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Segregation-Resistant Carbon Microfibre Reinforced Self-Consolidating Concrete

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This paper presents the segregation resistance and flowability of self-consolidating concrete (SCC) including carbon microfibres. Initially, six SCCs were produced incorporating 0–0.50 vol.% of carbon microfibres at the two water-to-binder (W/B) ratios of 0.40 and 0.50. Later, two more SCCs were prepared using viscosity-modifying admixture (VMA) with 0% and 0.25% carbon microfibres at the W/B ratio of 0.40 for further improvement of segregation resistance. All SCCs were tested for slump flow and T_{50} flow time to determine flowability. The segregation resistance of SCCs was measured with respect to sieve segregation index (SSI). In addition, the appearance of SCCs was checked after the slump flow test to obtain visual stability index (VSI). The distribution of coarse aggregate particles in the two split halves of Ø100 mm x 200 mm cylinders was also examined as another indicator of the segregation resistance of SCC. Test results revealed that the SCCs made with the W/B ratio of 0.40 had excellent segregation resistance and good flowability. Carbon microfibres significantly decreased the flowability of SCC but increased its segregation resistance. Therefore, slump flow and SSI were lower whereas T_{50} flow time was higher for the SCCs with carbon microfibres. Moreover, the VSI of SCC became better with the inclusion of carbon microfibres. VMA further improved the SSI and VSI of SCC through enhanced viscosity. The distribution of coarse aggregate particles was also more uniform in the SCCs including carbon microfibres with or without VMA. Overall, the best performance of SCC with respect to both segregation resistance and flowability was observed for 0.25% carbon microfibres.

Keywords: *carbon microfibres, flowability, segregation resistance, self-consolidating concrete, viscosity-modifying admixture.*

Introduction

Self-consolidating concrete (SCC) is a highly flowable material that spreads through congested reinforcement and fills every corner of the formwork under self-weight without requiring any external compaction efforts such as vibration (Safiuddin 2008, Santos et al. 2017). It is a good choice for many structural elements where placing and compaction of ordinary concrete can be difficult due to the complex

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shape of formwork and congested reinforcement. The key workability properties of SCC are flowability and segregation resistance (Safiuddin, West et al. 2010). The merits of SCC depend on its flowability and segregation resistance. SCC must possess excellent flowability and adequate segregation resistance for good performance after being used in structures. However, SCC may suffer from inadequate or excessive flowability and poor segregation resistance if not designed properly (see Figure 1). In such case, SCC might exhibit segregation in the forms of bleeding, paste or mortar separation, and non-uniform distribution of coarse aggregates, which affect the properties and durability of hardened concrete (Safiuddin et al. 2009).

Figure 1. *Poor Segregation Resistance of SCC*

SCC was invented in Japan in 1980s to resolve the shortage of skilled labourers and to enhance the durability of concrete (Okamura & Ozawa 1995). It was initially developed using a high-range water reducer or superplasticizer (SP) and higher contents of cement and fine aggregate but a lower amount of smaller-size coarse aggregate with no fibres (Ashish & Verma 2019, Okamura & Ozawa 1995, Okamura 1997, Okamura & Ouchi 2003). Fibre-reinforced SCC is a relatively new development in concrete technology. The foremost aim of including fibres in SCC is to increase the ductility, thus overcoming its inherent deficiency of high brittleness. The fibres arrest the cracks and allow much larger deformation of concrete beyond the peak stress (Barluenga & Hernández-Olivares 2007). Hence, the inclusion of randomly distributed fibres in SCC would increase its tensile strength, stiffness, ductility, and toughness by preventing or controlling the initiation, propagation, and connectivity of cracks.

The use of fibres might also increase the segregation resistance of SCC through reductions in bleeding, paste or mortar separation, and aggregate settlement. However, the incorporation of fibres into SCC is a big challenge, since they significantly lessen the flowability of concrete (Yakhlaf et al. 2013). Yet many studies have been conducted to include different types of fibres in SCC. A literature review revealed that several researchers used steel, glass, and polypropylene fibres in SCC without adversely affecting its flowability (Corinaldesi & Moriconi 2004, Torrijos et al. 2008). Also, few studies showed that steel and glass fibres can be used in producing

SCC with an increased resistance to segregation (Barluenga & Hernández-Olivares 2007, Grünewald & Walraven 2001). In comparison, limited research was conducted to produce SCC using carbon microfibres, although the inclusion of such fibres in non-self-consolidating concrete is not completely new.

There is a potential for producing SCC with carbon microfibres, which could eliminate the shortcomings of other fibres. Steel fibres can cause corrosion problems when exposed on the surface of concrete (Safiuddin 2003). Glass fibres may suffer from embrittlement and strength loss (Safiuddin, Abdel-Sayed et al. 2010). Polypropylene fibres have some drawbacks such as poor fire resistance, low modulus of elasticity, low bond strength and high sensitivity to sunlight, although they are chemically inert and stable in the alkaline environment of concrete (Safiuddin, Abdel-Sayed et al. 2010). Carbon microfibres can be used to overcome these drawbacks. They are very attractive for their superior chemical stability at ambient temperatures. Carbon fibres are inert, physically as strong as steel fibres, and chemically more stable than glass and polypropylene fibres in an alkaline environment (Safiuddin 2003). They possess much higher modulus of elasticity and better thermal resistance than polypropylene fibres. Carbon fibres are also lighter and their strength-to-density ratio is higher than many other fibres (Safiuddin, Abdel-Sayed et al. 2010). Furthermore, the benefits of carbon microfibres could be enhanced by using ultrafine supplementary cementing materials such as silica fume (Yakhlaf 2013, Safiuddin et al. 2018).

The above-mentioned benefits of carbon microfibres might not be realized for SCC unless its flowability and segregation resistance are adequately achieved. Hence, experimental research should be carried out to investigate the effects of carbon microfibres on the flowability and segregation resistance of SCC. In this perspective, carbon microfibres obtained from recycled carbon-fibre-reinforced polymers can be used with sustainability benefits. Moreover, viscosity-modifying admixture (VMA) is known to improve the segregation resistance of SCC (Lachemi et al. 2004, Piekarczyk & Ła´zniewska-Piekarczyk 2021). VMA can be used additionally to produce segregation-resistant carbon microfibre reinforced SCC (CMFRSCC). For this, the synergistic effect of VMA and carbon microfibres on the segregation resistance of SCC should also be investigated. The present research was performed to produce CMFRSCC with excellent segregation resistance, while maintaining good flowability. The research tasks were carried out through selection of constituent materials, design of concrete mixtures, and testing of different fresh and hardened CMFRSCCs to examine the effects of carbon microfibres and VMA on the flowability and segregation resistance of concrete. Based on the experimental results, the optimum content of carbon microfibres was determined.

Research Significance

The outcomes of this study will create new opportunities for the construction industry. The research findings are expected to promote the production of CMFRSCC and accelerate its usage in new construction, precast concrete elements (wall panels, spandrel panels, decorative frames, etc.), and repair or rehabilitation work. The application of CMFRSCC in the repair or rehabilitation of aged structures will decrease the demands of cement and aggregates through a significant reduction in the required amount of concrete for new construction. Consequently, this will reduce the environmental pollution caused by aggregate harvesting from quarries and CO_2 emissions from cement factories. The usage of CMFRSCC will also reduce the ultimate quantity of construction and demolition wastes. Moreover, CMFRSCC was produced in this study by using Portland limestone cement, silica fume, and carbon microfibres. The manufacturing of Portland limestone cement declines the carbon footprint of cement factories by about 10%. In addition, silica fume is generated as a by-product of the silicon and ferrosilicon industries. Also, carbon microfibres used in this study are manufactured from recycled carbon-fibre-reinforced polymers. Hence, the use of these materials in CMFRSCC will help to mitigate the waste disposal and air pollution issues, thus contributing to environmental sustainability.

Experimental Materials and Methods

Concrete Materials

General-use Portland limestone (CSA Type GUL) cement, pea gravel (10 mm nominal maximum size), pit sand (5 mm nominal maximum size), carbon microfibres, densified silica fume, polycarboxylate-based SP, VMA, and normal tap water were used in the present study. Carbon microfibres (CMF) manufactured from recycled carbon-fibre-reinforced polymers were used, as they are less expensive and more sustainable than virgin carbon fibres. Pea gravel was used as coarse aggregate (CA) and pit sand was used as fine aggregate (FA). Type GUL cement (C) was used as the main binding material whereas silica fume (SF) was used as a supplementary cementing material. SF was used to ensure that the minimum specified compressive strength at 28 days is achieved, particularly as required for various chloride and freezing exposures described in CSA A23.1:19/CSA A23.2:19. It also aided the dispersion of CMF in concrete mixtures. SP was used in all concrete mixtures to obtain the required flowability of SCC. Tap water (W) was suitable for making concrete mixtures. In addition, VMA was used in two selected concrete mixtures for enhanced segregation resistance. Some of the physical properties of the constituent materials are given in Table 1.

Most of the properties presented in Table 1 were used to judge the suitability of the constituent materials and to determine the mixture proportions of concretes. Both fine and coarse aggregates satisfied the grading requirements of CSA A23.1: 19/CSA A23.2:19. The sieve analysis results of pit sand and pea gravel are shown in Table 2. The fineness modulus of sand was 2.7 whereas it was 5.9 for gravel. Cement and SF fulfilled the specified physical and chemical requirements. The fineness of cement fulfilled the requirements as specified in CSA A3001-13. The limestone content of the cement was 9.5%. The chemical compositions of cement and SF are shown in Table 3. SF was very rich in silica content. It fulfilled the minimum requirement of SiO_2 (85%) specified in ASTM C1240-20. The SO_3 concentration and loss on ignition (LOI) of the cement were below the maximum limits as stated in ASTM C595/C595M-21.

Table 1. *Physical Properties of the Constituent Materials of Concretes*

Constituent Material	Properties
Portland limestone cement*	Specific gravity: 3.11, Percent passing 45-μm sieve: 98.9%, Blaine specific surface area: 445 m^2/kg
Pea gravel	Specific gravity: 2.66, Absorption: 1.2%
Pit sand	Specific gravity: 2.66, Absorption: 1.4%
Silica fume†	Median particle size: 8 μm, Specific gravity: 2.24
Carbon microfibres‡	Fibre length: 6 mm, Fibre diameter: 7 μm Specific gravity: 1.80
Superplasticizer†	Specific gravity: 1.08, Solid content: 36%
Viscosity-modifying admixture†	Specific gravity: 1.02
Tap water	Density: 997.5 kg/m^3

*Properties were acquired from Lafarge Canada Inc. †Properties were sourced from Sika Canada Inc. ‡Properties were obtained from ELG Carbon Fibre Ltd.

Table 2. *Gradations of Pea Gravel and Pit Sand*

Pea Gravel		
Sieve Size	**Mass Percent Passing**	**CSA Limits**
14 mm	100	100
10 mm	91	85–100
5 mm	10.9	10–30
2.5 mm	3.5	0–10
1.25 mm	1.5	0–5
Pit Sand		
Sieve Size	**Mass Percent Passing**	**CSA Limits**
10 mm	100	100
5 mm	97.6	95–100
2.5 mm	82.4	80–100
1.25 mm	68.6	50–90
630 μm	51.7	25–65
315 μm	24.1	10–35
160 μm	6.6	2–10

Table 3. *Chemical Compositions of Cement and Silica Fume*

Chemical Component	Mass Content (%)	
	Cement*	**Silica Fume†**
Calcium oxide (CaO)	62.8	< 2%
Silicon dioxide (SiO_2)	19.0	≥ 90% > 85% (ASTM limit)
Aluminum oxide (Al_2O_3)	4.6	–
Iron oxide (Fe_2O_3)	3.0	–
Sulphur trioxide (SO_3)	2.8 ≤ 4.0% (ASTM limit)	–
Magnesium oxide (MgO)	0.8	–
Free CaO	1.0	–
Equivalent sodium oxide (Na_2O_{eq})	0.49	–
Limestone ($CaCO_3$) addition	9.5	–
Loss on ignition (LOI)	5.0 ≤ 10.0% (ASTM limit)	–

*Chemical composition was obtained from Lafarge Canada Inc. †Chemical composition was sourced from Sika Canada Inc.

Concrete Mixture Proportions

In total, eight SCC mixtures were designed and prepared in this study. Initially, six SCC mixtures were produced based on the water-to-binder (W/B) ratios of 0.40 and 0.50, and using 0%, 0.25% and 0.50% CMF by volume of concrete. Later, two additional SCC mixtures were produced using VMA along with 0% and 0.25% CMF at the W/B ratio of 0.40. In all concrete mixtures, SF was used by replacing 5% of the cement by weight. The guidelines of American Concrete Institute (ACI PRC-237-07) were followed to determine the mixture proportions of C, W, SF, FA, CA, and CMF. SP and VMA dosages were fixed based on the flowability and segregation resistance or stability of trial batches. A minimum slump flow of 550 mm as a measure of acceptable flowability and a maximum sieve segregation index of 18% for adequate stability were targeted for the SCC mixtures. The details of concrete mixture proportions are shown in Table 4.

Table 4. *Concrete Mixture Proportions*

Mixture Designation	W/B Ratio	CMF		C	SF	W	FA	CA	SP	VMA
		Vol. %	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	% B	% B*
CGUL40CF0	0.40	0	0	443.7	23.3	186.8	836.0	836.0	1.000	–
CGUL40CF25	0.40	0.25	4.5	443.7	23.3	186.8	829.4	836.0	4.250	–
CGUL40CF50	0.40	0.50	9.0	443.7	23.3	186.8	822.8	836.0	7.500	–
CGUL50CF0	0.50	0	0	392.8	20.7	206.8	836.0	836.0	0.625	–
CGUL50CF25	0.50	0.25	4.5	392.8	20.7	206.8	829.4	836.0	3.750	–
CGUL50CF50	0.50	0.50	9.0	392.8	20.7	206.8	822.8	836.0	7.000	–
CGUL40CF0V	0.40	0	0	443.7	23.3	186.8	836.0	836.0	1.000	0.118
CGUL40CF25V	0.40	0.25	4.5	443.7	23.3	186.8	829.4	836.0	4.750	0.118

*C + SF

Preparation and Testing of Concretes

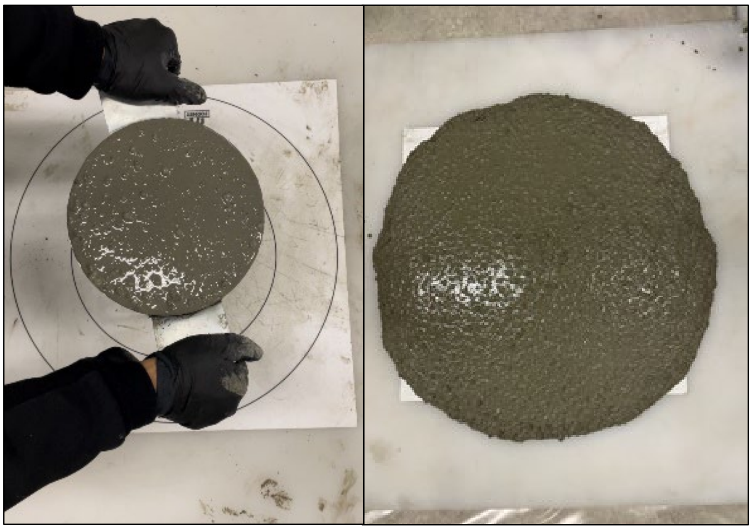
Fresh concretes were prepared using a pan-type shear mixer as illustrated in Figure 2. At first, pea gravel and pit sand were charged and mixed with the first one-third of the mixing water for 1 minute. Then the mixer was stopped, the binding materials (cement plus silica fume) were incorporated, and the mixing was continued for 2 minutes after adding the second one-third of the mixing water blended with half of the SP dosage. Thereafter, the mixer was stopped and carbon microfibres were spread by hand followed by 1 minute of mixing – this step was omitted in the cases of the control concretes without fibres. After that, the final one-third of the mixing water blended with the remaining half of the SP dosage was added and the mixer was run further for 2 minutes. When needed, an additional mixing of 1 minute or 2 (1 + 1) minutes was adopted by judging the flowability of concrete, particularly in the presence of carbon microfibres.

Immediately after the completion of mixing, the fresh concretes were discharged from the mixer into a steel tray, and tested for flowability and segregation resistance. The flowability of the concretes was determined with respect to slump flow and T_{50}

flow time following the procedures given in ASTM C1611/C1611M-21. The slump flow of the concretes was measured using an Abram's cone in its inverted position on a levelled baseplate (refer to Figure 3). The inverted cone was filled with freshly mixed concrete in one lift and without any compaction. Then the cone was raised vertically and the flow time of the concrete sample to spread 50 cm (T_{50}) was measured by a stopwatch. In addition, the largest and associated perpendicular diameters of the concrete spread (refer to Figure 3) at the end of the slump flow test were measured. The average diameter was recorded as the slump flow.

Figure 2. *Post-mixed Fresh Concrete*

Figure 3. *T_{50} Flow Time and Slump Flow Test for Flowability*



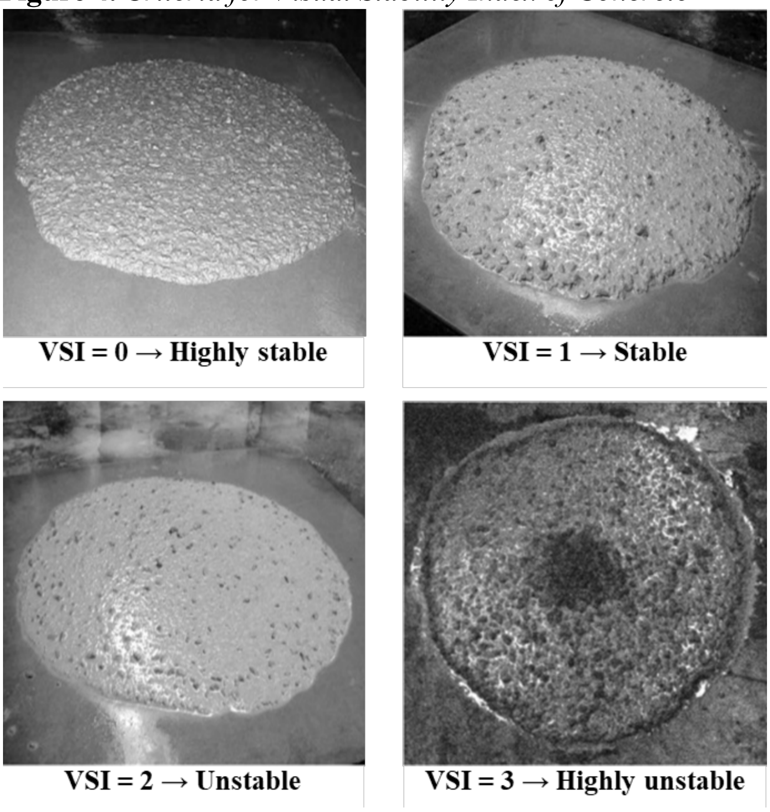
The segregation resistance of the concretes was measured using a 300-mm diameter No. 4 sieve according to the procedure depicted in Safiuddin et al. (2012). About 2 L of fresh concrete filled in a cylindrical container was poured onto the sieve placed on a pan. After 2 minutes of resting time, the measurements for the weights of the entire concrete sample and the mortar fraction passing No. 4 sieve were taken. Then sieve segregation index (SSI) was calculated using the following equation:

$$SSI = \frac{W_m}{W_c} \times 100\%$$

where
W_m = weight of the mortar fraction passing No. 4 sieve
W_c = weight of the entire concrete sample

The segregation resistance of the concretes was also visually assessed after conducting the slump flow test and expressed in terms of visual stability index (VSI). As a qualitative measure of segregation resistance, the VSI of the concretes was determined based on their appearance in respect of bleeding, mortar halo, and aggregate pile. While deriving VSI, the criteria shown in Figure 4, as given in ASTM C1611/C1611M-21, were used. Along with SSI and VSI, the distribution of coarse aggregate (pea gravel) particles in hardened concrete was also observed as another qualitative measure of segregation resistance. For this purpose, the two halves of Ø100 mm x 200 mm cylinder specimens after splitting longitudinally at the age of 28 days (Figure 5) were visually examined. The presence of pea gravel on the split faces was checked and photographed to judge the segregation resistance of concrete.

Figure 4. *Criteria for Visual Stability Index of Concrete*



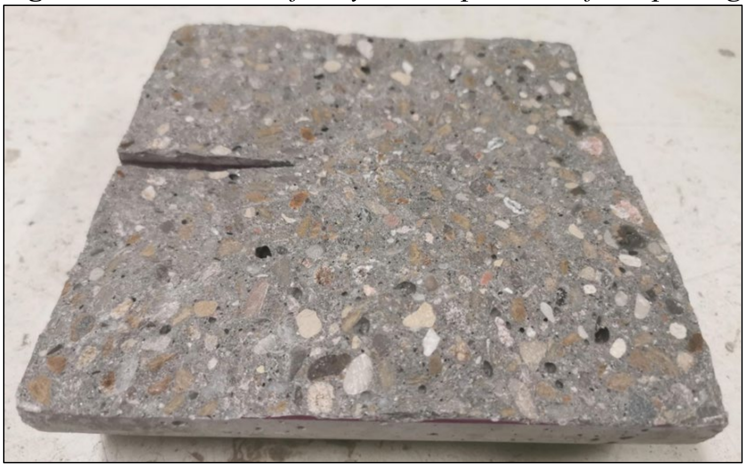
VSI = 0, no evidence of segregation or bleeding.

VSI = 1, no evidence of segregation but slight bleeding observed as a sheen on the concrete mass.

VSI = 2, a slight mortar halo ≤ 10 mm and/or aggregate pile in the center of the concrete mass.

VSI = 3, clearly segregating by evidence of a large mortar halo > 10 mm and/or a large aggregate pile in the center of the concrete mass.

Figure 5. *Two Halves of a Cylinder Specimen after Splitting*



Test Results and Discussion

The concretes were tested to determine their flowability (slump flow and T_{50} flow time) and segregation resistance (SSI) quantitatively. The segregation resistance of the concretes was also qualitatively examined with respect to the VSI of fresh samples and the distribution of coarse aggregate particles in hardened cylinder specimens. Experimental results were analyzed to determine the effects of carbon microfibres, W/B ratio, and VMA on the flowability and segregation resistance of SCC as well as to derive the optimum fibre content for CMFRSCC.

Flowability of Concretes

The flowability results in terms of slump flow and T_{50} flow time are shown in Table 5. All concretes provided a slump flow greater than 550 mm, which is the minimum acceptable value for SCC (Islam et al. 2022, SCCEPG 2005). The T_{50} flow time values of the concretes were comparatively high, except for CGUL50CF0. A T_{50} flow time less than 7 s is typically required for SCC (Islam et al. 2022). However, it is advised to set the T_{50} flow time more broadly for SCC (Koehler & Fowler 2007). This is because the SCC mixtures with a wide range of T_{50} flow time can be placed successfully. Moreover, it should be mentioned that a T_{50} flow time less than 7 s was suggested for the SCCs made without fibres. In the present study, the T_{50} flow time was recorded for the concretes with 0%, 0.25%, and 0.50% carbon microfibres. The concrete mixtures including 0.25% and 0.50% carbon microfibres provided a T_{50} flow time $\geq$ 11.5 s. Conversely, the control concrete mixtures without any fibres had a T_{50} flow time $\leq$ 9.3 s.

Table 5. *Flowability Results of Various Concretes*

Mixture Designation	W/B Ratio	CMF		SP	VMA	Slump Flow (mm)	T_{50} Flow Time (s)
		Vol. %	kg/m³	% B	% B*		
CGUL40CF0	0.40	0	0	1.000	–	675	9.3
CGUL40CF25	0.40	0.25	4.5	4.250	–	625	13
CGUL40CF50	0.40	0.50	9.0	7.500	–	645	14
CGUL50CF0	0.50	0	0	0.625	–	660	4.1
CGUL50CF25	0.50	0.25	4.5	3.750	–	575	11.5
CGUL50CF50	0.50	0.50	9.0	7.000	–	580	13
CGUL40CF0V	0.40	0	0	1.000	0.118	605	15.4
CGUL40CF25V	0.40	0.25	4.5	4.750	0.118	615	17.7

*C + SF

The incorporation of carbon microfibres significantly decreased the flowability of concrete, as demonstrated by lower slump flow and higher T_{50} flow time. Similar results were found in earlier research (Yakhlaf 2013, Yakhlaf et al. 2013). The SCC mixtures with carbon microfibres provided a lower slump flow and a higher T_{50} flow time. These flow results are related to the greater surface area of total solid materials in the presence of carbon microfibres. The wettable surface area increased and therefore the water demand became higher for the targeted slump flow. However, as the water content was kept constant (refer to Table 4), high SP dosages were needed to achieve a slump flow greater than 550 mm (refer to Table 5). Polycarboxylate-based SP improved the flowability of concrete. It helped to disperse the binder (cement and silica fume) particles and carbon microfibres by its repelling and steric hindrance actions. The SP dosage increased with a higher content of carbon microfibres. The largest SP dosage was required for 0.50% carbon microfibres. It should be noted that the SP dosage for 0.50% carbon microfibres was extremely high as compared to the recommended amount given by the manufacturer for non-fibre-reinforced SCC. This is due to the greater surface area and volume concentration of fibres which increased the water demand for the targeted slump flow (≥ 550 mm). Furthermore, the larger SP dosages were needed for the concretes made with the W/B ratio of 0.40. This is because the binder content was higher whereas the water content was lower for these concretes.

The concretes made with the W/B ratio of 0.40 provided higher slump flow and T_{50} flow time, as evident from Table 5. This is mostly due to the relatively high cohesiveness of concrete which was linked with the proportions of cement, silica fume, and water. It can be seen from Table 4 that the coarse aggregate (pea gravel) content remained the same for all concretes. In comparison, the fine aggregate (pit sand) content slightly decreased with the inclusion of carbon microfibres. This is because the amount of carbon microfibres was considered in the concrete mixture design by replacing an equal volume of pit sand. Nevertheless, the corresponding concretes with the same amount of carbon microfibres had the equal sand content. In general, the proportions of pea gravel and pit sand indicate that they did not play a dominant role in varying the cohesiveness of concrete. In contrast, the cement and silica fume contents were much higher whereas the water content was considerably lower for the concretes made with the W/B ratio of 0.40. Because of a lower water content with higher amounts of cement and silica fume, the cohesiveness of concrete increased. Consequently, the viscosity of concrete became higher which is evident from the results of T_{50} flow time. Furthermore, the deformability of concrete can be higher due to its more cohesiveness. As a result, an increase in slump flow might occur, as observed in the present study. However, it should be mentioned that very high viscosity caused by excessive cohesiveness may diminish the slump flow of concrete which was noticed for the VMA concretes in this study.

The SCC mixtures with VMA were highly cohesive as compared to the corresponding mixtures without VMA, as obvious from the results of slump flow and T_{50} flow time (see Table 5). The slump flow values of CGUL40CF0V and CGUL40CF25V were relatively low, although they remained above the targeted minimum value of 550 mm. In addition, the highest level of T_{50} flow time ($\geq$ 15.4 s) was obtained for these two SCCs. These results suggest that the viscosity of concrete increased substantially when VMA was used. Therefore, the flowability of SCC decreased and a higher SP dosage was needed for the targeted slump flow, particularly in the presence of carbon microfibres.

Segregation Resistance

The results obtained from the sieve segregation test and visual observation of slump flow spreads (SSIs and VSIs) are given in Table 6. The slump flow spreads assessed for the VSIs of different concretes are also shown in Figure 6 and Figure 7. Generally, the SSI results were consistent with the VSI values. The SSI values of all concretes were greatly lower than 18%, which is the maximum allowable limit for SCC (Salam et al. 2019, Parez et al. 2002). It suggests that all SCC mixtures possessed a high segregation resistance. However, the SCC mixtures made with the W/B ratio of 0.40 exhibited more segregation resistance providing lower SSI and VSI values. This is because these SCC mixtures were produced using the higher amounts of cement and silica fume at a lower water content which increased the viscosity of concrete, as evident from the results of T_{50} flow time (refer to Table 5). The higher viscosity contributed to improving the segregation resistance of concrete.

The incorporation of carbon microfibres increased the segregation resistance of concrete, as evident from the SSI and VSI values given in Table 6. Both SSI and VSI became lower with the higher amount of carbon microfibres in SCC, thus indicating a better segregation resistance. When no VMA was used, the lowest SSI and VSI values were obtained for 0.50% carbon microfibres. The improvement in segregation resistance by carbon microfibres was particularly more pronounced for the concretes prepared with the W/B ratio of 0.40 (see Table 6). The segregation resistance of concrete was enhanced by carbon microfibres because of reduced fluidity. The slump flow of concrete decreased whereas its T_{50} flow time increased with the higher content of carbon microfibres. Such results of slump flow and T_{50} flow time suggest that the flowability of concrete decreased in the presence of carbon microfibres. The decrease in concrete flowability contributed to improving the segregation resistance of SCC.

The VSI values of the concretes including carbon microfibres and VMA separately or combinedly were 0–1.00. An SCC with a VSI of ‘0’ is ‘highly stable’ whereas an SCC with a VSI of ‘1.00’ is ‘stable’ according to the criteria given in

ASTM C1611/C1611M-21. Hence, the VSI values of 0–1.00 imply that the SCC mixtures including carbon microfibres and/or VMA were resistant to segregation. However, it should be noted that an excellent segregation resistance was achieved when carbon microfibres and VMA were used together in the concrete mixture. Indeed, the combined use of carbon microfibres and VMA was highly effective to produce segregation-resistant SCC.

Table 6. *Stability or Segregation Resistance Results of Various Concretes*

Mixture Designation	W/B Ratio	CMF		SP	VMA	SSI (%)	VSI
		Vol. %	kg/m^3	% B	% B*		
CGUL40CF0	0.40	0	0	1.000	–	4.5	1.00
CGUL40CF25	0.40	0.25	4.5	4.250	–	2.2	0.50
CGUL40CF50	0.40	0.50	9.0	7.500	–	1.0	0.25
CGUL50CF0	0.50	0	0	0.625	–	5.8	1.25
CGUL50CF25	0.50	0.25	4.5	3.750	–	3.6	1.00
CGUL50CF50	0.50	0.50	9.0	7.000	–	2.9	0.75
CGUL40CF0V	0.40	0	0	1.000	0.118	2.1	0
CGUL40CF25V	0.40	0.25	4.5	4.750	0.118	1.3	0.25

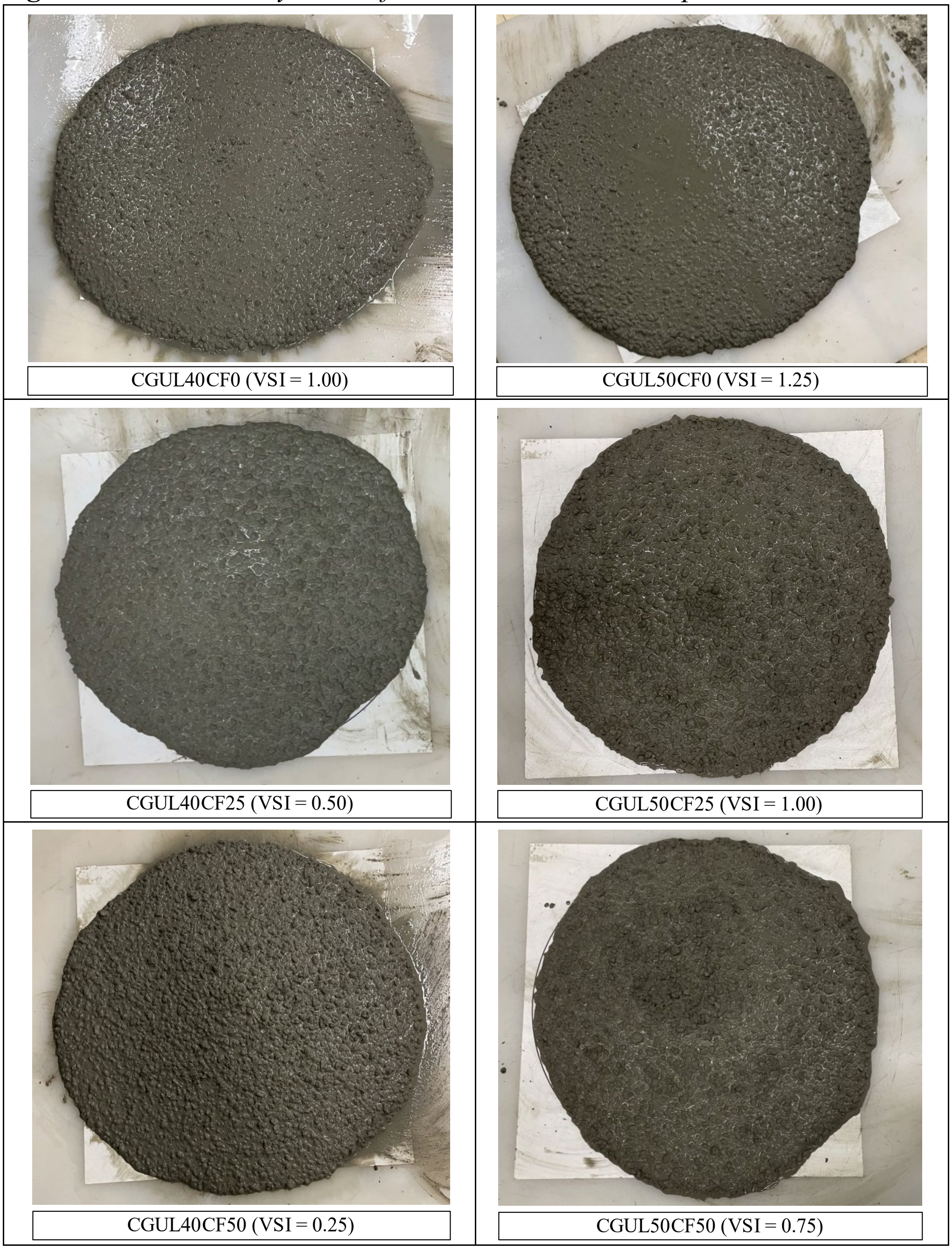
*C + SF

The use of VMA greatly increased the segregation resistance of SCC. Hence, the SSI and VSI values of the two VMA concretes (CGUL40CF0V and CGUL40CF25V) were significantly lower than their corresponding non-VMA concretes (refer to Table 6 and Figure 7). Indeed, the uniformity of fresh concrete improved with lower bleeding and mortar halo for the SCC mixtures prepared with VMA. In addition, the settlement of larger coarse aggregate particles was minimized when VMA was used in SCC (see Figure 8). Therefore, the distribution of coarse aggregate was more uniform in the cylinder specimens (see Figure 9), which were fabricated using the VMA concretes with and without carbon microfibres. The enhanced viscosity resulting from VMA impeded the settlement of aggregates and thus reduced the heterogeneity in concrete. This effect became more pronounced when VMA was used in the presence of carbon microfibres.

Optimum Content of Carbon Microfibres

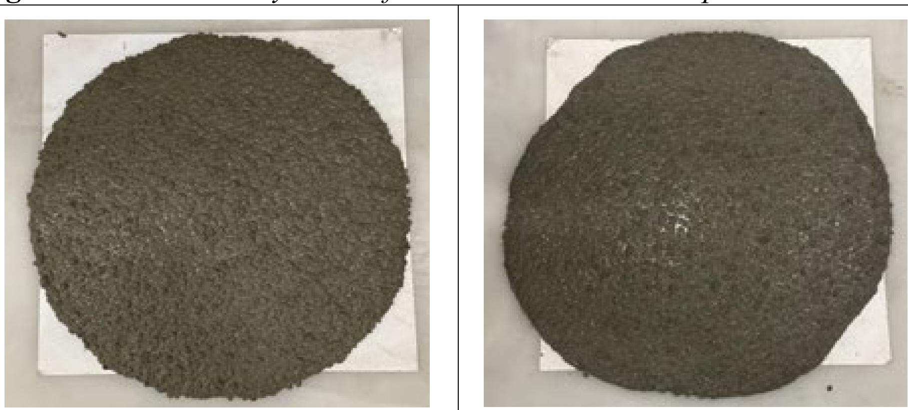
The overall findings of the present study revealed that segregation-resistant SCC can be produced using carbon microfibres with or without VMA. In the present study, SCC mixtures were produced incorporating 0–0.50 vol.% of carbon microfibres. The inclusion of carbon microfibres greatly increased the segregation resistance of concrete. The SSI and VSI values decreased with the higher content of carbon microfibres, thus indicating a greater segregation resistance. In particular, the SSI and VSI values were significantly low for 0.50% carbon microfibres. However, the incorporation of carbon microfibres substantially decreased the flowability of concrete. This effect was more pronounced for the SCC mixtures including 0.50% carbon microfibres. Therefore, the extremely high SP dosages were needed to achieve the required slump flow of concrete when 0.50% carbon microfibres were used. Very high SP dosages can cause undesirable bleeding and setting problems after placing fresh concrete. Hence, considering both the flowability and segregation resistance of concrete, 0.25% was decided as the optimum content of carbon microfibres. The concrete mixtures including 0.25% carbon microfibres with or without VMA provided good flowability and excellent segregation resistance.

Figure 6. *Visual Stability Index of Fresh SCC Mixtures Prepared without VMA*



CGUL40CF0 (VSI = 1.00)
CGUL50CF0 (VSI = 1.25)
CGUL40CF25 (VSI = 0.50)
CGUL50CF25 (VSI = 1.00)
CGUL40CF50 (VSI = 0.25)
CGUL50CF50 (VSI = 0.75)

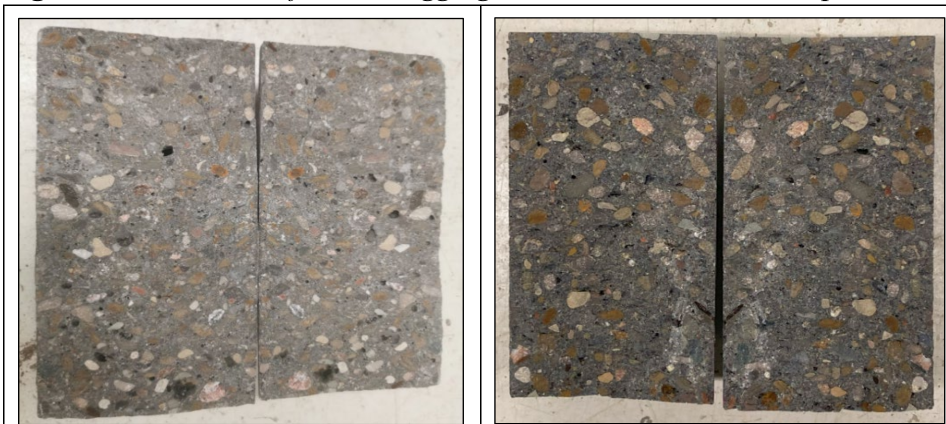
Figure 7. *Visual Stability Index of Fresh SCC Mixtures Prepared with VMA*



CGUL40CF0V (VSI = 0) | CGUL40CF25V (VSI = 0.25)

Figure 8. *Cylinder Specimens Cast Using SCC Mixtures Made with VMA*

Figure 9. *Distribution of Coarse Aggregates in Hardened SCCs Prepared with VMA*



CGUL40CF0V | CGUL40CF25V

Conclusions

The following conclusions are drawn from the findings of this study on the flowability and segregation resistance of CMFRSCC.

1. Carbon microfibres, VMA, and W/B ratio notably influenced the flowability and segregation resistance of SCC.
2. The SCC mixtures made with the W/B ratio of 0.40 provided higher slump flow and T_{50} flow time due to a relatively high cohesiveness of concrete resulting from the higher amounts of cement and silica fume at a lower water content.
3. Carbon microfibres significantly decreased the flowability of concrete due to the increased surface area of total solid materials and therefore needed a higher SP dosage to achieve the targeted slump flow.
4. In the presence of carbon microfibres, slump flow decreased whereas T_{50} flow time increased with a greater fibre content, which increased the water demand, and thus needed a higher SP dosage for the required flowability of SCC.
5. Carbon microfibres greatly increased the segregation resistance of SCC due to higher viscosity resulting from the reduced fluidity of concrete.
6. The segregation resistance was higher for the SCC mixtures made with the W/B ratio of 0.40 due to the enhanced viscosity of concrete caused by the higher amounts of cement and silica fume at a lower water content.
7. Among various non-VMA CMFRSCCs, the concrete mixture prepared with the W/B ratio of 0.40 and 0.50% carbon microfibres showed the highest segregation resistance with the lowest SSI and VSI values.
8. The use of VMA decreased the flowability of SCC but greatly increased its segregation resistance due to higher viscosity.
9. An excellent improvement in the segregation resistance of SCC was observed due to the synergistic effect of VMA and carbon microfibres.
10. In the context of the present study, the optimum content of carbon microfibres was 0.25 vol.%, for which the SCC mixtures exhibited the best performance with respect to flowability and segregation resistance.

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References

ACI PRC-237-07 *Self-consolidating concrete (reapproved 2019)*. Farmington Hills, MI: American Concrete Institute.

Ashish DK, Verma SK (2019) An overview on mixture design of self-compacting concrete. *Structural Concrete* 20(1): 371–395.

ASTM C595/C595M-21. *Standard specification for blended hydraulic cements*. West Conshohocken, PA: ASTM International.

ASTM C1240-20. *Standard specification for silica fume used in cementitious mixtures.* West Conshohocken, PA: ASTM International.

ASTM C1611/C1611M-21. *Standard test method for slump flow of self-consolidating concrete*. West Conshohocken, PA: ASTM International

Barluenga G, Hernández-Olivares F (2007) Cracking control modified with short AR-glass fibers at early age. Experimental results on standard concrete and SCC. *Cement and Concrete Research* 37(12): 1624–1638.

Corinaldesi V, Moriconi G (2004) Durable fiber-reinforced self-compacting concrete. *Cement and Concrete Research* 34(2): 249–254.

CSA A23.1:19/CSA A23.2:19. *Concrete materials and methods of concrete construction/ Test methods and standard practices for concrete*. Toronto, ON: Canadian Standards Association.

CSA A3001-13. *Cementitious materials for use in concrete*. Toronto, ON: Canadian Standards Association.

Grünewald S, Walraven JC (2001) Parameter-study on the influence of steel fibers and coarse aggregate content on the fresh properties of self-compacting concrete. *Cement and Concrete Research* 31(12): 1793–1789.

Islam GMS, Akter S, Reza TB (2022) Sustainable high-performance, self-compacting concrete using ladle slag. *Cleaner Engineering and Technology* 7: Article 100439.

Koehler EP, Fowler DW (2007) *Self-consolidating concrete for precast structural applications: mixture proportions, workability, and early age hardened properties (FHWA/TX-08/0-5134-1)*. Austin, TX: Center for Transportation Research, The University of Texas at Austin.

Lachemi M, Hossain KMA, Lambros V, Nkinamubanzi P-C, Bouzoubaâ N (2004) Self-consolidating concrete incorporating new viscosity modifying admixtures. *Cement and Concrete Research* 34(6): 917–926.

Okamura H (1997) Self-compacting high-performance concrete. *Concrete International* 19(7): 50–54.

Okamura H, Ouchi M (2003) Self-compacting concrete. *Journal of Advanced Concrete Technology* 1(1): 5–15.

Okamura H, Ozawa K (1995) Mix design for self-compacting concrete. *Concrete Library of JSCE* 25(6): 107–120.

Parez N, Romero H, Hermida G, Cuellar G (2002) Self-compacting concrete, on the search and finding of an optimized design. In *Proceedings of the First North American Conference on the Design and Use of Self-Consolidating Concrete*. Chicago, IL: Hanley-Wood LLC.

Piekarczyk A, Ła´zniewska-Piekarczyk B (2021) Impact of self-compacting concrete admixtures on frost resistance and compressive strength—commensurability of frost resistance criteria. *Materials* 14: Article 2922.

Safiuddin M (2003) *High performance mortar reinforced with short carbon fibers* (master's thesis). Windsor, ON: The University of Windsor.

Safiuddin M (2008) *Development of self-consolidating high performance concrete incorporating rice husk ash* (doctoral thesis). Waterloo, ON: The University of Waterloo.

Safiuddin M, Abdel-Sayed G, Hearn N (2010) *High performance mortars with short carbon fibers: properties and mix optimization*. Saarbrücken, Germany: Lambert Academic Publishing.

Safiuddin M, West JS, Soudki KA (2009) *Self-consolidating high performance concrete with rice husk ash: components, properties, and mixture design*. Saarbrücken, Germany: VDM Publishing House Ltd.

Safiuddin M, West JS, Soudki KA (2010) Flowing ability of self-consolidating concrete and its paste and mortar components incorporating rice husk ash. *Canadian Journal of Civil Engineering* 37(3): 401–412.

Safiuddin M, West JS, Soudki KA (2012) Properties of freshly mixed self-consolidating concretes incorporating rice husk ash as a supplementary cementing material. *Construction and Building Materials* 30: 833–842.

Safiuddin M, Yakhlaf M, Soudki KA (2018) Key mechanical properties and microstructure of carbon fibre reinforced self-consolidating concrete. *Construction and Building Materials* 164: 477–488.

Salam MA, Safiuddin M, Jumaat MZ (2019) Segregation resistance of self-consolidating concrete incorporating palm oil fuel ash. In *Proceedings of the 7^th^ International Materials Specialty Conference, CSCE 2019 Annual Conference*. Laval, Quebec: Canadian Society for Civil Engineering.

Santos SA, da Silva PR, de Brito J, Evangelista L (2017) Fresh state properties of self-compacting concrete with recycled aggregate – A literature review. *Athens Journal of Technology & Engineering* 4(1): 33–46.

SCCEPG (2005) *The European guidelines for self-compacting concrete: specification, production and use*. Self-Compacting Concrete European Project Group (SCCEPG). Available at: theconcreteinitiative.eu.

Torrijos MC, Barragán BE, Zerbino RL (2008) Physical-mechanical properties, and microstructure of plain and fibre-reinforced self-compacting concrete. *Construction and Building Materials* 22(8): 1780–1788.

Yakhlaf M (2013) *Development of carbon fiber reinforced self-consolidating concrete patch for repair applications* (master's thesis). Waterloo, ON: The University of Waterloo.

Yakhlaf M, Safiuddin M, Soudki KA (2013) Properties of freshly mixed carbon fibre reinforced self-consolidating concrete. *Construction and Building Materials* 46: 224–231.