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Production of roller-compacted concrete using glass powder: Field study

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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 roller-compacted concrete (RCC) caused major shift in construction practice of mass concrete and pavement slabs. Large amounts of mineral admixtures (fly ash, slag, and natural pozzolan) are used in RCC to reduce both adiabatic temperature rise of concrete and costs, and improves durability. Mixed-colored glass, which cannot be recycled, is sent to landfills causing obvious environmental problems. So valorization of this glass when grounded to same cement fineness can be used as an alternative supplementary-cementitious material (ASCM) in concrete, especially it demonstrates pozzolanic behavior. This study presents mechanical and durability aspects of using glass powder (GP) to replace 20% of cement content in RCC used for interior and exterior slab-on-ground during construction of Tricentris plant in Lachute-QC/Canada. However, the results of GP-RCC showed slight lower 7-day strength compared to control, increases of 15% in flexural strength and 5% in compressive strength were obtained at 91 days. The resistance to freeze-thaw cycles was also improved. Scanning electron microscopy (SEM) observations showed that the properties of RCC are directly linked to the effectiveness of the compaction operation. The addition of GP yields a higher degree of cement hydration and enables to densify the C-S-H.

1. Introduction

The roller-compacted concrete (RCC) differs from conventional concrete principally in its consistency requirement. The ACI 207.5R-11 [1] defines the RCC as concrete compacted by roller compaction. The RCC mixture in its unhardened state must support a roller while being compacted. The RCC is a zero-slump concrete whose properties are strongly dependent on the mixture proportions and on the quality of compaction. Concrete is consolidated in the field using vibrating rollers. For effective consolidation, the RCC mixture must be dry enough to prevent sinking of the vibratory roller equipment but wet enough to permit adequate distribution of the binder mortar in concrete during the mixing and vibratory compaction operations [2].

The first successful application of RCC technology was demonstrated in 1974. The repair of the collapsed intake tunnel of Tarbela Dam proved that the material had more than adequate strength and durability. The maximum placement of 18,000 m^3 of RCC in one day, which is still the world's record, was a clear evidence of the potential of this new construction method. By 1997, 150 projects using RCC, including 46 new dams, were completed in the United States [2].

The RCC development caused a major shift in the construction practice of mass concrete such as in dams, because the traditional method of placing, compacting, and consolidating of mass concrete is a slow process. The use of RCC in mass concrete made the construction of earth and rock-filled dams speedier and, therefore, more cost-effective. For large projects, RCC dams can be finished

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1–2 years earlier compared to regular mass concrete dams. Depending on the complexity of the structure, RCC costs 25%–50% less than conventional concrete. Pipe cooling is unnecessary because of the low temperature rise associated with the RCC. The RCC is placed by the layer method, leading to lower formwork costs [3].

In addition to economic benefits, the RCC is considered as a “green” concrete because the cement consumption in the RCC is lower as the RCC mixtures are normally designed with leaner binder content. Mineral admixtures are used extensively in RCC mixtures. The use of large amounts of mineral admixtures improves durability, reduce adiabatic temperature rise of concrete, construction costs, and gas emission accompanied with the manufacturing of cement clinker. Class F and Class C fly ashes, slag, and natural pozzolan have been used as mineral admixtures in the RCC [4].

Coarse aggregate size has a significant influence on the degree of RCC compaction in small layers and less effect in relatively thicker layers especially when large vibratory rollers are employed. The coarse aggregates with maximum-size diameter greater than 76 mm are seldom used in the RCC manufacturing because they cause problems in the layers spreading and compaction. However, the use of coarse aggregates with maximum-size diameter finer than 75 mm reduces the volume of voids and produces more cohesive mixture. In RCC mixtures of dry consistency, the chemical admixtures have limited effectiveness. The Air-entraining and water-reducing admixtures are used in the RCC compositions that contain higher volume of paste. Set-retarding admixtures can be also employed in the RCC mixtures to extend the time up to which the concrete lift should remain unhardened, reducing the risk of cold joints with the subsequence lift [2].

Mixed-colored glass, which cannot be recycled, is normally landfilled causing obvious environmental problems. So valorization of this glass when grounded to same fineness of cement can be used in concrete. The ground glass is called “*glass powder* (GP)” [5,6]. The high silica content ($SiO_2 > 70\%$), high surface area, and amorphous nature of the GP suggests that the GP could perform as an alternative supplementary-cementitious material (ASCM) to replace a portion of the cement in concrete. This would reduce the cement production that is commonly costly and natural resources’ consumer, as well as it has negative effects on environmental conditions through CO_2 emission and greenhouse effect [6]. The GP gives additional advantage by demonstrating pozzolanic activity, where 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 (CSH).

Shao et al. [6] investigated the pozzolanic activity and strength of concrete made with 30% replacement of cement by GP of particle sizes of 150, 75, and 38 μm, silica fume (SF), and fly ash (FA). It was concluded that the mixtures with 75 and 38 μm GP achieved strength similar to that contains FA [6]. The GP was employed in concrete mixtures to partially replace cement by Tagnit-Hamou and his co-workers with percentages up to 25% [7–11]. Several studies have shown the beneficial effects, including increased workability and reduced chloride-ion permeability when using GP as an ASCM [12–15].

In the frame of searching for new ASCM, three slabs-on-ground were constructed with RCC (two slabs incorporating GP and one reference slab without GP) at Tricentris center in Lachute/QC/Canada. The GP was used to replace 20% of cement content in RCC mixture for indoor and outdoor slabs. This study presents the mechanical and durability aspects of the RCC made with and without GP used to cast these slabs. The construction took place July 12th, 2013. This case study presents also the environmental effect (indoors vs. outdoors weathering conditions) on the performance of RCC slabs made with GP. The three slabs were subjected to further testing on core samples taken from the slabs after an age of 1.18 years (on September 16th, 2014), as also highlighted in this research.

2. Description of field site and experimental program

Tricentris is a major recyclable material company in Quebec/Canada, constructed in 1998, and can treat up to 72,000 tons of recycle materials per year. Tricentris has built micronization plant in Lachute/Quebec/Canada inaugurated in 2014, where the crushed wine glass bottles of mixed colors can be transformed into coarse glass aggregates, glass sand, and GP with approximately same fineness of Portland cement. During the construction of the company’s facility in Lachute, three slabs-on-ground were selected to be cast with RCC: two of them containing GP. The GP was used as a partial replacement of Type general use (GU) cement by 20% in an interior (Int.GP) and exterior (Ext.GP) slabs. The two GP slabs were compared to a reference slab without GP (Int.Ref.), as shown in Fig. 1. The concrete was cast on July 12th 2013 and was delivered by one of the specialist plants in making the RCC.

To follow the evolution of deformation and temperature changes of the RCC with time, each of the three slabs (Int.Ref, int. GP, and Ext.GP) was instrumented with one vibrating wire gauge and connected to a data acquisition system.

3. Mixture proportions of roller-compacted concrete

Faubert [16] studied the effect of cement replacement by 10%–25% GP on overall performance of RCC made with water-to-cementitious materials ratio (*w*/*cm*) of 0.32 and 0.37. The RCC made with *w*/*cm* of 0.37 and 10%, 15%, and 20% GP replacements showed better or at least similar 91-days compressive strength (f_c) compared to the reference concrete without GP. The respective values for the 10%, 15%, and 20% GP replacements were 55.2, 57.7, and 54.2 MPa compared to 55.5 MPa for the reference concrete without GP. When the GP replacement increased to 25%, the f_c dropped to 51.8 MPa. Similar enhancements in the splitting-tensile and flexural strength results were observed with the GP replacement up to 20% before a drop in the performance with the 25% GP replacement. This study demonstrated that the GP can replace partially the cement in the RCC up to 20% with affecting the mechanical performance of concrete.

Based on the study of Faubert [16], two RCC mixture compositions with *w*/*cm* of 0.37 were proposed by the research team to the concrete producer for the slab casting: one without GP serving as a reference (Int.Ref.) and one containing 20% GP as a partial cement replacement for the exterior and interior slabs (Ext.GP and Int.GP, respectively). During the placement, more water was added by the concrete manufacture, so the final *w*/*cm* reached 0.43. The final RCC mix designs after the water modification by the concrete manufacture that were used in the slab casting are presented in Table 1.

The target 28-days f_c is 40 MPa and flexural strength (*fl*) is 5.5 MPa, respectively. The table show also the target ranges for the unit weight of concrete mixtures.

4. Sequence of RCC placement in field

A specialist concrete plant for producing the RCC in Quebec has moved and installed its mobile plant at the Tricentris factory in Lachute (Fig. 2) for batching the RCC for the current three slabs. The Factory floor was leveled using foundation aggregates before concrete placement. After batching, the RCC was transported using trucks to an asphalt-paver which used in placement of the RCC. A steel-drum vibratory roller compactor was used to compact the RCC and finishing the concrete surface (Fig. 2).