 and 234 MPa, respectively.

It is worth noting that QP is considered a microaggregate (an inert part) in UHPC design. It is characterized by the polymorphic modification of β -quartz, and it shows significant pozzolanic activity when its particle size is finer than $5\text{ }\mu\text{m}$ or it is subjected to hydrothermal treatment at temperatures above $150\text{ }^\circ\text{C}$

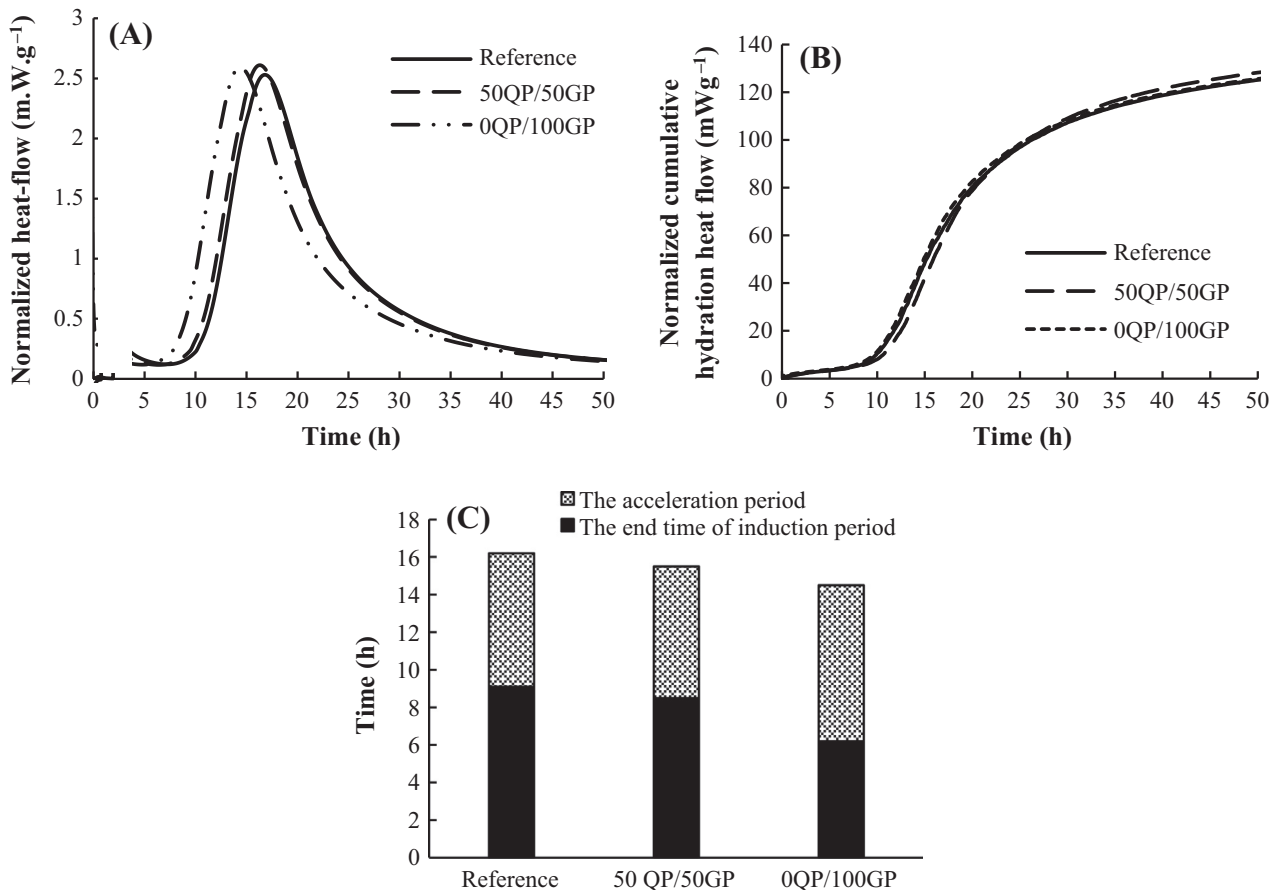


Fig. 7. Hydration process of UHPC containing quartz powder with various levels of glass-powder replacement: (A) evolution of normalized hydration heat flow, (B) normalized cumulative hydration heat flow, and (C) acceleration and induction periods.

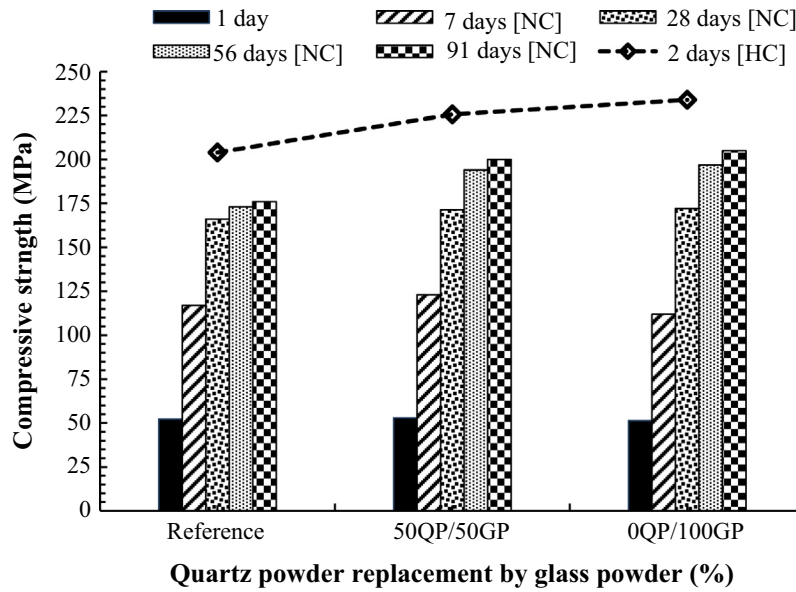


Fig. 8. Effect of quartz-powder replacement with glass powder on compressive strength at different ages after normal curing (NC) and hot curing (HC).

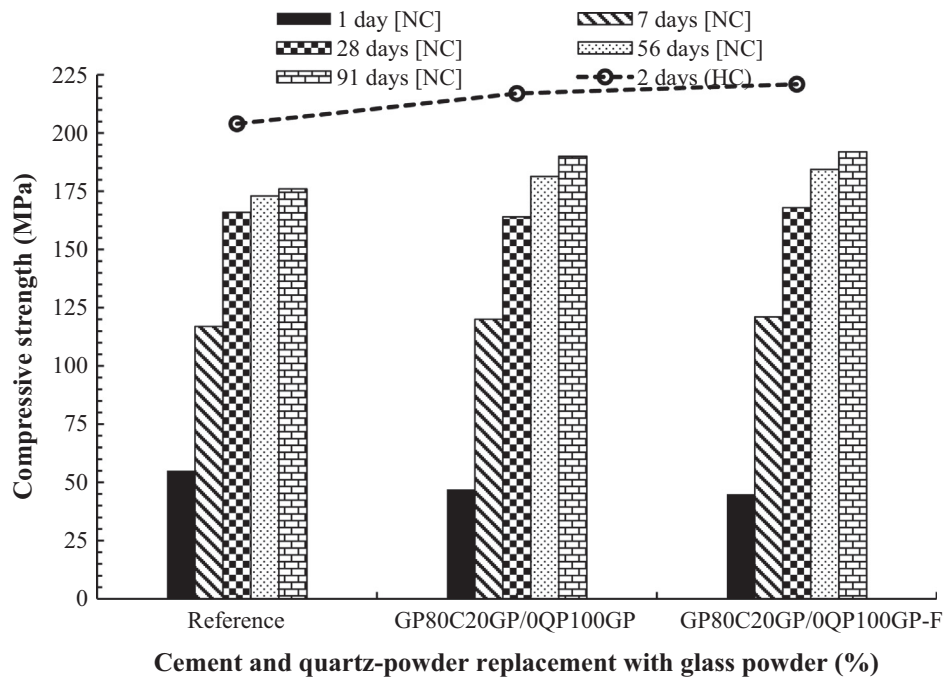


Fig. 9. Synergetic effect of cement and quartz-powder replacements with glass powder on compressive strength at different ages after normal curing (NC) and hot curing (HC).

[12,47]. In contrast, ground GP with a particle size finer than 38 μm can exhibit pozzolanic activity at ambient temperature. Moreover, the GP increased cement solubility, which leads to increased portlandite. The amorphous silica in glass powder can be react with CH and forms C-S-H at a later stage of hydration [30]. Thus, concrete microstructure and compressive strength could be increased significantly and UHPC with superior mechanical properties prepared. In addition, the strength and rigidity improvements were also due to the fact that the glass particles served as inclusions with very high strength and elastic modulus (70 GPa).

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.

4.3. Synergetic Effect of Cement and QP Replacement with GP

Based on the foregoing results, the 20% GP as partial replacement of cement and 100% GP as a replacement of QP can be considered to obtain an optimal UHPC containing GP. Therefore, the following section presents the fresh and mechanical properties of an UHPGC with such a combination (80C20GP/0QP100GP). This

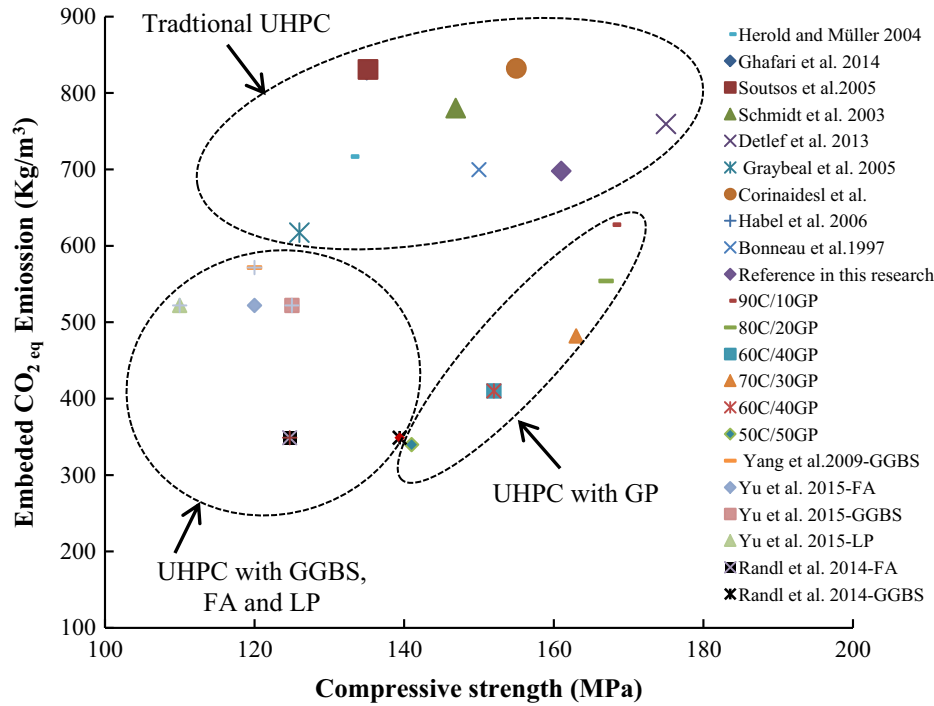


Fig. 10. Relationship between embodied CO₂ eq for the cement content and compressive strength at 28 days under NC regime.

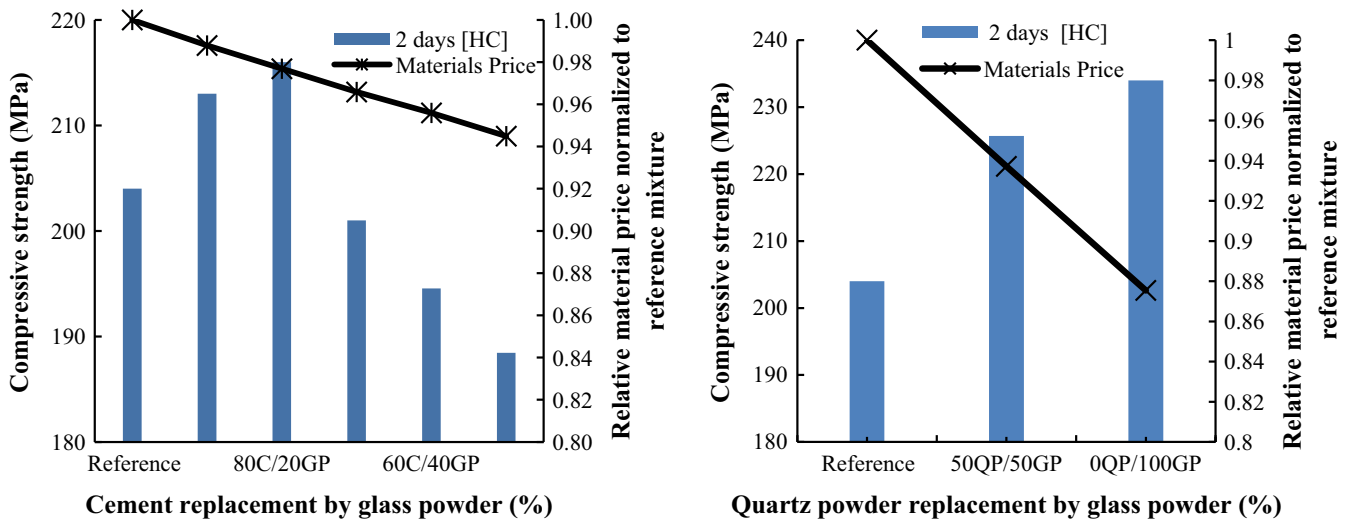


Fig. 11. Relative material price normalized to reference mixture and the 2-day compressive strength obtained under hot curing for UHPC containing GP; cement replacement by GP (right) and QP replacement by GP (left).

mixture was batched with 2% steel fibers. The results of 80C20GP/0QP100GP (without steel fibers) and 80C20GP/0QP100GP-F (with fibers) is presented in comparison to the reference UHPC without GP.

4.3.1. Fresh properties

Table 3 provides the fresh properties of the mixtures tested. The slump flow for the 80C20GP/0QP100GP was 220 mm compared to 190 mm for the reference. Incorporating steel fibers did not affect the fresh properties of the UHPC. The corresponding value for 80C20GP/0QP100GP-F was 217 mm. The air contents for 80C20GP/0QP100GP and 80C20GP/0QP100GP-F were similar to that of the reference mixture.

4.3.2. Mechanical properties

Fig. 9 shows the compressive-strength results of the mixtures after NC for 1, 7, 28, 56, and 91 days and after HC for 2 days. As expected, the concrete samples with GP showed slightly higher f_c results compared to the reference. For example, the f_c values for reference and 80C20GP/0QP100GP were 176 and 190 MPa after 91 days of NC and 204 and 217 MPa after 2 days of HC, respectively. This increase in the f_c can be attributed to the pozzolanic reactivity and rigidity of GP particles. Based on this observation, it can be concluded that GP content significantly influences the f_c of UHPC.

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 80C20GP/0QP100GP and 80C20GP/0QP100GP-F were 221 and 217 MPa, respectively. After 28 days of NC, the f_c values were approximately similar (164 and 168 MPa, respectively). The respective values after 91 days of NC were 190 and 192 MPa. These results are consistent with those obtained by Schmidt et al. [48], who reported that their UHPC mixtures containing 2.5% of steel fiber (per volume) showed no compressive-strength increase compared to the reference.

Fig. 9 compares the compressive-strength results obtained after NC and HC. The compressive strength of the UHPC generally appeared to increase with increasing heat treatment. The compressive strength of the UHPC under HC was an average of 30% higher than that of the samples under NC for 28 days. Its compressive strength after NC for 91 days was, however, slightly higher. HC only accelerated strength development. After HC and 91 days of NC, the strength-development values of the samples containing GP were 10% and 22% higher, respectively, than the reference concrete.

The inclusion of 2% fiber increased the flexural strength from 24 to 26 MPa after 91 days of NC and from 27 to 29 MPa after 2 days of HC. The hot curing showed no significant increase in flexural strength.

The modulus-of-elasticity results indicate that the concrete with GP or with 2% fiber revealed no significant differences between the NC and HC samples. The measured values for all of the concrete mixtures were about $50 + 5$ GPa.

4.4. Evaluation of embedded CO₂ emission and health impact of UHGC

To prove that the designed UHPGC is materials green and eco-friendly, its embedded CO₂ eq emission from cement and GP is evaluated in this study, focusing on the amount of cement and GP required for 1 m³ of UHPC. The amount of CO₂ eq emission was estimated according to [49], which 1 ton of cement and GP produces 846 and 63 kg CO₂ eq, respectively, including average transportation of raw materials with global US and Canadian data. Fig. 10 presents the relationship between embodied CO₂ eq for the cement content and compressive strength at 28 days under NC regime for the concrete developed in this research as well as these references [5,13,16,17,45,49–57]. Obviously, the enhancement of compressive strength of all the analyzed UHPCs corresponds to an increase of the embedded CO₂ emission and environmental impact. The UHPC mixtures designed with GGBS, FA and LP have a low embedded CO₂ emission, with a comparable compressive strength at the same age. It can be notice that UHPGC developed in this study still have high compressive strength, and their embedded CO₂ eq emissions are still low. For example, The CO₂ eq and f_c values for the reference mixture were 700 kg/m³ and 169 MPa at 28 days of NC, respectively, while the CO₂ eq of 70C/30GP and 50C/50GP were 482 and 410 kg/m³ and f_c were 163 and 152 MPa at 28 days of NC, respectively. In sure the designed UHPGC has a lower environmental impact than the other UHPCs. Hence, In order to achieve “greener” concrete concept as well as with higher mechanical properties, cement was replaced by GP as well as the concrete design should be based on the optimized particle packing model. By this strategy, the CO₂ emission can be reduced and also the glass can be reused and therefore less material have to be landfilled and more natural resources could be saved.

4.5. Cost analysis and health impact of UHGC

Table 2 presents the *cost index* for all the tested UHPC mixtures. The cost presented refers to the price of the cementitious materials, excluding the cost of steel fibers. Fig. 11 presents the *cost index* for all UHPC mixtures normalized to the reference mixture (reference mixture). The 2-day compressive strength obtained under hot curing for those UHPC mixtures containing GP is also presented in Fig. 11(left).

The replacement of cement by GP led to a slight increase in the compressive strength up to the 20% replacement followed by slight decrease thereafter. However, a slight continuous decrease in the *cost index* can be observed with the augmentation of the replacement ratios. With the higher replacement ratios of QP by GP, a remarkable increase in the compressive strength and decrease of the *cost index* can be obtained as illustrated in Fig. 11(right). In addition, the transportation cost of materials could also be reduced when using locally available GP in the production of UHPC.

An intensive effort to replace crystalized QP by other safe and healthy material, due its health problems, is demanded by the Environment Canada and the International Agency for Research on Cancer. The current research offers the amorphous GP as a safe and healthy material to replace QP [58].

5. Conclusions

Sustainable ultra-high-performance glass concrete (UHPGC) has been developed through the use of glass powder. The glass powder was obtained from recycled glass cullets. The glass powder was used to replace cement and quartz powder in conventional UHPC. Typical UHPGC mixes were optimized using the compressible packing model. Based on the results obtained in our study, the following conclusions can be drawn:

- UHPGC can be designed with a ternary system of cement, glass powder, and silica fume.
- This UHPGC offers enhanced fresh behavior owing to its negligible water-absorption capability and smooth surface; the higher glass-powder content results in greater workability.
- Calorimetric analysis shows that replacing cement with GP reduces the maximum heat flow and total heat due to the dilution of cement in the concrete mixture. Replacing the quartz powder, however, didn't affect total heat. The replacement of cement of up to 20% with glass powder accelerated hydration kinetics. Beyond this level, hydration was delayed due to the dilution effect. Replacing the quartz powder accelerated hydration at every percentage of replacement.
- The BSC images of the reference, 80C/20GP, and 0QP/100GP subjected to hot curing for 48 h evidenced a C–S–H hydration rim forming around cement and GP particles. Partial separation of QP particles from the surrounding C–S–H phase was also observed.
- In terms of concrete compressive-strength development, the optimum replace of cement with glass powder was 20%, although 50% seems to be the optimum replacement with respect to flowability and sustainability. Compared to the reference, the mix with 50% glass powder exhibited 90% strength at 2 days under hot curing and 100% strength at 91 days under normal curing.
- Up to 100% of quartz powder can be replaced with glass powder and achieve compressive strengths up to 234 MPa after hot curing. Compared to the reference, the concrete with total quartz-powder replacement exhibited higher increases in compressive strength of about 12% and 17% at 56 and 91 days, respectively, under normal curing.
- More sustainable UHPGC can be produced when glass powder is used to replace both cement and quartz powder, such as in 80C20GP/0QP100GP, which recorded compressive strength, flexural strength, and modulus of elasticity of 220 MPa, 29 MPa, and 55 GPa, respectively. The total amount of glass powder used was about 400 kg/m³. The replacement of quartz powder and cement with glass powder can significantly reduce the cost of UHPC and decrease the carbon footprint of a typical UHPC. The cost for transporting materials could be reduced when UHPC is produced with glass powder available locally.

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