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The influence of high volume of fly ash and slag on the compressive strength of self-consolidating concrete

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ABSTRACT

This research seeks to optimize the sustainability aspect of a self-consolidating concrete (SCC) for structural applications by maximizing supplementary cementitious material (SCM) content.

Four supplementary cementitious materials were used: two fly ash and two slag. Twenty-one mixes were made with 0–100% Portland cement replaced with SCMs.

Early age compressive strength development of the SCM mixtures was normally less than the control (only Portland cement). At higher replacement levels, performance varied significantly based on the SCM used.

Bolomey and Féret strength equations were used to evaluate the SCM's efficiency. Reasonable agreement between binder's $CaO/(SiO_2 + Al_2O_3)$ ratio and the efficiency factor was observed.

1. Introduction

Cement production is one of the major sources of CO_2 emissions in the world. According to the European Cement Association, cement production was responsible for 2.83 billion tons of CO_2 emissions (roughly 2.3% of the total emissions) worldwide in 2008 [1]. Portland cement has so far been the primary content in the binder of concrete. Therefore, concrete's carbon footprint can be significantly reduced by lowering the amount of cement in the binder [2,3]. Materials that are commonly used as cement replacement in concrete are fly ash and slag.

Slag can be used in large quantities as a supplementary cementitious material (SCM) because of its inherent cementitious (hydraulic) properties. Fly ash, however, has limited hydraulic properties because the amount of calcium oxide in the binder is usually low [4]. Even so, a concrete with 100% Class C fly ash for binder was used in a commercial cast-in-place application. This concrete was used in the foundation walls and footings, the floor slab, two structural load-bearing beams, and various nonstructural elements such as architectural panels. The structure has now been operational for over a year [5].

When properly used, SCMs can improve the fresh and hardened state properties of concrete. At lowers replacement levels (less than 40%), fly ash usually improves the workability of fresh concrete because the fly ash particles are more spherically shaped than cement, resulting in less water demand [4]. However, concrete containing SCMs tends to have slower strength development especially at high cement replacement rates, since the Portland cement reaction (hydraulic) is much faster than the SCM reaction. The pozzolanic reaction can only take place if there is available calcium hydroxide, a by-product of the hydraulic reaction. The pozzolanic reaction can thus only happen after the hydraulic reaction.

A considerable amount of research has been done on concrete, which contains SCMs as partial cement replacement. Some researchers have proposed strength equations for concrete containing SCM by using activation energy, which is the least amount of energy needed for a chemical reaction to take place [6]. Others have tried to link the compressive strength to the SCM's fineness and the amount of CaO, loss of ignition, and ratio of potassium to alumina [7]. Most researchers have looked for the optimum amount of SCM in concrete so nearly all of the SCM is reacting, to obtain maximum strength [8,9]. A number of researchers have suggested using efficiency factor to calculate the maximum strength from the SCM [10–15]. Most studies focus on the use of fly ash, although slag has also been investigated. Fly ash has been investigated more frequently in part because there is more fly ash available. Additionally, the fly ash chemical composition is

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dependent on the coal or raw material that used in the plant and the operating conditions dictate the physical properties of the ash, such as the particle size. Regardless of the SCM used, typical replacement levels used in prior research are between 20% and 50%, and rarely exceed 70%.

The aim of this research is to minimize Portland cement content, and therefore embedded carbon content, of a self-consolidating concrete (SCC) for structural applications by maximizing SCM content. SCC has advantages in reinforced concrete and composite construction by facilitating rapid construction. Possible composite components include concrete filled tubes for structural columns and dual skin composite shear walls to resist gravity and seismic loadings. A further advantage of using a high-volume SCM concrete in these applications is that early strength is not required from the concrete, since the steel jacket is capable of supporting the initial construction loads and formwork is not removed (as would be required for a reinforced concrete component). Therefore, concrete containing high volume of SCM can be more readily used in composite construction, even though a low early strength ($\leqslant$14 days) is often associated with such concrete.

2. Research significance

This research focuses more on the strength development behavior of SCC with high volume ($\geqslant$60% replacement) of fly ash (FA) and slag (SL), rather than maximizing strength. It is not necessary that all the SCM reacts with water; some can serve as an inert filler, if the strength is sufficient. This research examines also the correlation between replacement, compressive strength and SCM's chemical compositions.

Twenty binary mixes (cement and one SCM) were made with 20%, 40%, 60%, 80% and 100% cement replacement. One control mix was established with only Portland cement. All of the mixes were made with locally available materials with proportions of admixture, aggregate, sand, water and binder that are typical for SCC on a construction site in the Pacific Northwest of the United States.

3. Materials and test procedure

3.1. Materials

Properties of the Portland cement and the SCMs used in this research are given in Table 1. The cement used was ASTM I Portland Lafarge Cement [16]. Two blast furnace slags (Seattle SL and St. Mary's SL) were used in the binary mixes. Both slags were classified as grade 100 [17,18]. Two sources of fly ash (Boardman FA and Centralia FA) were used in the binary mixes. The Canadian standard [19] classifies the Boardman FA and the Centralia FA as class CH (high calcium content) and class CI (Intermediate calcium content), respectively. According to ASTM C 618 the Boardman FA is classified as Class C fly ash and the Centralia is classified as Class F fly ash [20].

Table 1 presents the active silica values for the SCMs in this research. According to European Standard EN 197-1 [21], active silica is defined as the fraction of the silicon dioxide that is soluble after treatment with hydrochloric acid and with boiling potassium hydroxide solution. The European Standard EN 196-2 [22] was used to determine the active silica contents of all SCMs used in this research. Both SL have almost all the silica active (98–99%) whereas the FA has less active silica (70–79%). These results were expected since SL that is suitable for concrete is usually more reactive than FA and can be used at higher cement replacement levels.

The activity index (AI) [18,20], which is also given in Table 1, is measured by testing a compressive strength of mortar with SCM replacement and compared to a control with 100% Portland cement at days 7 and 28. Twenty percent replacement is used to determine AI of FA and 50% replacement is used to determine AI of SL. The AI shows less noticeable difference between SL and FA. The active silica test might give better indication how reactive SCM is compared to the AI. Particularly at high replacement levels (60–100%) where the pozzolanic reaction will depend on available calcium hydroxide, whereas the AI is limited to only 20% and 50% replacement levels for FA and SL, respectively.

3.2. Specimens preparation and curing

A total of 21 mixtures were cast: one control and 20 binary mixtures. The control mix design was as follows: 474 kg/m^3 Type I cement (LaFarge), 168 kg/m^3 water, 807 kg/m^3 sand (river sand, SG = 2.57), 820 kg/m^3 coarse aggregate (9.53 mm diameter, SG = 2.59) and 1.69 L/m^3 combination accelerator–superplasticizer–viscosity modifying chemical admixture (SIKA ViscoCrete 2100). Cement replacements occurred according to weight with the sand amount adjusted as needed to achieve the unit weight.

Samples were mixed in a rotary drum mixer. First, the dry ingredients (coarse aggregate, sand, cement and SCM, if applicable) were combined. Next, the wet ingredients (water and chemical admixture) were added and the ingredients were mixed until a homogeneous mixture was achieved. As needed, a small amount of additional water was added to control the rheology of the mixture so that the target inverted slump flow of 660–740 mm [23] was attained. This range is typical for SCC mixes with good workability. Samples were cast into 101.6 $\times$ 203.2 mm (4 $\times$ 8 in.) cylindrical molds. Once sufficient strength was reached, the specimens were demolded and stored at 100% relative humidity until testing.

3.3. Testing of specimens

The specimens were tested at age 7, 14, 28, 56, 84 and 168 days. Three replications were made per age. Compression strength was measured according to ASTM C 39 with specimens loaded to failure, at a rate of 0.25 +/−0.05 MPa/s [24]. Compression strength was defined as the maximum load sustained divided by the original cross-sectional area of the sample. Initial time of setting [25] and air content [26] were also determined for each concrete mixture.

4. Analysis of experimental results

4.1. Properties of fresh concrete

Table 2 presents the air content and initial time of setting for each mix. The air content of the mixes varies from 1.5% to 1.9%, which is typical for SCC. Fig. 1, displays the set time of the SCM mixes as a function of percent replacement. The setting time is generally greater, or close to, the setting time of the base mix except for high replacement (60–100%) of the Boardman FA. For the high Boardman FA replacement, the setting time decreases rapidly.

Table 1
Physical properties and chemical analysis (%) of cement, fly ash (FA) and slag (SL).

Compounds (%)	Shorthand notation	ASTM Type I	Boardman FA	Centralia FA	Seattle SL	St. Mary's SL
SiO_2	S	20.0	32.2	51.0	35.5	40.7
Al_2O_3	A	4.4	15.5	16.2	14.7	7.2
Fe_2O_3	F	3.3	7.5	6.2	–	–
$K_2O + Na_2O$	K + N	–	–	–	0.5	0.5
SO_3	$\hat{S}$	2.6	2.6	0.8	2.1	2.9
CaO	C	64.8	28.2	13.6	45.3	39.2
MgO	M	0.8	6.7	4.3	–	–
Loss on Ignition	LOI	2.6	–	0.2	–	–
Specific gravity (g/cm^3)	SG	3.15	2.58	2.63	2.89	2.89
Active SiO_2 (%)	γ	–	79	70	98	99
Activity index, 7 day (%)	7 AI	–	91	85	88	86
Activity index, 28 day (%)	28 AI	–	103	91	116	107