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Field trials with concrete incorporating biomass-fly ash

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HIGHLIGHTS

- Using biomass-fly ash (BFA) in concrete reduces its landfills, concrete cost, and footprint.
- The use of BFA in concrete densifies concrete microstructure especially with age.
- BFA leads to higher mechanical strength and durability properties.
- A significant reduction in pore system and permeability can be observed for BFA concrete.
- With a given air-bubbles distribution, the BFA concrete shows excellent frost resistance.

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ABSTRACT

The global cement industry contributes about 5% of carbon dioxide emission to the atmosphere, which affects greenhouse-gas emission. To address the environmental effects associated with cement manufacturing and constantly reducing natural resources, there is a necessity to develop alternative supplementary cementitious materials (ASCM) to secure sustainable concrete. Many industrial by-products such as fly ash have been employed over decades to partially substitute cement in concrete with more economic and durable concrete mixtures. Given the lack of the traditional fly ash in the near future due to the strategy of closing the coal-based electricity power plants all over the world, biomass-fly ash (a by-product of combustion of de-inking sludge, bark, and residues of woods in fluidized-bed system) can be an alternative.

After successful use of biomass-fly ash as partial replacement of cement in concrete in laboratory experiments, the current research presents its long-term in-situ performance using full-scale concrete structural elements. The biomass-ash is used to replace 15%–25% of cement in normal- and fiber-reinforced concretes used for casting external and internal slabs as well as sidewalks.

The results showed the possibility of using biomass-fly ash as a cement replacement with a higher mechanical strength than the reference concrete made only with Portland cement especially at an age beyond 91 days. The concrete incorporated 20% biomass-fly ash decreased the permeability, and resulted in excellent resistance to freezing-thawing and de-icing salt scaling deterioration.

1. Introduction

The biomass-fly ash (BFA) is a by-product pulp and paper industry resulting from the combustion of biomass wastes in a cogeneration plant. It allows reducing (by 40–50%) the volume to bury the primary and secondary sludge from their wastewater, the deinking sludge from chemical treatment, bark, and wood waste, including construction and demolition materials from sorting centers [1,2]. However, the inorganic components of biomass represent about 5% for the wood, 15% for the primary and secondary sludge, and 40% of the deinking sludge so that its combustion generates a significant and problematic amount of ashes. The BFA has a wide range of particle sizes and physicochemical properties as their physicochemical and mineralogical characteristics vary according to the heat treatment, the composition of the sludge and the rate of cooling [2–12]. The BFA was characterized and used since the late 90 s as a cementitious material in laboratory studies on mortar and concrete mixtures [1–16]. For example, recent studies of Xie and Davidenko [9,12] have shown that a cementitious binder with

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up to 20% of BFA can satisfy the strength activity index (SAI) required by the ASTM C618 [18]. They reached 7-day SAI ranging between 0.80 and 0.95, which was significantly greater than the 0.75 Standard limit. They referred this improvement in the SAI to that fact that the BFA leads to a denser and less permeable cement matrix when using the BFA as partial cement replacement [9,12]. However, Roby [7] monitored about 58% decrease in the compressive strength (f_c) when incorporating BFA in normal concrete mixtures with a water-to-binder ratio (*w/b*) of 0.40, given that fact that the concrete exhibited about 22% increase in the 91-day permeability. Part of the decrease in the mechanical resistance was attributed to the early development of a highly porous paste with a coarse structure mainly due to the expansive nature of the hydration products [6,8,9]. Lessard et al. [14–16] used the BFA in laboratory and field study to produce dry concrete (roller-compacted and paver-compacted concrete). They observed a significant reduction in the f_c, attributing to an early development of a highly porous paste with a coarse structure due to the expansive nature of the hydration products of BFA used by them. As a conclusion, the BFA and cement interactions are difficult to predict, however, improved mechanical strength and durability results can be possibly obtained when the incineration process and the source of raw materials are well controlled.

In accordance with the Practical Guide of CSA A3004-E1 "Standard practice for the evaluation of alternative supplementary cementing materials (ASCMs) for use in concrete" [17], the laboratory results should be evaluated on real structures. The field assessment of BFA concrete using large-scale field projects are necessary to evaluate the performance of BFA concrete exposed to various environmental and weathering conditions. Limited researches have been conducted regarding the use of BFA concrete in field study.

After the successful use of the BFA in laboratory studies in various cement-based mixtures (cement paste, mortar, and concrete) by Xie [9] and Davidenko [12], the current research presents a following step of using certain optimized BFA concrete mixtures in laboratory for casting different full-scale structural elements in field. The structural elements included outdoors and indoor slabs, and sidewalks. The BFA concretes were fully characterized at the time of casting by taking samples and tested after different ages of laboratory curing. The performance of the BFA concrete structures were also assessed at the long-term by testing core-cut samples from these concrete structures after certain periods of exposure to the surrounding environmental conditions.

2. Experimental program

2.1. Testing program and test methods

The first projects evolved two exterior slabs at Kruger Mill in Bromptonville/Quebec that were cast on August 9th 2007 with normal concrete mixtures (S.Ex.N-REF, S.Ex.N-BFA) (Fig. 1A). The S.Ex.N-BFA mixture included 25% BFA as cement replacement, while the S.Ex.N-REF mixture with only Portland cement served as a reference (Table 1). The 25% replacement ratio was selected in consideration of both mechanical and durability properties carried out in a previous laboratory investigation by Xie [6]. The two concrete mixtures were produced by Carrières de St-Dominique Ltée and placed and finished by workers from Kruger Mill. The latter worker had limited experience regarding the concrete placement and finishing. At the time of casting, in addition to the fresh properties, the concrete mixtures were sampled for the mechanical and durability properties. These tests were conducted at different concrete ages subjecting to laboratory curing. The two slabs were cored on February 15th 2008 (age of 190 days) and on January 15th 2014 (age of 2351 days) for further investigation of the concrete performance after long-term of in-situ service. The tests performed on laboratory-cured and core-cut specimens are summarized in Table 2.

The second project included casting an exterior slab in the courtyard of the Bellemare factory in Trois-Rivières/Quebec with a total area of 384 m^2 and a thickness of 0.15 m (about 60 m^3 of concrete) on October 12th 2011. The slab was designed to serve as a bench area for the heavy load trucks. The construction site and its shape are shown in Fig. 1B. A fiber-reinforced concrete with 20% BFA substitution of portland cement (S.Ex.F) (Table 1) was used for the slab casting. The mixing and transportation of concrete were conducted by Thomas Bellemare Ltée Group. Samples were taken at the casting time and tested after laboratory curing at different ages up to one year. Cores were taken from the slab on May 8th 2014 (age of 1271 days) for assessing the concrete performance after exposing to the environmental condition. Table 2 summarizes the tests performed on the laboratory-cured and cores samples.

The third project was a sidewalk in Louisville (Québec) with a total surface area of about 13 m^2 and a thickness of 0.15 m (about 2 m^3 of concrete) on November 2nd 2011. A normal concrete with 20% BFA was incorporated in place of portland cement (Sdk.N), as indicated in Table 1. The concrete mixture is similar to the S.Ex.F mixture, expect for the inclusion of fiber and superplasticizer dosage. The site during construction is shown in Fig. 1C. Thomas Bellemare Ltée Group was in charge of making and placing the concrete. The concrete was characterized by taking samples at the time of casting and test it at different ages after laboratory curing according to the schedule in Table 2. For technical reasons, it was difficult to take core samples from these sidewalks after casting.

The fourth project included casting an interior slab (S.In.N) in the office area at Kruger Mill in Trois-Rivières with a normal concrete containing 15% BFA as a cement replacement. The concrete was provided and placed by Béton Crete on April 29th 2014. The concrete was tested at time of casting and also by taking core samples at early age of 9 days (on May 8th 2014). Fig. 1D presents photos for this project.

2.2. Concrete mixtures

The design of the concrete mixtures used for the casting of the various projects are shown in Table 1. The water-to-binder ratio (*w/b*) of 0.40 was used for all concrete mixtures, except for the S.In.N mixture that was designed with *w/b* of 0.39. The BFA was used to replace 15%–25% of Type GU cement. As shown in the table, the mixtures designed with BFA required higher dosage of high-range-water-reducing admixture (HRWRA) than that of the control due to the fine BFA particles. Polycarboxylate (PCE)-based HRWRA (HRWRA1) with a specific gravity of 1.07 and solid content of 32% was used for all concrete mixtures, except for the S.In.N mixture that was designed with naphthalene sulfonated (NS)-based HRWRA (HRWRA2) with a specific gravity of 1.19. In addition to the HRWRA2, the S.Ex.F and Sdk.N mixtures contained a commercial mid-range water reducer (WRA) with a dosage rate of 960 and 300 ml/100 kg of cement, respectively. Three air-entraining agents (AEAs) were incorporated in the mixtures design to secure given entrapped air: AEA1 for S.Ex.N-REF and S.Ex.N-BFA mixtures, AEA2 for S.Ex.F and Sdk.N mixtures, while AEA3 for S.In.N mixture. The specific gravity values for the three AEAs were 1.007, 1.013, and 1.050, respectively. A 0.45% Tuf-Strand synthetic macro fiber was used for the S.Ex.F mixture.

2.3. Material properties

Table 3 presents the physical properties and chemical composition of BFA used in various projects, compared to the Standard limits for the fly ashes classes C and F as well as the Portland cement. The high content of calcium oxide (more than 35%) under hydraulic phases such as anhydrite, gypsum, and free lime suggested that the BFA could have potential hydraulic properties to be further amplified by the reactivity of its crystalline and glassy calcium-aluminate phases [9]. The sum of aluminum oxide, iron oxide, and silica (the main elements responsible of pozzolanic reactions when having amorphous form) in the BFA is more than 35%, which was lower than other classical mineral admixtures (50%).

The BFA particles are porous and mainly angular with rough textures, with few spherical of smooth surfaces, as illustrated in micrograph (Fig. 2A). Black carbon can also be detected. The XRD diffraction pattern for the BFA (Fig. 2B) reveals that it could be distinguished as crystalline forms because of its close and distinctive peaks. The figure shows a complex mineralogical composition composed of anhydrite, quartz, calcite, free lime, anorthite, gelignite, tricalcium aluminate (C_3A), Portlandite, and gypsum. The ternary phase diagram (SiO_2, Al_2O_3, and CaO), for the BFA compared to other cementing materials are presented in Fig. 3.

3. Results and discussion

3.1. Fresh concrete properties

As soon as the concrete trucks arrived at the construction site (approximately 0.5 to 1.0 h after mixing), the fresh concrete properties were evaluated. The results are summarized in Table 4. The slump and air content results satisfied the target requirements. The target air contents was 5–8%, the slump for the S.Ex.N-REF and S.Ex.N-BFA slabs was 220 ± 30 mm, while for the other three remaining slabs was 120 ± 30 mm. The slabs in Bromptonville were cast in August in a day of high temperature (ambient temperature of