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Long-term performance of glass-powder concrete in large-scale field applications

Ahmed F. Omran [a,b,*], Etienne D.-Morin [a], David Harbec [a], Arezki Tagnit-Hamou [a]

[a] Dept. of Civil Eng., Université de Sherbrooke, Canada
[b] Dept. of Civil Eng., Faculty of Engineering, University of Minoufiya, Egypt

HIGHLIGHTS

- Using glass powder in concrete reduces its landfills, and concrete cost and footprint.
- Glass powder enhances mechanical properties at later age due to its pozzolanic activity.
- Glass powder improves pore structure and durability of concrete.
- Glass powder reduces significantly chloride-ion penetrability of concrete.

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ABSTRACT

Development of local alternative supplementary-cementitious materials (ASCM) such as ground mixed-waste glass is demanded especially when other ASCM are not locally available or costly. The promising performance of glass powder (GP) in concrete mixtures in laboratory scale motivated the current study that focussed on presenting the long-term performance of GP-concrete in large-scale field applications. The evaluated structural elements (constructed between 2006 and 2011) included interior and exterior slabs and walls. The results of core samples extracted from the structural elements after several years of exposure were compared to the laboratory-cured samples taken at the time of casting. The 6.7-year core results showed a continuous improvement in the mechanical performance and resistance chloride-ion penetration of the GP concrete due to its pozzolanic reactivity. The water absorption of and porosity were also decreased obtained when using GP due to the microstructure densification.

1. Introduction

The finely ground (38–45 μm) glass powder (GP) with high silica content ($SiO_2 > 70\%$), high surface area, and amorphous nature suggest that GP could perform as an alternative supplementary cementitious material (ASCM) to partially replace cement in concrete [1–4]. The GP was successfully employed in laboratory in concrete mixtures as an ASCM to partially replace cement with percentages of up to 30% [5–16]. These studies have shown beneficial effects when using GP as an ASCM, including increased workability and reduced chloride-ion permeability. The GP provides an additional advantage by demonstrating pozzolanic activity, in which the amorphous silica (SiO_2) in the GP reacts with the portlandite [$Ca(OH)_2$], generated during cement hydration, and forms gels of calcium silicate hydrate (C-S-H) [14–17]. This pozzolanic reactivity is directly linked to the fineness of the GP. Fine GP particle with diameters of about 88% lower than 10 μand only 12% greater than 15 μm was used by [15] while GP with mean-particle diameter (d_{50}) about 22 μm was used in [16] to secure the pozzolanic reaction of the GP. Concrete containing GP (with Blaine surface area of 440 m^2/kg) was also used to produce reinforced-concrete columns and resulted in strength capacity increase due to the pozzolanic reactivity of the GP [18,19]. Recently, the GP with d_{50} of about 12 μm was used as a partial substitution of cement and quartz powder to develop new ultra-high-strength concrete with compressive strength exceeding 250 MPa [20].

In order for the concrete made with GP as partial replacement of cement to comply with the new practical guidelines of the CSA A3000-E1 "Standard practice for the evaluation of alternative supplementary cementing materials (ASCM) for use in concrete", the performance of the GP concrete must be evaluated on construction

* Corresponding author at: 2500, Boul. de l'Université, Sherbrooke, QC J1K 2R1, Canada.
E-mail addresses: A.Omran@USherbrooke.ca (A.F. Omran), Etienne.Dumas.Morin@USherbrooke.ca (E. D.-Morin), David.Harbec@USherbrooke.ca (D. Harbec), A.Tagnit@USherbrooke.ca (A. Tagnit-Hamou).

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field sites for a long term. The GP concretes were used to cast various structure elements in Quebec-Canada between 2006 and 2011. The performance of samples taken from these concretes and subjected to ideal laboratory curing are presented in [21,22]. The results showed improved mechanical and durability properties compared to the reference mixtures. However, it should be mentioned that these concrete samples were not representative to those used in field in terms of consolidation, finishing, or curing conditions. Limited investigations were found in literature regarding the behaviour of GP concrete in field projects under long term. Only the study of Shayan and Xu [15] that carried out on 10 on-ground slabs (1.5 × 2.5 × 0.25 m) with 40 MPa concrete mixtures containing GP as a cement replacement in combination with glass aggregates as natural sand replacement. The results indicated that both GP and glass aggregate can be used together without adverse reaction (for example, on the expansion from alkali-silica reaction, ASR), and can provide considerable economic and environmental benefits to the community. At 404 days, concrete mixtures containing 30% GP replacement exceeded the target strength and reached 55 MPa. However, the core-cuts from the slab showed lower strength than the laboratory-cured samples, which has been attributed to less efficient curing and compaction in field. Therefore, further results on the performance and durability of GP concrete in field projects (different structural elements) under various environmental conditions are still needed for the wide acceptance of GP concrete.

The current research aimed at evaluating the performance of GP concrete (with replacement ratios between 10% and 30% by cement content) used in various structural elements including, interior slabs, exterior slabs (sidewalks), and structural wall elements in various environmental conditions – indoors and outdoors). A long-term evaluation of the GP-concrete performances were conducted by testing core samples (between August 2013 and Feb 2016) extracted from four field sites that were previously constructed in Quebec-Canada between 2006 and 2011. The performance of the core samples that were exposed to different environmental and service conditions were compared to the concrete performances that were initially sampled and cured in optimal laboratory conditions at the time of casting. The microstructure analysis on all concrete cores were also presented and correlated to the concrete performance. The available equations in the guidelines and Standards for predicting the mechanical performance of GP concrete were applied and compared to the measured values.

2. Experimental program

The research includes full characterization of different concrete mixtures containing GP (obtained from ground bottle glass of mixed colors) that were used to cast various structural elements (slabs, sidewalks, and walls) exposed to different environmental conditions (indoors and outdoors). Photos for these field projects are illustrated in [22]. The details of these projects are given below.

2.1. Interior slabs

(A) Two on-ground slabs were cast at the branch of *Société des alcools du Québec* (SAQ) in Rivière des Prairies with concrete having 20% GP as a partial replacement of cement (SAQ-GP) and a reference mixture without GP (SAQ-Ref) on December 20, 2006 by concrete producer A. A drilling machine was used to extract 100-mm diameter core samples on August 20, 2013, at the age of 6.7 years. Small concrete batch with a mix design similar to the original concrete used in the slab casting was prepared to fill the holes created by cores, and then the surface of concrete was finished after concrete hardening.

(B) Two reinforced-on-ground slabs at *La Maison du développement durable* [The Center for Sustainable Development (CSD) in Montréal]. The CSD was developed as a showcase of Québec's expertise in the field of sustainable development and awarded LEED Canada NC Platinum certification. A slab was poured with GP concrete (CSD-Int.Slab.GP) in the center's conference lobby and compared to a slab cast in a storage room with concrete without GP to serve as a reference (CSD-Int.Slab.Ref). The CSD-Int.Slab.Ref and CSD-Int.Slab.GP slabs were cast on October 26 and December 3, 2010, respectively. Concrete producer B supplied the two concrete mixtures. Before taking cores on September 5, 2013 (ages of 2.9 and 2.8 years, respectively), the two slabs were subjected to radar scanning to avoid any wire or steel cut that might be imbedded in the slabs.

(C) Two slabs at the Integrated Research Laboratory on Materials Valorization and Innovative and Durable Structures at the University of Sherbrooke (UofS) in Sherbrooke, Quebec. During the laboratory's construction, two interior on-ground reinforced slabs were poured with concrete of a ternary binder. Type GUb-SF cement with 20% GP for one slab (UofS-GP) and with 20% class F fly ash for the other (UofS-FA). Each slab measured 3.7 m × 5.3 m with a thickness of 0.20 m. The concretes were batched and cast by concrete producer C on December 20, 2007. To investigate the performance of these slabs after long lifetime, core-cuts were taken from these slabs on July 9, 2014 (age of 6.6 years). Before taking cores, the slabs were scanned by radar scanner to avoid any destruction of wires or steel bars that might be imbedded in the concrete.

2.2. Exterior sidewalks

Two sidewalk sections on Saint Catherine Street (in front of the CSD building in Montréal)—one without GP (CSD-Ext.Sdk.Ref), to serve as a reference, and with GP (CSD-Ext.Sdk.GP)—were cast on October 26, 2010 and February 15, 2011, respectively. Over the course of a year, the temperature typically varies from −14 to +26 °C and the relative humidity typically ranges from 37% to 89%. Concrete producer B supplied the concrete for CSD-Ext.Sdk. GP mixture and concrete producer C provided the CSD-Ext.Sdk. Ref. The two sidewalks were cored at ages of 2.6 and 2.9 years, respectively.

2.3. Exterior structural walls

During the construction of the Tricentris recycling plant in Gatineau (Tri-Gat), two reinforced-concrete wall panels (4 m in height and 0.20 m in thickness) were selected for casting with GP concrete. The GP was used to replace 10% of Type GU cement for Wall 1 (Tri-Gat-Wall#1-10%GP) and 30% for Wall 2 (Tri-Gat-Wall#2-30% GP). The two GP concrete walls were compared to a reference wall with only GU cement (Tri-Gat-Wall#3-Ref.). The three walls were poured on September 23, 2011; concrete producer A provided the concrete. Over the course of a year, the temperature typically varies from −16 to +26 °C and the relative humidity typically ranges from 41% to 99%. The coring of the three walls were carried out on October 23, 2013 (age of 2.1 years) and on Februray 24 2016 (age of 4.4 years). Radar scanning was also conducted on the surface of the three walls before coring to avoid reinforcing bars cut. The drilling machine was positioned in horizontal direction.

The core samples extracted from the interior slabs, exterior slabs/sidewalks, and structural wall elements in the four field sites (SAQ, CSD, Tri-Gat, and UofS projects) were used to determine the concrete characteristics after certain periods in service. The cores were 100 mm in diameter and lengths ranging between 150 and