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Mechanical and durability properties of high performance glass fume concrete and mortars

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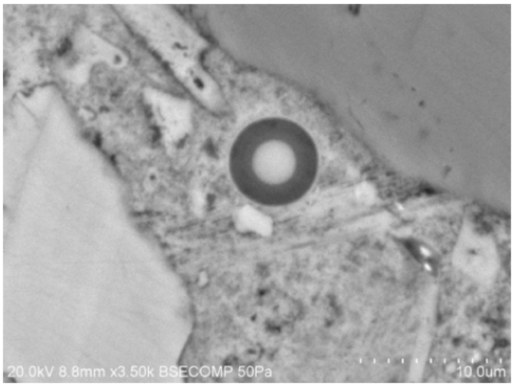
HIGHLIGHTS

- GF was produced with a complete spherical morphology with a 30–200 nm diameter.
- Comparatively to SF, GF improve the fresh properties of cement mortars.
- GF high-performance concrete (HPC) achieves comparable strengths to SF-HPC.
- GF reduces the alkalinity of the pore solution and densifies the cement paste.
- GF controls the chloride penetration, alkali-silica and sulfate attack expansions.

GRAPHICAL ABSTRACT



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ABSTRACT

Based on its high content in amorphous silica ($SiO_2 > 70$ wt.%), waste glass is an excellent material for valorization into pozzolanic nanoparticles or the so-called "glass fume" (GF). GF, produced using a scalable radiofrequency induction-coupled-plasma (RF ICP) spheroidization technology, mainly consists in an emulation of silica fume (SF) composed of spherical and amorphous silica-based nanoparticles (dia. of 30–200 nm). To test the impact of GF on the mechanical and durability properties of cement-based materials, compressive strength and rapid chloride ion penetration tests (RCPT) were conducted on high-performance concrete (HPC). Meanwhile, measurements of the resistances to alkali-silica reaction (ASR) and to sulfate attack were performed on mortar bars.

As SF, GF increased the compressive strength of HPC at early age (<7 days) by its nucleation and filler effects, but also its high alkali content (11–12 wt.%). At late age (>28 days), GF is characterized by a slower pozzolanic reactivity than SF. However, GF-contained HPC achieve similar compressive strength than SF-contained HPC after 91 days of curing.

At early age, GF-contained HPC and mortars yielded lower durability properties (RCPT, ASR and sulfate attack) than SF-contained HPC and mortars due to the slower pozzolanic reactivity of GF. In fact, they

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Abbreviations: AEA, air-entraining admixture; ASR, alkali-silica reaction; BET, Brunauer, Emmett, and Teller; BSE, backscattered electron mode; CH, portlandite; C/S, calcium over silica ratio; C-S-H, calcium silicate hydrates; EDS, energy dispersive spectroscopy; FEGSEM, field emission gun scanning electron microscopy; GF, glass fume; GP, glass powder; GU cement, general use Portland cement; HPC, high performance concrete; ITZ, interfacial transition zone; LOI, loss on ignition; PCA 1, polycarboxylate-type superplasticizer 1; PCA 2, polycarboxylate-type superplasticizer 2; PSD, particle-size distribution; RCPT, rapid chloride ion penetration test; RF ICP, radiofrequency induction-coupled-plasma; SA, sulfate attack; S/B, sand-to-binder ratio; SCM, supplementary cementitious materials; SF, silica fume; SP, superplasticizer; SSA, specific surface area; TEM, transmission electron microscopy; TGA, thermogravimetry analysis; VP-SEM, variable-pressure scanning electron microscopy; W/B, water-to-binder ratio; XRF, X-ray fluorescence.

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Plasma spheroidization
Glass powder

yielded similar durability properties compared to the plain cement HPC and mortars (control mixtures). At late age, the alkalinity of the pore solution is reduced and the cement paste is densified by the pozzolanic calcium silicates hydrates (C-S-H) and the durability properties are greatly improved with respect to a control HPC.

1. Introduction

High performance concrete (HPC) is widely used throughout the world for high strength and high durability applications: highway bridges, parking decks, marine structures and bridge deck overlays [1]. HPC is achieved by reducing the water-to-binder ratio (W/B) and porosity of the microstructure of the cement paste with supplementary cementitious materials (SCMs) [2]. Silica fume (SF) is mainly used as SCM for the production of HPC.

SF is a by-product of the silicon industry produced by plasma arc. It is a highly fine reactive amorphous and spheroidized mineral additive for cement, with an average particle diameter of 100 nm and a minimum silica content of 85% wt [3]. In addition to its pozzolanic reactivity, SF is well known for its filler effect and high pozzolanic reactivity due to its high fineness and high amorphous silica content [1]. Specifically, SF improves the concrete mechanical properties by its three roles: 1) pore-size refinement and matrix densification, 2) pozzolanic reaction with portlandite and 3) cement paste-aggregate interfacial refinement [1]. Although SF reduces the workability of concrete as a function of the level used in concrete [2,4–6], the improved concrete mechanical properties are linked to the production of pozzolanic calcium silicate hydrates (C-S-H), densification of the cement paste, reduction of the thickness of the cement paste-aggregate interfacial transition zone (ITZ).

Improvement in the mechanical properties influences the durability properties. Pozzolanic C-S-H are characterized by a lower calcium over silica ratio (C/S) than hydraulic C-S-H. This characteristic of the pozzolanic C-S-H give them more ability to fix alkalis from the pore solution than hydraulic C-S-H, reducing the potential drawbacks from the alkali-silica reaction (ASR) [7,8]. But, researchers specified that the reduction of ASR is not directly linked to the depletion of the portlandite (CH) content in the concrete, but on the content of alkalies in the pore solution [7,8]. However, when SF is used in a binary concrete-system, it rapidly binds the alkalies at early age, probably due to the similarities between the pozzolanic reaction and ASR, but can release these alkalies in the pore solution at late age for a possible exchange with the initial ASR products [7]. The densification of the cement paste and ITZ reduces the transport mechanisms within the concrete such as porosity, gas, chloride and sulfate permeability and diffusion, and improves the durability of HPC [1,9–11]. The resistance to sulfate attack is also reduced by the dilution of C_3A in the binder and the reduction of portlandite by the pozzolanic reaction, which can generate gypsum formation upon sulfate attack [12].

The use of silica fume is however limited due to its scarcity and high cost. In Quebec, about 200 million wine and spirits glass bottles are yearly deposited in recycle bins [13]. Recycling of waste glass is attractive to glass manufacturers, because it decreases the costs associated with raw materials, energy consumption and technological processes. Recycling also reduces landfilling. However, to recycle waste glass effectively within the glass industry, it must contain glass of similar composition, which has been separated from contaminants that can decrease the quality of new glass products [14]. Therefore, only clear bottles are currently recycled to reprocess new bottles, while the waste glass bottles are mostly colored. In addition to the environmental problematic, the cost of waste glass landfilling (50-125 CDN$ per tonne) is now becoming more expensive than that of its treatment (15-35 CDN$ per tonne) for recycling centers [15].

One great solution to valorize waste glass is to grind it to a fineness at the micrometric level slightly higher than that of cement. Replacing up to 50% of cement in mortar and in concrete by fine glass powder (GP) has shown to decrease expansion related to ASR [16–18] and permeability [19–21], and to produce cement-based materials with similar, even higher, mechanical properties than that of plain cement ones [19,20]. GP trigger a pozzolanic reaction that generates additional C-S-H gels densifying the cementitious matrix around the glass grains [14,18,20].

In the view to confer nucleation effect, activating and filler effect properties to waste glass, glass fume (GF) is being synthesized using the radiofrequency induction-coupled-plasma (RF ICP) spheroidization technology at the nanometric level [22] as a potential alternative to SF. The authors previously showed that GF, used as SCM, is able to develop similar early and late age strengths to SF in mortars [23]. At early age, these alkalis contained in GF (≈12 wt.%) are dissolved in the pore solution of cement-based materials during the first hours of hydration, activating the hydration of calcium silicates and calcium aluminate phases of cement. Because of its large SSA, the GF also plays the role of a nucleating agent. At late age, the amorphous silica of the GF reacted slowly with CH via the pozzolanic reaction. Above a threshold level of GF content in the mortars, an adequate amount of GF, depending on the W/B, reacted with CH to yield pozzolanic C-S-H, thereby yielding compressive strengths comparable to those obtained with the SF mortars [23].

In this paper, the authors present the impact GF vis-à-vis SF in mechanical and accelerated durability testing of laboratory scale-HPC and mortars. The effect of GF on the mechanical properties and on the permeability is tested on HPC cylinders. The impact of GF on the ASR and the resistance to sulfate attack is characterized on mortar bars.

2. Materials and methodology

2.1. Laboratory-scale plasma spheroïdization

GF is produced by the induction plasma spheroidization of glass powder (GP). GP possesses a random edged morphology with a particle size distribution (PSD) in the 1–100 μm range with a d_{50} of 12.3 μm [20,24,25]. Prior its spheroidization, GP is heated to 80 °C and sieved with 600 μm mesh to remove residual humidity and agglomeration. In Fig. 1, a powder feeder supplied GP into the injection probe of a laboratory-scale 50 kW RF ICP torch. The plasma torch is attached at the top extremity of a vertical stainless steel water-cooled cylindrical reactor. The high-temperature plasma flame (≈8000 K) initially vaporizes the GP, reducing it to nanoclusters. A cold gas annular quench at the tail of the plasma flame controls the coalescence and coagulation of the nanoclusters into glass nanodroplets. Downstream, these nanodroplets traveled through a colder temperature region in the reactor chamber where the GF was formed. The filter consists of 4 porous metal cylinders to separate the particles from the exhaust gas stream [22]. As for