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Electrical conductivity method to assess static stability of self-consolidating concrete

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ABSTRACT

The objective of this study is to evaluate the applicability of the electrical conductivity method to assess the stability of self-consolidating concrete (SCC) at early age. The method consists in inserting four electrode pairs at different depths of concrete to monitor local change in ionic concentrations with time. Such variations can reflect migration of bleed water along concrete column during the plastic stage. The experimental set-up consisted of a rectangular column measuring 1005 mm in height and 250 × 250 mm in cross section. The variations in ionic concentrations were exploited to derive stability indices with regards to bleeding and homogeneity of concrete. Derived stability indices included bleeding coefficient, segregation coefficient, and homogeneity index.

Various SCC mixtures made with a fixed water-to-cementitious materials ratio (w/cm) of 0.42, different aggregate gradations, and slump-flow values of 650 ± 10 and 700 ± 10 mm were evaluated. Analysis of changes in ionic concentrations along column samples with time provided adequate evaluation of stability of SCC. For example, the increase in the concentration of viscosity-modifying admixture from 1% to 2% was shown to decrease the homogeneity index from 0.36 to 0.27, reflecting better stability. Validation procedure was carried out by correlating stability indices derived from electrical conductivity measurements to physical variations of coarse aggregate concentrations determined on plastic concrete sampled from the tested column elements at the end of electrical conductivity monitoring period. Good correlations between stability indices and aggregate concentrations are established.

1. Introduction

Because of its fluid nature and low yield stress, self-consolidating concrete (SCC) is more susceptible to segregation than conventional concrete. Static segregation is the process in which coarse aggregate separates from the paste and settles down when the concrete is in plastic after casting. The segregation of coarse aggregate can lead to heterogeneous properties of the hardened concrete with direct impact on mechanical, transport properties, and durability. Control of segregation is therefore critical for the material to achieve adequate mechanical properties and structural performance. Stability of fresh concrete is largely dependent on the mixture composition and kinetic of cement hydration at early age. The latter is greatly influenced by the presence of high-range water-reducer (HRWR), viscosity-modifying admixture (VMA), and supplementary cementitious materials (SCMs) [1–6].

Static segregation cannot be easily detected on exposed surfaces of concrete structures unless the mixture exhibits excessive bleeding. On the other hand, in the case of high cohesive concrete mixtures, such as those containing silica fume or VMA, even in the absence of external bleed water, static segregation can still take place [5,7]. This is due to the difficulty of bleed water to travel along bleeding channels in viscous systems. Proper evaluation of the evolution of solution migration at early age can therefore help in developing good understanding of the segregation process in SCC. For example, the evaluation of the migration of internal free water into the system can provide useful information on its heterogeneity. However, there is a lack of tools that can enable the generation of real-time data on the kinetics of bleeding, which is essential to develop fundamental understanding of stability of SCC [6,7].

With the growing use of SCC as a standard material for repair and construction, it is important to adopt accurate and reliable test methods to assess static segregation. Limited number of standard test methods exists to evaluate the stability of SCC. Bleeding is usually measured by collecting excess solution at the upper surface of the concrete as a function of time after placement [8–10]. The observation of the coarse aggregate distribution in a cored sample offers a direct means of determining segregation in the hardened concrete [5]. Segregation and bleeding can also be evaluated by determining the surface settlement (or subsidence) per unit height of concrete [1,2,5,7]. The susceptibility of fresh concrete to segregate can be assessed by observing the material scattering following a given drop over a cone at a certain height, or following some jolting of a given column of concrete [11]. Image analysis along a saw-cut concrete sample is also employed to assess stability [12]. Visual stability rating can be employed to evaluate the stability of SCC. In this method, the SCC cylinder is cut lengthwise, and the cut surface is then used to observe the distribution of coarse aggregates. A Hardened

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Visual Stability Index (HVSI) can be determined and used to assess stability [8,10].

Recently, a new test method to evaluate the combined effects of water migration, consolidation, and segregation of cement-based materials using the electrical conductivity approach was proposed [6,13–15]. The electrical conductivity of plastic concrete is a function of various parameters, including the volume fraction of the cement paste, pore-size distribution, ionic composition of the liquid phase, presence of chemical admixtures, and pore network. Following the initial contact between cement and water, conductivity increases due to rapid dissolution of alkali sulfates and other cement oxides, which results in increasing the ionic concentration of the pore solution. Conductivity increases with the hydration of cement process to reach a peak value beyond which conductivity starts to decrease due to further precipitation of the hydration products and reduction of mobility of ions through the pore solution. The variation of conductivity as function of time can indeed reflect internal changes of the pore solution with time.

The main objective of the study presented here is to evaluate the applicability of the electrical conductivity test to assess segregation of SCC using relatively large samples and to correlate the non-destructive method results to physical segregation and external bleed values. The test method is based on multi-pair electrode conductivity measurements that consist in monitoring the differences in ionic species throughout a concrete column measuring 1005 mm in height as a function of time. The variations in the ionic concentration are used to derive indices that reflect stability of plastic concrete and interpret the material homogeneity. The stability deducted from the non-destructive electrical conductivity method is compared to stability indices determined by washing fresh concrete samples on a 5-mm sieve and determining aggregate distribution along the test specimen.

2. Experimental program

The experimental program undertaken in this study aimed at evaluating the applicability of electrical conductivity measurements to assess segregation resistance of various SCC mixtures made with fixed water-to-binder ratio of 0.42 and binder content of 450 kg/m^3. As summarized in Table 1, all mixtures were proportioned with relative coarse aggregate volume of 32%, fixed sand-to-total aggregate ratio (S/A) to 0.50, by mass, various aggregate grain-size distributions of aggregate, different VMA dosages, and different silica fume contents. The selected mixture parameters are based on research targeting the optimization of SCC mixtures with different stability levels. The influence of slump flow level, casting rate, and vibration consolidation on stability of SCC was also evaluated.

In total, 11 SCC mixtures were investigated. SCC1, SCC2, and SCC3 mixtures with different stability levels corresponding to relatively low, medium, and high stability, respectively, were used to evaluate the sensitivity of conductivity measurements to assess stability of concrete. Stability was adjusted by means of changing the maximum size of aggregate (MSA) and aggregate gradation, corresponding to discontinuous and continuous sand–coarse aggregate combinations (Fig. 1), and incorporating 1% VMA (moderate segregation mixture, SCC2). SCC1 and SCC2 mixtures were made with discontinuous aggregate having MSA of 16 and 12.5 mm, respectively. SCC3 mixture was proportioned with continuous aggregate where an intermediate portion of 8–12.5 mm aggregate size was added to secure continuous gradation. SCC4-11 mixtures were prepared to investigate the effect of slump flow level (650 vs. 700 mm), as well as the incorporation of VMA, silica fume, precipitated silica, and set-retarder on stability of concrete. SCC4, SCC6, and SCC7 mixtures were re-produced to investigate the effect of casting rate (30 vs. 90 m/h) on static stability. On the other hand, SCC7 and SCC9 were used to investigate the effect of vibration consolidation on stability.

3. Materials

The investigated mixtures were systematically proportioned using ordinary Portland cement (CEM I 52.5 N) combined with either a Class F fly ash (binary system) or silica fume and Class F fly ash (ternary system). The chemical and physical properties of SCMs are summarized in Table 2. A crushed aggregate with different MSA of 8, 12.5, and 16 mm was used. The aggregate has a specific gravity of 2.65 and a water absorption of 0.5%. Three different aggregate combinations, including continuous gradation with MSA of 12.5 mm and discontinuous gradation with MSA of 12.5 and 16 mm, were used. These aggregates were employed in combination with binary (cement and fly ash) and ternary (cement, silica-fume, and fly ash) binders to achieve different packing densities of the powder phase. Well-graded river bed siliceous sand of 0–4 mm was used. The particle size distributions of the sand and coarse aggregate are shown in Fig. 1. The gradations of different aggregate–sand combinations are given in Fig. 2.

A polycarboxylate-based HRWR with a specific gravity of 1.07 and a solid content of 30% was used. A powdered cellulose-based VMA was incorporated. Precipitated silica was also used. A set-retarder was incorporated in some mixtures at a typical dosage of 0.3%, by mass of cement, to ensure good fluidity retention and delay setting.

4. Test procedures

The investigated mixtures were prepared in batches of 100 L using a pan mixer with a capacity of 120 L. The mixing sequence consisted of homogenizing the sand and coarse aggregate for 1 min before introducing 1/3 of the mixing water. The binder was then introduced along with the HRWR diluted in the second 1/3 of the water. After 3 min

Table 1
SCC mixtures proportioning.

Mixture	SCC 1	SCC 2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8	SCC9	SCC10	SCC11
Type CEM I 52.5 cement, kg/m^3	350	350	350	350	350	350	315	315	315	315	350
Fly ash, kg/m^3	100	100	100	100	100	100	100	100	100	100	100
Silica fume, kg/m^3	–	–	–	–	–	–	35	35	35	35	–
Total cementitious materials, kg/m^3	450	450	450	450	450	450	450	450	450	450	450
Total water, kg/m^3	189	189	189	189	189	189	189	189	189	189	189
w/cm	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Sand (0–4 mm), kg/m^3	850	850	850	850	850	850	850	850	850	850	850
Coarse aggregate (4–8 mm), kg/m^3	–	–	170	170	–	–	–	–	–	–	–
Coarse aggregate (8–12.5 mm), kg/m^3	–	850	680	680	850	850	850	850	850	850	850
Coarse aggregate (8–16 mm), kg/m^3	850	–	–	–	–	–	–	–	–	–	–
Polycarboxylate HRWR, L/m^3	2.7	2.9	2.7	2.7	2.7	2.7	3.5	7.5	5	9	8.6
VMA,% of binder	–	1	–	–	–	–	–	–	–	–	2
Precipitated silica,% of binder	–	–	–	–	–	–	–	–	1.5	1.5	–
Set-retarding agent,% of binder	0.3	0.3	–	0.3	–	0.3	0.3	0.3	0.3	0.3	0.3

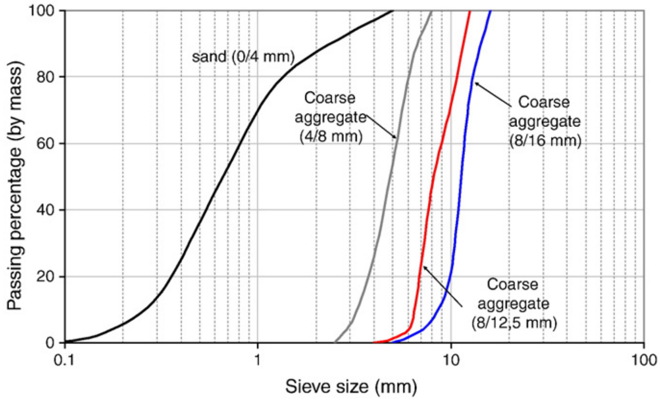


Fig. 1. Particle size distribution of sand and coarse aggregate.

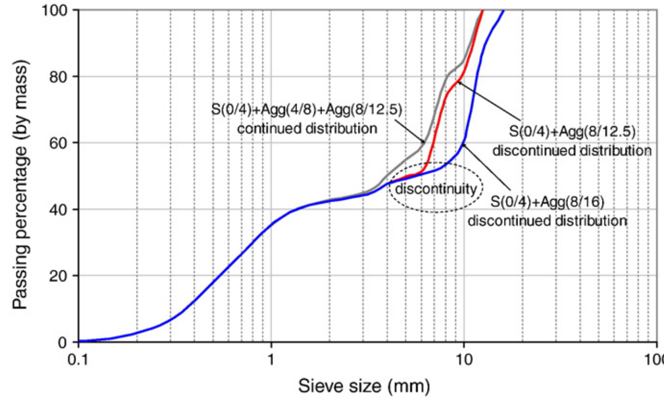


Fig. 2. Particle size distribution of sand–coarse aggregate combinations.

of mixing, the VMA and set retarder diluted in the remaining water were introduced into the mixer, and the concrete was mixed for 2 min. This sequence of addition was proven to be efficient in reducing the HRWR demand.

Immediately after the end of mixing, the consistency of the SCC was determined using the slump flow test (ASTM C 1611), followed by unit weight, air volume, and temperature. The mixing process and testing were conducted in a controlled ambient temperature of 20 ± 2 °C. The test column used to evaluate segregation resistance was a non-conducting plastic mold measuring 1005 mm in height and 250 × 250 mm cross section in which multi-electrode probes were inserted at four heights (Fig. 3). The concrete was cast in one lift at a constant rate of casting of 30 m/h.

4.1. Electrical conductivity measurements

Electrical conductivity measurements were monitored using the multi-electrode probes located at four different heights along the column elements. Measurements were made using a 5-V square-wave operated with excitation voltage at a frequency of 1 kHz. The electrode pairs consisted of brass bolts measuring 45 mm in diameter and 25 mm in length fixed in polyvinyl chloride (PVC) rods. The electrode probes were calibrated before use in concrete. The calibration consisted in determining the effective cell constant for each cell. This was performed by immersing the probe into a standard NaCl solution of known conductivity and measuring sequentially the electrical conductivity for each electrode pair [13–15].

The test consisted of determining the differences in electrical conductivity measured at different depths of the specimen during 150 min. The variations in electrical conductivity throughout the sample as a function of time are used to interpret the material homogeneity. This method enabled one to evaluate the combined effect of water migration, consolidation, and segregation of cement-based materials during the plastic stage of cement hydration.

Table 2
Chemical and physical properties of SCMs.

	Cement	Fly ash	Silica fume
SiO_2	20.6	52.7	92.9
Al_2O_3	3.6	32.7	–
Fe_2O_3	4.1	6.4	–
CaO	65.4	3.1	1.3
MgO	0.9	0.8	0.4
Na_2O	0.2	0.7	1.2
K_2O	0.3	1.2	0.6
SO_3	2.7	0.9	3.6
TiO_2	0.2	1.5	–
Specific gravity	3.16	2.5	2.2
Blaine finesse (g/cm^2)	3800	4350	–

Stability indices reported by Khayat et al., including bleeding index (B.I.), segregation index (S.I.), and homogeneity index (H.I.) are employed to assess stability of SCC [13]. As shown in Table 3, the bleeding index (B.I.) is defined as the cumulative area between conductivity values determined at the top electrodes and the mean of values obtained from all electrodes, monitored for three hours divided by the elapsed time. The segregation index (S.I.) is defined as the cumulative area between conductivity of the bottom electrode and the mean conductivity of all electrodes monitored over three hours, divided by the elapsed time. The homogeneity index (H.I.) is defined as the cumulative area between conductivity values of the top and bottom of electrodes monitored over three hours, divided by the elapsed time. Further details on the calculation of these indices can be found in the cited references [13–15].

4.2. Determination of coarse aggregate distribution

At the end of conductivity measurements, which corresponds to 150 min after casting the column elements, the column was turned gently to its horizontal position. As illustrated in Fig. 4, the lateral side of the mold was then removed, and thin metal plates were inserted into the plastic concrete at distances to separate the concrete into four zones. Zones 1 and 4 correspond to the bottom and upper portions of the column, respectively. Each concrete zone measures approximately 150 × 250 × 250 mm. The steps followed during this experiment are schematically presented in Fig. 4. Concrete portion was then used to determine the water and coarse aggregate contents. The concrete was heated at a constant temperature until reaching a constant mass. The water content was determined as the difference in mass before and after heating divided by the mass sampled concrete. The coarse aggregate content was determined by washing a portion of concrete on 5-mm sieve. The coarse aggregate retained on the sieve was dried for 24 h in an oven at 100 °C. The mass of coarse aggregate at different depths (Gi) was determined. The relative percentage of coarse aggregates at depth i (i varies from 1 to 4) was calculated as the ratio of the mass of coarse aggregate retained on the sieve and mean mass of coarse aggregate in the initial concrete, i.e. theoretical unit weight of coarse aggregate retained on 5-mm sieve, as follows: $\frac{G_i - G_{mean}}{G_{mean}} x100$ where, i indicates the zone from which the concrete is taken. The variations of the relative coarse aggregate distribution of the tested SCC mixtures are presented in Table 4.

In order to quantify the stability of concrete for the column, various stability indices, including segregation coefficient (Sc), bleeding coefficient (Bc), and homogeneity coefficient (Hc), were employed as follows:

$$Sc = \frac{G_{Bottom\ zone} - G_{mean}}{G_{mean}} x100 \quad (1)$$

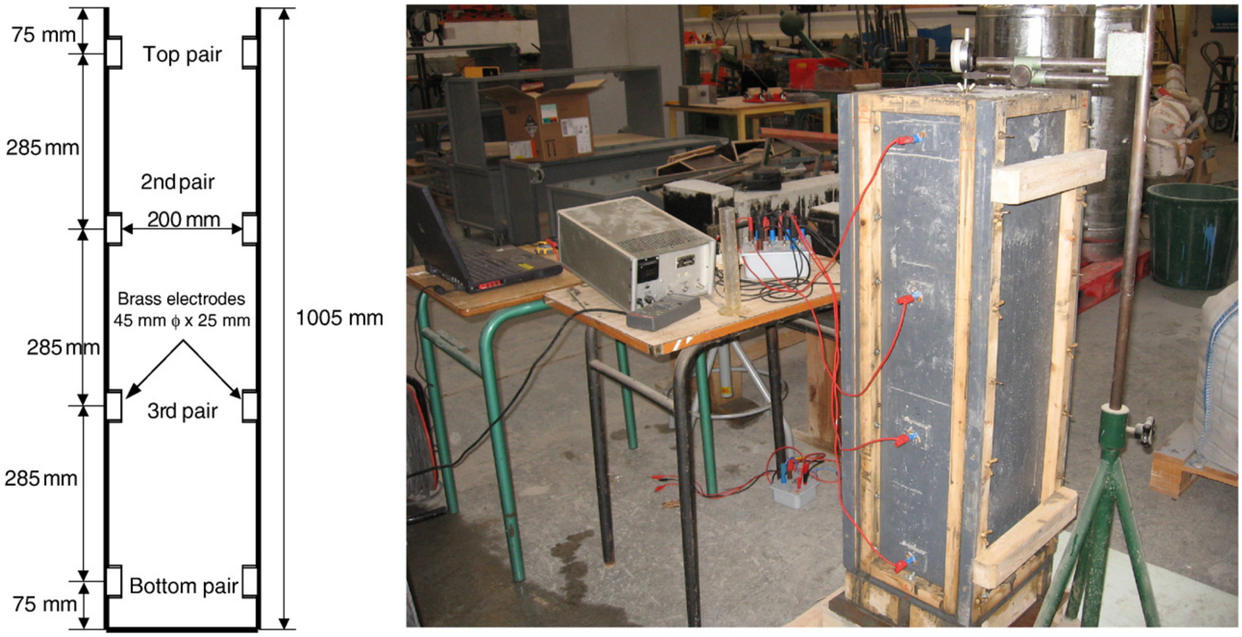
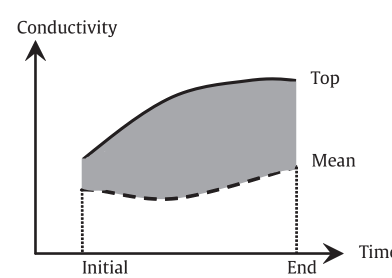
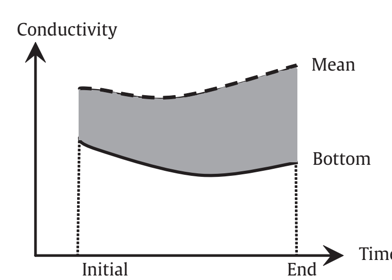
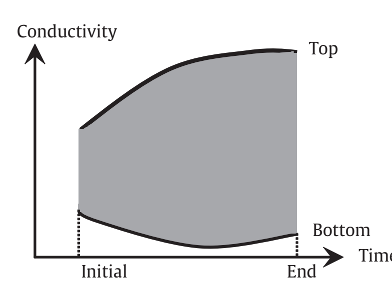


Fig. 3. Schematic of multi-electrode probe and test specimen.

Table 3
Definitions of stability indices.

Index	Formula	Schematic sketch
Bleeding index	$BI = \frac{\text{Cumulative area top pair to mean}}{T_{End} - T_{initial}}$	
Segregation index	$SI = \frac{\text{Cumulative area mean to bottom pair}}{T_{End} - T_{initial}}$	
Homogeneity index	$HI = \frac{\text{Cumulative area top pair to bottom pair}}{T_{End} - T_{initial}}$	

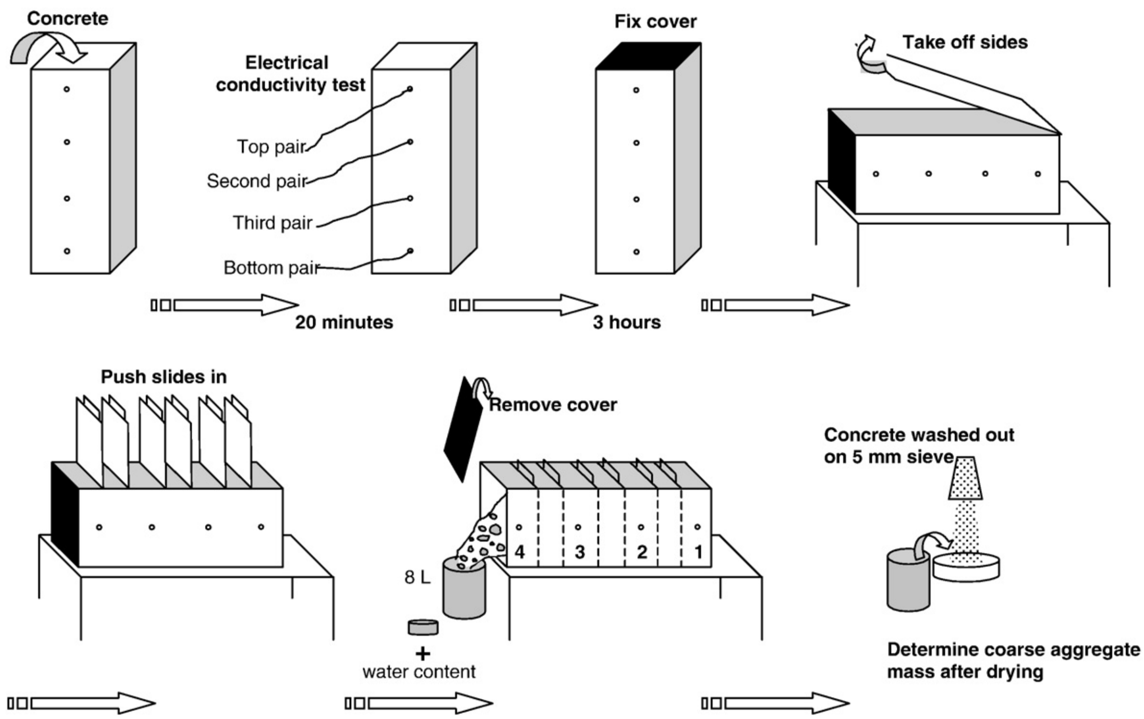


Fig. 4. Schematic diagram of experimental procedure for physical stability measurements.

$$Bc = \frac{\%W_{top\,zone} - \%W_{mean}}{\%W_{mean}}\,x\,100 \tag{2}$$

$$Hc = \frac{SC + BC}{2} \tag{3}$$

where $W_{top\text{-}zone}$ represents the water content determined on the top potion of the concrete column, and W_{mean} is the mean water content determined for the four zones of the column.

Stability characteristics of the investigated SCC mixtures obtained from the multi-electrode conductivity approach were compared to the results of relative distribution of coarse aggregate concentrations determined on washed concrete samples.

Table 4
Relative distribution of coarse aggregate obtained on plastic concrete.

Mixture codification	Relative coarse aggregate distribution (%)			
	Bottom zone (Sc_{bottom})	2nd zone	3rd zone	Top zone (Sc_{Top})
SCC1	7.30	1.64	0.18	−9.12
SCC2	4.16	1.31	0.44	−5.90
SCC3	0.31	−0.16	0.00	−0.15
SCC4	1.03	0.60	−0.59	−1.02
SCC5	2.59	0.86	0.76	−4.21
SCC6	3.36	−0.03	0.01	−3.35
SCC7	2.49	−0.36	1.07	−3.20
SCC8	7.10	−0.14	0.41	−7.38
SCC9	2.17	−1.78	1.65	−2.04
SCC10	2.21	−1.54	0.45	−1.12
SCC11	3.46	−0.19	0.31	−3.58
SCC4/90	1.72	1.54	0.94	−4.21
SCC6/90	9.31	9.15	10.13	−28.59
SCC7/90	2.21	−0.09	−0.58	−1.54
SCC7/V	9.06	5.73	1.38	−16.17
SCC9/V	7.08	−1.66	−2.65	−2.77

5. Test results and discussions

5.1. Sensitivity of conductivity measurements

Table 5 summarizes the stability characteristics of the various SCC mixtures evaluated from the electrical conductivity approach and the physical aggregate distribution along the experimental column elements. The variations in conductivity determined on SCC1 (high segregation), SCC2 (medium segregation), SCC3 (minimum segregation) mixtures are summarized in Figs. 5–7, respectively. As can be observed, mixtures undergo more or less phase separation upon casting into the column element resulting in initial heterogeneous conductivity response. The segregation processes, being the counterpart of the solution migration towards the upper portion of the column, is apparent from the decrease in conductivity in the case of stable concrete (SCC3) and from the spread in conductivity between different electrode pairs. For example, in the case of unstable concrete (SCC1), a significant spread between top and bottom pairs is observed, reflecting a considerable migration of bleed water to the top of the specimen. In the case of stable

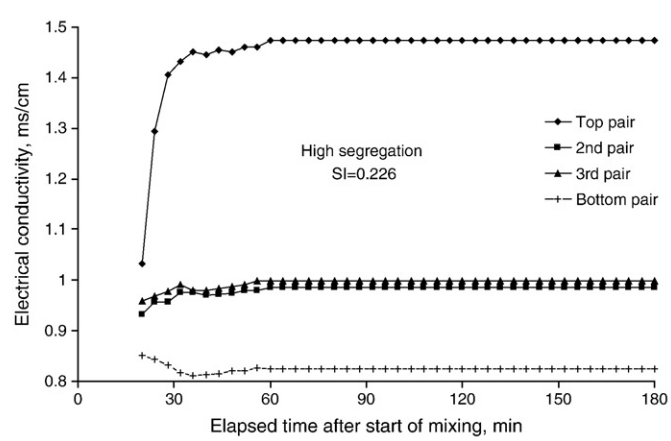


Fig. 5. Variation of electrical conductivity of SCC1 mixture (high segregation).

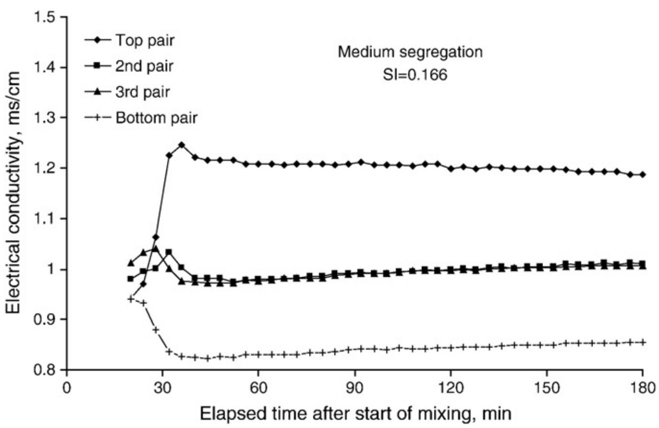


Fig. 6. Variation of electrical conductivity of SCC2 mixture (medium segregation).

SCC, this difference is very limited compared to the difference observed in the case of medium and high segregation mixtures.

Spreads observed between conductivity values are also reflected by differences in segregation index values (SI). Indeed, the SCC1, SCC2, and SCC3 mixtures showed different stability levels with SI values of 0.226, 0.166, and 0.041, respectively. Furthermore, the segregation process is reflected more distinctively in the conductivity response at the lower half of the samples, typically, as a negative slope in the electrical conductivity vs. time curve (Figs. 6 and 7). The gap between the top pair's conductivity curve and remaining curves in Fig. 5 obtained beyond 60 min of age could be related to the extent of bleeding of the unstable concrete, such as SCC1 proportioned with a discontinuous aggregate gradation having the largest MSA and containing a set-retarder. This mixture showed a significant difference in conductivity measured with the top pair (approximately 1.5 ms/cm), the medium pair (1 ms/cm), and the bottom pair (0.8 ms/cm) electrodes, reflecting high degree of segregation. The use of discontinuous aggregate with lower MSA and 1% VMA (SCC2) resulted in lowering the difference in conductivity between top and bottom pairs, which reflects less water migration along the concrete height. For example, in the case of SCC1 the spread in conductivity between the top and bottom pairs was 0.70 ms/cm (1.5–0.8). In the case of SCC2, this difference was limited to 0.4 ms/cm (1.2–0.8). The use of stable mixture (SCC3) resulted in lower spread in conductivity between the top and bottom pairs of 0.25 (1.25–1.10).

Comparison between conductivity measurements of SCC8 specimen and SCC8 cast with some vibration consolidation (Fig. 8) indicated that the vibration indeed promotes segregation and bleeding of concrete resulted in higher water migration through the sample, which is reflected by higher conductivity values. For example,

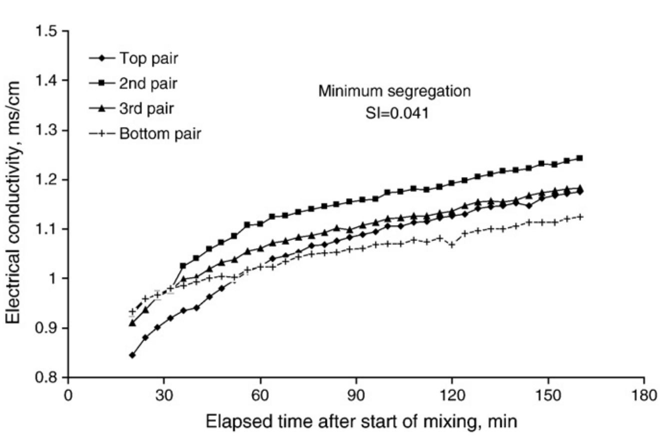


Fig. 7. Variation of electrical conductivity of SCC3 mixture (minimum segregation).

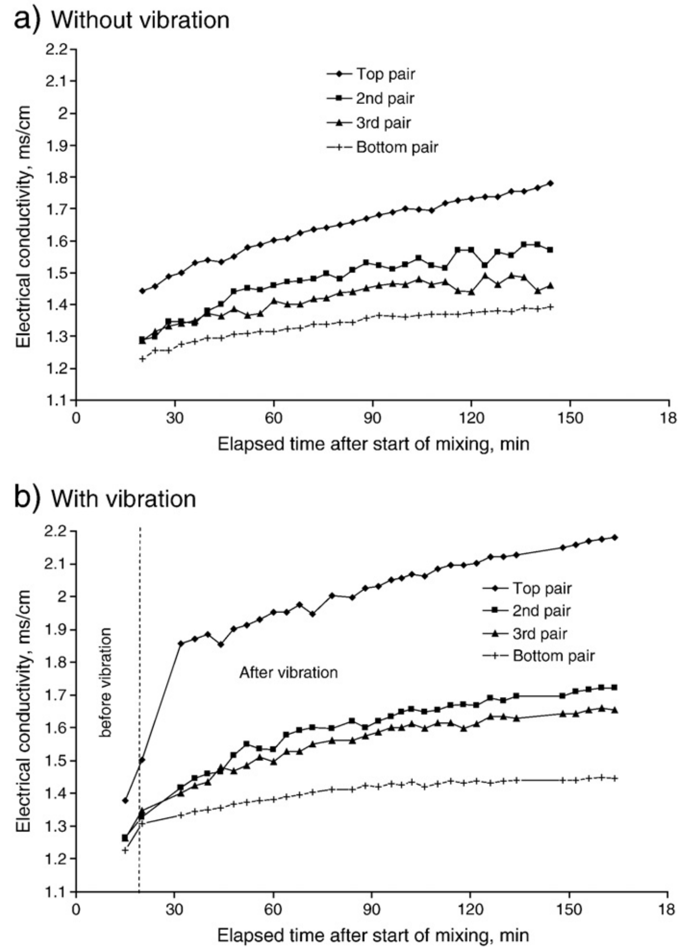


Fig. 8. Variation of electrical conductivity of SCC8 mixture (without and with vibration).

in the case of column cast without vibration, the top probe indicated a conductivity value of 1.78 ms/cm. In the case of vibration, this value increased to 2.18 ms/cm.

5.2. Effect of silica fume, precipitated silica, and VMA

SCC mixtures incorporating silica fume (SCC7 and SCC8), precipitated silica (SCC9 and SCC10), and VMA (SCC2 and SCC11) were prepared to highlight the effect of these materials on stability. All considered mixtures were proportioned with discontinuous aggregate with 12.5 mm MSA. For a given mixture type, the HRWR dosage was adjusted at two different contents to secure initial slump flow of 650 and 700 mm.

Test results obtained on mixtures SCC6, SCC7, and SCC8 (Table 4) revealed that the use of approximately 10% silica fume replacement of cement required higher demand of HRWR to achieve the targeted slump flow. For example, in the case of SCC7, 3.5 L/m^3 of HRWR was necessary to secure a slump flow of 650 mm. In order to achieve a slump flow value of 700 mm, the required HRWR content increased to 7.5 L/m^3. On the other hand, for a given slump flow of 700 mm, the replacement of 8% of the binder by silica fume did not enhance stability. This may be due to the high dosage of HRWR required to secure the targeted slump flow, which can result in excessive delay in setting. By comparing test results obtained on SCC7 (slump flow of 650 mm) and SCC8 (slump flow of 700 mm), it can be observed that the silica fume was more efficient on stability when used in mixture with lower slump flow and lower HRWR content. For example, in the case of SCC7, the stability index (SI) and homogeneity

Table 5
Characteristics of evaluated concretes.

Results from electrical conductivity							Results from physical tests		
Mixture codification	Casting rate (m/h)	Vibration (30 s)	Slump flow (mm)	B.I.	S.I.	H.I.	Bleeding coefficient (%), Eq. (2)	Segregation coefficient (%), Eq. (1)	Homogeneity coefficient (%), Eq. (3)
SCC1	30	Without	700	0.489	0.226	0.650	83.2	7.3	45.2
SCC2	30	Without	700	0.196	0.166	0.357	16.2	4.2	10.2
SCC3	30	Without	700	0.074	0.041	0.012	2.8	0.3	1.6
SCC4	30	Without	700	0.027	0.093	0.130	2.3	1.0	1.7
SCC5	30	Without	700	0.102	0.117	0.223	11.5	2.6	7.0
SCC6	30	Without	700	0.146	0.116	0.174	16.5	3.4	9.9
SCC7	30	Without	650	0.160	0.132	0.280	22.0	2.5	12.3
SCC8	30	Without	700	0.410	0.210	0.605	56.3	7.1	31.6
SCC9	30	Without	650	0.122	0.110	0.250	21. 9	2.2	12.4
SCC10	30	Without	700	0.170	0.116	0.280	16.3	2.2	9.1
SCC11	30	Without	700	0.162	0.130	0.270	12.1	3.5	7.8
SCC4/90	90	Without	700	0.117	0.096	0.187	12.4	1.7	7.1
SCC6/90	90	Without	700	0.579	0.295	0.813	127.1	9.3	68.2
SCC7/90	90	Without	650	0.079	0.106	0.203	8.6	2.2	5.4
SCC7/V	30	With	650	0.423	0.256	0.641	60.8	9.1	35.0
SCC9/V	30	With	650	0.256	0.202	0.448	21.9	7.1	22.1

(HI) index were 0.132 and 0.280, respectively. In the case of SCC8, these values were 0.210 and 0.605, respectively, reflecting lower stability resistance.

The use of 1.5% precipitated silica with SCC7 (slump flow of 650 mm) and SCC8 (slump flow of 700 mm) to produce SCC9 and SCC10 led to greater HRWR demand corresponding to 5 vs. 3.5 L/m^3 and 9 vs. 7.5 L/m^3, respectively, and relatively lower stability index, reflecting better stability. For example, in the case of SCC7, the stability indices (SI) and homogeneity index (HI) were 0.132 and 0.280, respectively. In the case of SCC9, these values were 0.122 and 0.250, respectively. It can be mentioned that the use of 8% silica fume in combination with 1.5% precipitated silica was efficient in improving stability of SCC. It should be mentioned that a higher dosage of precipitated silica was showed to greatly improve stability but resulted in high demand of HRWR.

By comparing test results obtained with SCC6 and SCC2, it can be observed that the use of cellulosic-based VMA at 1%, by mass of binder, did not improve stability of SCC. Indeed, this dosage is generally recommended to improve robustness of SCC. The increase in VMA dosage from 1% to 2% required higher HRWR demand (2.9 vs. 8.6 L/m^3) and resulted in better stability. For example, the SI and HI indices decreased from 0.166 to 0.130 and from 0.357 to 0.270, respectively, with the increase in VMA dosage from 1% to 2%.

5.3. Effect of casting rate and vibration consolidation

In order to investigate the effect of casting rate on stability, SCC4, SCC6, and SCC7 mixtures were used to cast columns in which concrete is placed at very high casting rate of 90 m/h. These results are compared to those obtained on specimens cast with similar mixtures at a lower casting rate of 30 m/h. SCC4 and SCC6 mixtures had slump flow values of 700 mm, while SCC7 containing 8% silica fume had a slump flow of 650 mm. In the case of SCC4 made with continuous aggregate skeleton, the increase in casting rate from 30 to 90 m/h did not have a significant effect on stability. For example, the SI and HI indices increased from 0.093 to 0.096 and from 0.130 to 0.187, respectively. However, in the case of SCC6 made with discontinuous aggregate skeleton, the effect of casting rate was more critical. Indeed, the SI and HI indices increased from 0.116 to 0.295 and from 0.174 to 0.813, respectively. This can be explained by stability level of the mixture. Indeed, SCC4 is characterized by excellent stability (HI<0.2), while the SCC6 had moderate stability with HI>0.7. In the case of SCC 4 and SCC6 mixtures, the use of higher casting rate of 90 m/h resulted in relatively higher SI and HI values compared to mixture cast at 30 m/h, reflecting lower stability. For example, in the case of SCC6 mixture, the SI and HI values increased from 0.116 to 0.295 and from 0.174 to 0.813 when the casting rate was increased from 30 to 90 m/h. However, in the case of SCC7 mixture containing precipitated silica, lower SI and HI values obtained at a casting rate of 90 m/h. For example, the SI value decreased from 0.132 to 0.106 when the casting rate increased from 30 to 90 m/h. This may be due to the relatively higher pseudoplastic behavior of mixture containing silica fume [16,17]. This can then be accompanied by lower apparent viscosity at higher casting regime, which may result in promoting bleed water migration within the concrete.

Results measured on SCC7 and SCC9 mixtures (slump flow of 650 mm) with and without vibration consolidation showed that the application of vibration consolidation reduced stability resistance of SCC resulted in relatively higher SI and HI indices. For example, in the case of SCC7 (Table 4), the SI and HI indices increased from 0.132 to 0.256 and from 0.280 to 0.641, respectively. It is worthy to note that the negative effect of vibration consolidation on stability is less important in the case of SCC9 reflected by lower stability indices. This may be due to the presence of VMA that secures higher stability. The application of vibration consolidation can cause aggregate to separate from the mortar, resulting in coarse aggregate settling down and the paste rising to the top portion of the column.

5.4. Correlations between electrical and physical stability measurements

Stability indices derived from variations in electrical measurements were correlated to the physical indices established on concrete samples as described earlier. The correlation between segregation index (SI) determined from electrical conductivity approach and the segregation coefficient (SC) determined from the evaluation of aggregate distribution of all the investigated SCC mixtures are illustrated in Fig. 9. On the other hand, bleeding and homogeneity coefficients derived from electrical measurements are compared to corresponding indices determined on concrete by conventional stability measurements on Figs. 10 and 11, respectively. As can be observed, stability indices derived from the non destructive electrical conductivity measurements correlate well with stability indices determined on concrete using conventional physical tests where higher correlation coefficients were obtained (R^2 higher than 0.94). This high degree of correlation between stability measurements determined on plastic and hardened concrete samples prove the adequacy of the proposed electrical conductivity procedure as a reliable and on-time methodology to assess stability of SCC.

As indicated in Fig. 11, concrete mixtures with homogeneity coefficient lower than 10, between 10 and 20, and 20 and 35, and higher than 35 can be considered to have excellent, high, medium and low

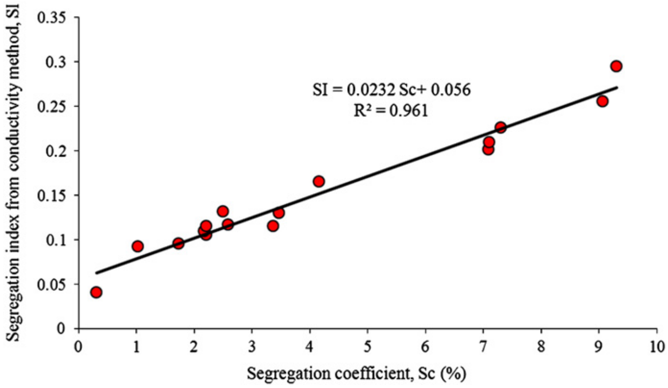


Fig. 9. Correlation between segregation index (SI) and segregation coefficient (SC).

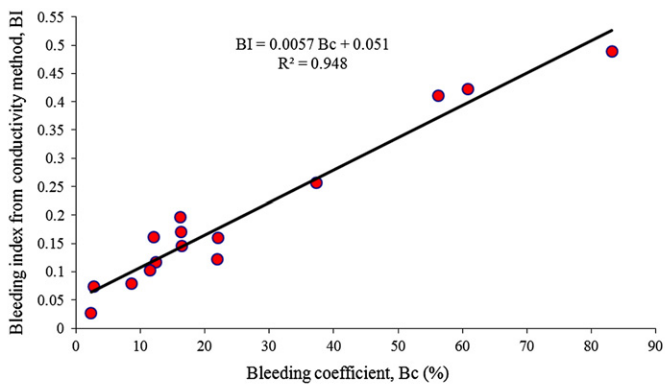


Fig. 10. Correlation between bleeding index (BI) and bleeding coefficient (BC).

stability, respectively, based on proposed values in reference 13. These values correspond to values of homogeneity index of 0.20, between 0.2 and 0.4, and 0.4 and 0.7, and higher than 0.7, that are determined using the electrical conductivity approach.

6. Conclusions

The non-destructive electrical conductivity test method that can used to assess stability of flowable concrete during the dormant period of cement hydration was validated using large-scale column specimens. The electrical conductivity method is shown to be applicable to a wide variety of SCC mixtures with different stability levels. Test results presented in this paper showed that the electrical conductivity method is sensitive to reflect small changes in static stability of SCC. Derived stability indices were proposed to quantify stability performance of various SCC mixtures, and the method is shown to be reliable to monitor the variations in local composition of SCC as function of time.

Validation of the developed test method is carried out by correlating the electrical conductivity-based stability indices to variations of coarse aggregate and water contents determined immediately after electrical measurements on the plastic concrete. High degree of correlation between the quantitative stability indices derived from the electrical conductivity measurements and results from the physical stability tests were established.

The conductivity approach can then be used as a non-destructive method to evaluate the static stability of flowable concrete immediately after casting. Such stability is affected by the intrinsic stability of the concrete as well as placement conditions and concrete temperature.

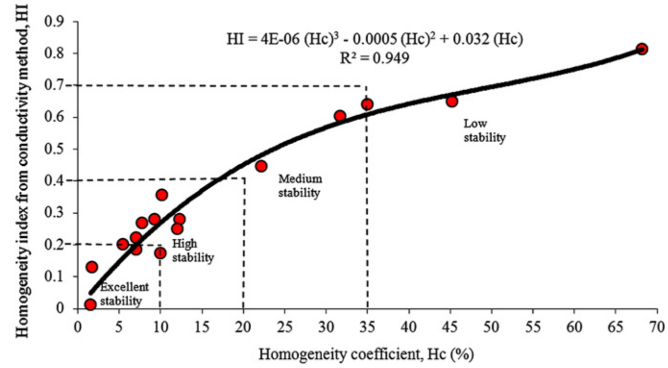


Fig. 11. Correlation between homogeneity index (HI) and homogeneity coefficient (Hc).

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