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Proposing new methods to appraise segregation resistance of self-consolidating concrete based on electrical resistivity

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HIGHLIGHTS

- Two new methods to assess segregation of SCC were proposed.
- The methods were based on electrical resistivity of concrete.
- These methods were verified with column technique method (ASTM C 1610).
- Increase in fly ash replacement resulted in higher *SI*, *PSI* and *ISI* at specific times.
- Substitution of silica fume lead to lower *SI*, *PSI* and *ISI* at specific times.

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ABSTRACT

The static segregation of self-consolidating concrete (SCC) can lead to some problems in the long-term properties of concrete. While there are few methods to evaluate the risk of segregation, which some of them are not precise and applicable, proposing new methods can be beneficial. In this experiment, two methods based on electrical resistivity were used in order to appraise and compare different mixtures of self-consolidating concrete. In order to verify the attained results, column technique (ASTM C 1610) was also used.

Seven mixtures containing fly ash and silica fume as partial replacements of cement were analyzed. Slump, J-ring flow and compressive strength of the samples were measured. The results revealed that increase in fly ash replacement resulted in higher segregation index (*SI*), higher periodic segregation index (*PSI*) and higher instant segregation index (*ISI*) at specific times. However, substitution of silica fume lead to lower *SI*, lower *PSI* and lower *ISI* at specific times. In overall, the results indicated that general trend of the mixtures is in good agreement with each other, and positive correlation between *SI* with *PSI* and *ISI* exist.
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1. Introduction

Self-consolidating concrete (SCC) is known as a new category of high-performance, high flowable and non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. In other words, it is used to facilitate and accelerate concrete placement without mitigating in situ properties and durability [1–3] which was first developed in Japan in 1988 [4].

SCC is increasingly being an appealing option worldwide because it improves the ease of placement, increases the rate of construction, and reduces cost via reducing construction time, labor and noise [5–10].Workability requirements for successful casting of SCC include high deformability, passing ability and proper segregation resistance [11–13].

Due to high flowability, relatively low yield stress of the concrete and in some cases, low viscosity, self-consolidating concrete is prone to segregation during mixing process, transporting, pumping, placement and dormant period. Static segregation is the process that granular particles separates from the paste and settles down when the concrete is in plastic state after casting. The segregation of coarse aggregate in cement-based materials can lead to heterogeneous properties of the hardened material with direct effect on mechanical properties and durability [14–18]. Segregation can reduce bond strength and weaken the interface between aggregate and cement paste, which have a direct influence on impermeability. Segregated SCC has a higher cracking risk because of the aggregate settlement, which leaves a top layer richer in paste and may experience more shrinkage in comparison with the

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unsegregated concrete. It also impairs the surface finish [19–25]. Therefore, control of segregation is especially critical in SCC, as well as in concretes made with supplementary cementitious materials used as partial replacement of cement [26,27]. The use of supplementary cementitious materials and other industrial byproducts has led to the development of more environmental-friendly concrete. The incorporation of such materials, however, can affect the stability of plastic concrete that is of critical interest in flowable cement-based systems [28,29]. Consequently, with the growing use of self-consolidating concrete, it is important to provide a proper assessment of the risk of segregation [30].

Resistivity methods were used to monitor the behavior of fresh cement-based materials during the consolidation, setting, and early hardening periods. The methods rely on differences in electrical resistivity measured at top and bottom height of column. The electrical resistivity of plastic concrete is a function of various factors, including moisture, salt content, temperature, water/cementitious materials ratio, volume fraction of the cement paste, the type and amount of supplementary cementitious materials, pore-size and tortuosity distribution, specimen age, aggregate type, degree of consolidation, Ionic composition of the liquid phase, the presence of chemical admixtures, type of curing, and pore network [26,31–33]. The variations in the ionic concentration of electrical resistivity are used to derive indices that reflect segregation of plastic concrete and interpret the homogeneity of the material.

The main objective of the study presented here is suggesting new methods of using the electrical resistivity of SCC which proposed to evaluate the static segregation of SCC containing fly ash and silica fume, as partial replacements for cement. In order to verify and determine correlation between test results of two indices, another test method used in this experiment was column technique. The column technique test involves the determination of the distribution of coarse aggregate by washing fresh concrete samples on a 4.75-mm sieve during dormant period [34,35].

Table 1
Chemical analysis and physical properties of cement, fly ash and silica fume.

Parameters	Cement	Fly ash	Silica fume
SiO_2	21.16	61.2	89.83
Al_2O_3	4.82		1.31
Fe_2O_3	3.9		1.12
CaO + MgO	65.04	12.2	1.77
$K_2O + Na_2O$	0.99	1.92	0.85
SO_3	2.51	0	2.5
LOI	1.32	2.6	1.59
fineness, m^2/kg	295		20700

2. Experimental programs

2.1. Materials and mix proportions

The chemical analysis and physical properties of cement, fly ash and silica fume are given in Table 1.

Experimental tests in mix proportion, especially the percentage by mass of superplasticizer were carried out by trial and error to determine the suitable proportion and the spread diameter of mixtures, in order to ease the comparison of mixtures.

Table 2 presents the sieve analysis of gravel, sand, limestone powder, and Table 3 shows the compositions of SCC mixtures. In this experiment, Type I Portland cement in accordance to ASTM C-150 [36] with specific gravity of 3.07 g/cm^3 was used. The sand with a fineness modulus of 3.37, specific gravity of 2.58 g/cm^3, and water absorption of 1.9% was also used. The coarse aggregate of SCC was crushed with a maximum size of 19 mm, specific gravity of 2.68 g/cm^3, and water absorption of 0.5%. The specific gravity of aggregates is in SSD condition. The ratio of gravel-to-total aggregate and sand-to-total aggregate were 0.3 and 0.6, respectively. Limestone powder was used as fine aggregate, with portion of 10% of aggregates.

In CFA5, CFA15, CFA25 mixtures, 5%, 15%, 25% of cement were substituted by fly ash class F, respectively, and 15%, 25% of cement were substituted by fly ash in CSF8FA15, CSF8FA25 mixtures, respectively. Similarly, 8% of cement were substituted by silica fume in the mixtures CSF8, CSF8FA15, CSF8FA25. The superplasticizer was a polycarboxylate-based gelenium 110p, with specific gravity of 1.08 g/cm^3. The ratio of w/cm and total cementitious materials were kept constant at 0.45 and 400 kg/m^3, respectively. The slump flow was tried to be fixed by adding extra

Table 2
Sieve analysis of the aggregates.

Sieve size (mm)	19	12.5	9.5	6.35	4.75	2.38	1.18	0.6	0.3	0.15
Gravel	100	52	6.1	0.8	0	0	0	0	0	0
Sand	100	100	100	97	92	77	52	28	8	3
LP	100	100	100	100	100	100	100	100	100	100
Mixture of aggregates	100	86	72	68	65	56	41	27	15	12

LP: Limestone powder.

Table 3
Mix design of concrete mixtures.

Mixture	Cement	Water	Fine Aggregate	Coarse Aggregate	LP	SF	FA	SP
	kg/m^3							
Ref.	400	180	1037	538	174	0	0	3.6
CFA5	380	180	1028	534	173	0	20	3.6
CFA15	340	180	1021	531	172	0	60	3.6
CFA25	300	180	1015	527	170	0	100	3.6
CSF8	368	180	1031	535	173	32	0	4.6
CSF8FA15	308	180	1014	527	170	32	60	4.6
CSF8FA25	268	180	1008	523	169	32	100	4.6

LP: Limestone powder.
SF: Silica fume.
FA: Fly ash.
SP: Superplasticizer.

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