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Low Portland Cement Content SCC Mixtures for Use in Structural Applications

Katherine Kuder[1], Kasandra Wells[2], and Rob Shogren[3]

[1]*Seattle University; Assistant Professor; Civil and Environmental Engineering; 901 10th Ave; Seattle, WA 98122-1090; USA;< kuderk@seattleu.edu>.*
[2]*Seattle University; Research Assistant; Civil and Environmental Engineering; 901 10th Ave; Seattle, WA 98122-1090; USA; <wellsk1@seattleu.edu>.*
[3]*Lafarge North America; Technical Service Engineer; 5400 W Marginal Way SW; Seattle, WA 98106; USA; <Rob.Shogren@lafarge-na.com>.*

ABSTRACT

Use of supplementary cementitious materials (SCMs) is becoming increasingly popular to produce sustainable concrete. However, in practice, replacement levels rarely exceed 50% and are often much lower, around 15%, with an emphasis on optimizing mechanical performance, rather than material sustainability. In this work, 20, 40, 60, 80 and 100% of Portland cement (by weight) are replaced by SCMs. Four SCMs (two slag and two fly ash) that are locally available in the Pacific Northwest of the United States are evaluated. Efficiency factors are used to describe the effect of the SCM replacement. Design expressions are developed for the four SCMs that allow for the optimization of material sustainability by maximizing SCM content based on a target compressive strength. Good agreement is seen between experimental and measured values, indicating the validity of the approach.

INTRODUCTION

Due to its design versatility, availability and cost efficiency, concrete continues to play a dominant role in the construction industry. However, the production of Portland cement, a primary component of typical concrete mixes, is known to have a serious impact on the environment. For every ton of cement produced, approximately a ton of CO_2 is emitted. According to the European Cement Association, 2.77 billion tons of cement was consumed worldwide in 2007 [CEMBUREAU 2008]. Thus, the carbon footprint associated with concrete production is high.

Increasing the use of supplementary cementitious materials (SCMs) in concrete is an obvious and necessary step to improve sustainability [Malhotra 2006; Mehta 2009]. SCMs, such as silica fume, fly ash and slag, are often waste materials from industrial processes that possess hydraulic and/or pozzolanic properties. When used at optimal levels, SCMs enhance fresh state properties, mechanical performance and composite durability. In terms of sustainability, inclusion of SCMs in concrete: (1) reduces Portland cement consumption, (2) can reduce the amount of inert filler (typically sand) required and (3) uses waste materials that would otherwise be land filled.

A significant amount of research has focused on optimizing the fresh and hardened state properties of cement-based composites in which Portland cement is partially replaced with SCMs. A major challenge to using large volumes of SCMs is the inherent variability of the waste materials. Based on the source and type of SCM, a significant range in performance is seen. Some authors have proposed the use of efficiency factors to classify the effectiveness of SCMs in enhancing compressive strength [Papadakis, Antiohos et al. 2002; Oner, Akyuz et al. 2005]. Most studies have involved the use of efficiency factors for evaluating optimal dosages for compressive strength in fly ash systems, although slag systems have also been considered. Research has typically involved replacement levels between 20-50% and has rarely exceeded 70%. To the authors' knowledge, efficiency factors have not been yet been considered for self consolidating concrete (SCC).

The present study aims at optimizing the sustainability aspect of SCC for use in two structural applications: concrete-filled tubes for rapid bridge construction and dual-skin composite walls to resist seismic loading. In these applications, early strength is not required due to the presence of the outer steel casing, which can sustain initial construction loadings. Thus, the slow early strength development sometimes associated with SCM-rich concrete is not prohibitive. Efficiency factors are used to describe the impact of fly ash or slag replacement on the compressive strength. The intent is to provide information about the maximum amount of Portland cement that can be replaced given a target compressive strength.

EXPERIMENTAL PROGRAM

SCC mixes were cast in which 0, 20, 40, 60, 80 and 100% of the Portland cement was replaced with either fly ash or slag. Two slag and two fly ash SCMs were used. Compressive strength was determined at 7, 14, 28 and 56 days. In addition, resistivity was measured at 28 and 56 days.

Materials. Table 1 summarizes the chemical composition of the binders used in the study. The cement was ASTM Type I. In addition, two fly ash and two slag samples that are locally available in the Pacific Northwest of the United States were used. Both fly ashes are Class C according to ASTM 618, while the Boardman and Centralia are classified as Cl and CH, respectively, according to CSA A3000-03. Currently, mercury is not monitored at either ash producing plant; however, the plants are working on installing equipment for mercury sequestration.

SCC Mix Design. The base mix was a SCC mix typically used in the field. The mix design was as follows: 474 kg/m^3 Type I cement (LaFarge), 168 kg/m^3 water, 807 kg/m^3 sand, 820 kg/m^3 aggregate (9.53 mm) and 1.69 L/m^3 combination accelerator-superplasticizer-viscosity modifying chemical admixture (SIKA ViscoCrete 2100).

Specimen Preparation. Samples were mixed in a rotary drum mixer. First, the dry ingredients (aggregate, sand, cement and SCM, if applicable) were combined. Next, the wet ingredients (chemical admixture and water) were added and the ingredients 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 [ASTM C 1611 2009] was attained. This range is typical for SCC mixes with good workability. Samples were cast into 101.6 x 203.2 mm cylindrical molds. Once sufficient strength was reached, the specimens were demolded and stored at 100% relative humidity until testing. In addition, air content [ASTM C 231 2009] and time of set was determined [ASTM C 403/403M-08 2008].

Table 1. Chemical Composition of Type I Portland Cement and Fly Ash (FA) and Slag (SL) Samples

Compounds	ASTM Type I	Boardman FA	Centralia FA*	Seattle SL	St. Mary's SL
Silicon Dioxide (SiO_2)	20	32.2	40.9	35.5	40.7
Aluminum Oxide (Al_2O_3)	4.4	15.5	15.8	14.7	7.2
Iron Oxide (Fe_2O_3)	3.3	7.5	3.9	--	--
$K_2O + Na_2O$	--	--	--	0.5	0.5
Sulphur Trioxide (SO_3)	2.6	2.6	0.5	2.1	2.9
Calcium Oxide (CaO)	64.8	28.2	11.6	45.3	39.2
Magnesium Oxide (MgO)	0.8	6.7	2.9	--	--
Loss on Ignition	2.6	--	0.47	--	--

*Values listed are an average of two measurements

Compressive Strength and Efficiency Factors. Compression strength was measured according to ASTM C39 with specimens loaded to failure at a rate of 0.25 +/- 0.05 MPa/s. Compression strength was defined as the maximum load sustained divided by the cross-sectional area of the sample. Three replications were made.

Efficiency factors were calculated using a modified version of the Bolomey equation, which is an empirical relationship used to predict compressive strength of concrete. The Bolomey equation is:

(1)

Where $f'c$ = compressive strength (MPa), w/c = water/cement ratio (kg/m^3 /kg/m^3) and A and B are constants that depend on the mix design and age (MPa). For structural concrete, Equation (1) can be simplified [Rajamane, Peter et al. 2007]:

(2)

A cementing efficiency factor, k, can then be computed according to:

(3)

Where P is the amount of SCM (kg/m^3). Thus, w/(c+kP) is the water/effective binder ratio and kP is the equivalent cement content. For k=1, the SCM is considered to be equivalent to cement.

Based on the average compressive strength of the control mix (100% Portland cement), A was calculated using equation (2). Efficiency factors were then determined using equation (3).

Resistivity. Resistivity is an electrical property of concrete that is related to transport properties and can, therefore, be used to monitor the development of hydration products over time. However, other factors, including moisture content and ionic concentration of pore fluid [McCarter, Starrs et al. 2009] also impact resistivity and must be considered.

In this study, a custom-designed and built Wenner Four Probe setup [Tinnea, Tinnea et al. 2009] based on the “Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability [FM 5-578 2004]” was used. Four equally-spaced electrodes were placed in direct and solid contact with the sample. The outside electrodes applied small alternating currents while the potential difference was measured between the two inner electrodes. Resistivity was determined as:

$$\frac{\qquad}{} \tag{4}$$

where ρ = resistivity (ohm-cm), A = distance between inner electrodes (cm), K = correction factor to account for specimen geometry, and R= resistance (ohms) measured with the AC resistivity meter. In the setup used, A= 3.81 mm; therefore, K = 1.8 [Morris, Moreno et al. 1996].

Four readings were taken for each specimen, one along each of the 4 longitudinal axes that are 90° apart. Three replications were made. As this is a non-destructive test, the specimens were removed from the curing chamber for the test and then replaced after testing. Measurements were taken at 28 and 56 days.

RESULTS AND DISCUSSION

Air Content and Time of Set. Table 2 presents the air content and time of set results for the SCC mixes cast. Air contents range from 1.5 – 1.9%. In most cases, the time of set remains close to, or is greater than, the time of set for the control mix with 100% Portland cement. At high replacement rates (60-80%), the time of set decreases for mixes with the Boardman fly ash. Decreased time of set has been previously reported with Class C fly ash at high replacement rates [Naik and Singh 1997; Cross and Stephens 2005]. Set retarding agents can be used to control the time of set as needed.

Table 2. Air Content and Time of Set for Self Consolidating Concrete Mixes with Varying Amounts of Supplementary Cementitious Materials

		Cement replacement, by weight, %					
		0	20	40	60	80	100
Boardman Fly Ash	Air Content %	1.8	1.6	1.7	1.7	1.5	1.5
	Time of set (min)	270	440	315	175	55	20
Centralia Fly Ash	Air Content %	1.8	1.5	1.5	1.9	1.9	1.5
	Time of set (min)	270	445	420	300	280	210
Seattle Slag	Air Content %	1.8	1.6	1.9	1.8	1.6	1.6
	Time of set (min)	270	285	290	300	365	385
St. Mary's Slag	Air Content %	1.8	1.8	1.5	1.9	1.7	1.4
	Time of set (min)	270	300	275	260	340	220

Compressive Strength. Table 3 presents the average compressive strength, efficiency factors and resistivity for the SCC mixes tested. As expected, compressive strength varies based on the type and amount of SCM as well as age. The slower strength gain of the SCM-rich mixes is apparent. Initially, SCC mixes with lower cement replacement values tend to have similar strengths to the control. At 56 days, mixes with 60% cement replacements have strengths similar to, or greater than, the base mix (all Portland cement). Additionally, all four mixes in which 80% of the Portland cement was replaced have compressive strengths greater than 45MPa, which is a sufficient amount of strength for many structural applications.

However, mixes in which 100% of the cement was replaced have very low strengths, suggesting that not enough calcium hydroxide is present for the pozzolanic reaction to occur.

In general, the efficiency factors increase with time, as expected (Table 3). Fig. 1 presents the equivalent cement content (kP) versus SCM content for the mixes tested at 56 days. The line corresponding to k=1 is also shown. For all SCMs, the equivalent cement content at 20 and 40% replacement values exceeds that of the control, while the 60% cement replacements are close to the base mix. The data also show that at 56 days, for the SCMs tested, fly ash tend to be more efficient at lower replacement levels and less efficient at higher rates, when compared to the slags.

The aim of this work was to obtain design expressions for SCC that optimize sustainability by maximizing SCM content for a specified compression strength at a given age. Due to space constraints in this document, the method proposed is presented based on the 56 day data. Similar analyses can be conducted at other ages. Table 4 presents the compression strength analysis for the 56-day data. Polynomial regression equations were used to relate equivalent cement content (kP) to SCM content (S). These expressions were then used to predict compression strength (Equation 3) based on equivalent cement content. These data can be used to determine the maximum amount of a particular SCM that can be used given a target performance (compressive strength at a specific age). In general, good agreement is seen between the calculated and experimental data, suggesting the validity of the approach. However, the percent difference seen for the 100% cement replacement mixes is relatively high. Since the A parameter in Equation (1) is calculated based on the 100% Portland cement mix, it seems reasonable that more variation would be seen as the amount of SCM replacement increases.

Resistivity. Table 3 presents the resistivity results for the mixes tested at 28 and 56 days. As expected, resistivity increases with age due to the continued hydration resulting in the formation of additional C-S-H gel that fills the voids, thus, reducing porosity. The effect of SCM replacement on resistivity is less clear. It would be expected that resistivity would decrease at higher replacement levels due to the reduced amount of C-S-H gel. However, in general, resistivity increases with increasing SCM content. It is suspected that this increase is due to the reduction in alkali content in the pore water of SCM-rich mixes, lowering conductivity. More data are needed to evaluate these trends.

Table 3. Compression Strength, Efficiency Factors and Resistivity for Self Consolidating Concrete Mixes with Fly Ash (FA) and Slag (SL) as Partial Replacements of Portland Cement

		Compressive Strength (MPa)				Efficiency Factor				Resistivity (ohm-m)	
Cementitous Material	% Replacement	7-day	14-day	28-day	56-day	7-day	14-day	28-day	56-day	28-day	56-day
Base	0	64.59	73.75	80.03	81.50	--	--	--	--	6.00	6.83
Boardman FA	20	64.59	70.67	80.02	88.64	1.00	0.83	1.00	1.36	8.86	12.00
	40	62.67	72.11	83.46	91.19	0.94	0.95	1.09	1.24	8.07	11.98
	60	50.71	63.28	75.75	86.55	0.71	0.81	0.93	1.09	5.87	8.88
	80	6.11	7.62	35.07	67.27	0.07	0.08	0.42	0.82	3.93	8.66
	100	4.80	6.37	7.04	8.90	0.24	0.25	0.25	0.27	6.80	8.30
Centralia FA	20	67.87	79.23	84.22	94.75	1.21	1.31	1.22	1.67	9.44	15.29
	40	65.28	70.54	87.04	94.93	1.02	0.91	1.18	1.34	10.45	20.50
	60	44.17	52.89	63.50	77.73	0.57	0.61	0.72	0.94	6.59	16.85
	80	19.96	21.04	32.01	45.59	0.29	0.26	0.38	0.55	5.43	12.19
	100	1.25	1.49	1.75	1.91	0.19	0.19	0.20	0.20	12.36	15.74
Seattle SL	20	53.19	61.79	71.85	80.79	0.27	0.33	0.58	0.96	8.48	9.85
	40	51.89	63.01	76.59	82.32	0.60	0.70	0.91	1.02	11.04	14.41
	60	43.72	55.20	66.44	77.33	0.56	0.66	0.77	0.93	14.08	22.50
	80	36.76	46.34	54.89	67.70	0.56	0.62	0.68	0.83	33.03	48.32
	100	12.12	16.60	20.39	26.65	0.33	0.36	0.39	0.45	34.40	46.10
St. Mary's SL	20	62.85	66.04	85.02	93.56	0.89	0.57	1.26	1.61	10.66	14.30
	40	51.09	66.07	83.49	88.47	0.57	0.79	1.09	1.18	13.01	19.39
	60	37.30	58.04	75.78	84.96	0.42	0.71	0.93	1.06	24.49	38.35
	80	28.65	43.13	50.95	53.23	0.43	0.57	0.63	0.64	62.95	82.57
	100	12.11	13.90	18.91	21.04	0.33	0.33	0.37	0.39	103.18	147.40

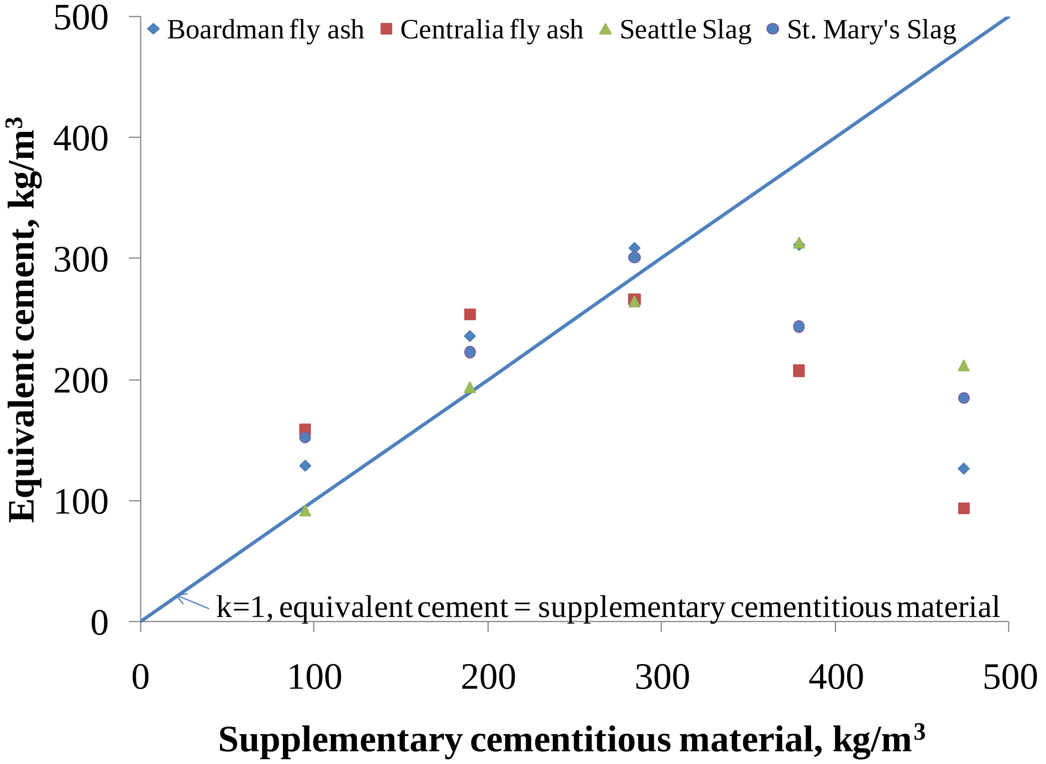

Fig. 1. Equivalent Cement Content Versus Supplementary Cementitious Material at 56 Days with Line Shown for Efficiency Factor, k = 1

Table 4. Compression Strength Analysis using Bolomey Strength Equation and Efficiency Factors for 56 Day Data

Cementitous Material	Replacement weight %	SCM content, S kg/m^3	Polynomial Regression	Compression Strength, MPa calculated	Compression Strength, MPa experimental	Difference %
Boardman FA	20	95	$-0.0052S^2 + 3.0266 S - 125.41$	84.13	88.64	5.10
	40	190		94.78	91.19	-3.94
	60	284		86.26	86.55	0.34
	80	379		58.55	67.27	12.96
	100	474		11.67	8.90	-31.10
Centralia FA	20	95	$-0.0039 S^2 + 2.0344 S + 3.1776$	93.61	94.75	1.21
	40	190		92.15	94.93	2.92
	60	284		76.32	77.73	1.82
	80	379		46.09	45.59	-1.10
	100	474		1.49	1.91	22.15
Seattle SL	20	95	$-0.0034 S^2 + 2.3221 S - 108.01$	77.31	80.79	4.31
	40	190		84.22	82.31	-2.32
	60	284		78.59	77.33	-1.63
	80	379		60.42	67.70	10.76
	100	474		29.71	26.65	-11.47
St. Mary's SL	20	95	$-0.0031 S^2 + 1.8726 S - 1.7387$	90.93	93.56	2.82
	40	190		90.75	88.47	-2.58
	60	284		79.14	84.96	6.84
	80	379		56.10	53.23	-5.39
	100	474		21.62	21.04	-2.76

CONCLUSION

The objective of this work was to develop SCC mix designs for structural applications in which sustainability of the concrete was optimized by maximizing SCM content. The proposed structural systems are composite systems with outer steel casings that can sustain initial construction loadings. Thus, the slow strength gain associated with SCM-rich concrete is not prohibitive. Design expressions were developed that relate compressive strength to water/effective binder, using a modified version of the Bolomey equation. Furthermore, SCM content was related to equivalent cement content based on the SCM used. The results show good agreement between predicted and calculated values, suggesting the validity of the approach. Future work should include varying the water/cement ratio so that more accurate regression coefficients can be obtained for the Bolomey strength equations. It would also be useful to extend the approach so that the effect of binary and ternary combinations of SCMs can be considered to optimize performance.

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