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Self-consolidating concrete incorporating new viscosity modifying admixtures

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Abstract

Self-consolidating concrete (SCC) is known for its excellent deformability, high resistance to segregation and use without applying vibration in congested reinforced concrete structures characterized by difficult casting conditions. The use of viscosity modifying admixtures (VMA) has proved very effective in stabilizing the rheology of SCC. Commercial VMAs currently available on the market are costly, which increases the cost of such a concrete. This article presents the suitability of four different types of new polysaccharide-based VMA in the development of SCC. A preliminary investigation was carried out on the rheological properties and setting times of mortar mixes with various types and dosages of VMA to study the influence and suitability of new VMAs. A more detailed study was then carried out on the SCC fresh and hardened properties such as slump flow, segregation, bleeding, flow time, setting time and compressive strength of different mixes with various dosages of an identified new VMA. The performance of various SCC mixtures with the new VMA was compared with a SCC using a commercial VMA designated as "COM" and a SCC mixture with Welan gum. The study on new VMA is encouraging and confirms the production of satisfactory SCC with acceptable fresh and hardened properties comparable with or even better than that made with commercial VMA and Welan gum. The suggested mix with 0.05% of the new Type A VMA satisfies the requirement of fresh and hardened properties of SCC and will require 7% less VMA dosage than that required in the commercial VMA mixture. The SCC with new VMA is also cost-effective.

Keywords: Self-consolidating concrete; Fresh concrete; Rheology; Stability; Admixture

1. Introduction

A self-consolidating concrete (SCC) is defined as a concrete that has excellent deformability and high resistance to segregation and can be filled in heavily reinforced or restricted area without applying vibration. SCC was developed in Japan [1] in the late 1980s, and recently, this concrete has gained wide use in many countries for different applications and structural configurations [2–8].

Several different approaches have been used to develop SCC. One method to achieve self-consolidating property is to increase significantly the amount of fine materials (e.g., fly ash or limestone filler) [9,10] without changing the water content compared with common concrete. One alternative approach consists of incorporating a viscosity modifying admixture (VMA) to enhance stability [11–13]. The use of VMA along with adequate concentration of superplasticizer (SP) can ensure high deformability and adequate workability, leading to a good resistance to segregation. Mixture containing VMA exhibits shear-thinning behavior whereby apparent viscosity decreases with the increase in shear rate. Such concrete is typically thixotropic where the viscosity buildup is promoted due to the association and entanglement of polymer chains of the VMA at a low shear rate that can further inhibit flow and increase viscosity. The thixotropic property increases the stability of the concrete and reduces the risk of segregation after casting. The use of Welan gum, a kind of natural polysaccharide, as VMA has proved very effective [14], but this product is costly and increases the price of concrete. Investigation is necessary to explore the potential use of new low-cost VMA in the development of SCC.

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A comprehensive research on the development of SCC incorporating new types of VMA and high volumes of supplementary cementing materials and on their structural applications is now ongoing at the Ryerson University in collaboration with CANMET/ICON. The SCC currently available on the market is expensive due to higher prices of VMA and high volume of binder in the mixture, and a cost-effective product is desired to produce a competitive concrete in the construction industry. The successful completion of this project can lead to the development of high performance, environmentally friendly and cost-effective SCC. The research on the application of such SCC for the construction and repair of structural elements will also lead to the development of innovative techniques that can be confidently used in the future.

This article presents the development of SCC with four different types of new VMA. This is a continuation of the previous research that studied the suitability of new VMAs based on the rheological aspect, washout resistance and stability of the cement pastes [15]. In accordance with the previous study, a preliminary investigation was carried out on cement mortars to determine the suitability of new VMAs. A series of tests using a viscometer measuring the rheological parameters of mortar such as yield stress and plastic viscosity as well as setting time were carried out to determine the viable dosages and types of VMA. A study was then carried out on the fresh and hardened properties of different SCC mixtures with various dosages of a chosen new VMA. The performance of various mixtures was compared with known commercial SCC mixtures using a commercial VMA and Welan gum.

2. Experimental program

The experimental investigation was carried out in two phases. In Phase 1, tests were carried out on various mortar mixes with four new VMA types in addition to a commercial VMA largely used in Canada. The Phase 2 investigated the suitability of production of SCC with new selected VMAs.

2.1. Materials

2.1.1. Cement and aggregates

Type 10 Portland cement (similar to ASTM Type I) with specific gravity of 3.17 and Blaine fineness of 4070 cm^2/g was used. Chemical and physical properties of cement are shown in Table 1.

Twenty-millimeter maximum size crushed limestone and local natural sand were used as coarse and fine aggregates, respectively. The coarse and fine aggregates each had a specific gravity of 2.70, a dry density of 2690 kg/m^3, a saturated surface dry density of 2710 kg/m^3 and water absorptions of 0.39% and 0.84%, respectively. Table 2 presents the grading of fine and coarse aggregates.

Table 1
Chemical and physical properties of cement

ASTM cement Type 1			
Chemical analyses (%)		Physical tests	
Calcium oxide (CaO)	62.0	Specific gravity	3.17
Silica (SiO_2)	20.3	Fineness	
Alumina (Al_2O_3)	4.2	Passing 45 μm (%)	94
Iron oxide (Fe_2O_3)	3.0	Specific surface, Blaine (cm^2/g)	4070
Sulfur trioxide (SO_3)	3.5	Compressive strength (MPa)	
Magnesia (MgO)	2.8	7 days	26.0
Sodium oxide (Na_2O)	0.2	28 days	32.0
Potassium oxide (K_2O)	0.9	Setting time, Vicat test (min)	
Loss on ignition	2.0	Initial setting	220
		Final setting	325
		Air content of mortar (vol.%)	5.5

2.1.2. Chemical admixtures

A SP composed of naphthalene formaldehyde condensates having specific gravity of 1.21 and total solid content of 40.5% was used. Four novel polysaccharide-based VMAs (suspension in water) classified as A, B, C and D having specific gravity of 1.42 and total solid content of about 81% were used (Table 3). All the tests in this study were carried out at room temperature. A known commercial VMA widely used in Canada and designated in this article as "COM" was also used for a comparative purpose. The specific gravity and total solid content of COM were 1.21% and 42.5%, respectively (Table 3). The chemical composition of COM is a proprietary secret and it is composed of a combination of SP and VMA. The percentages of VMA and SP were calculated on the basis of total solid content. A water-soluble polysaccharide-based Welan gum was also used. Welan gum is an anionic, long-chain biopolymer with sugar backbones substituted with sugar side chains, high molecular weight (around 2 million) polysaccharide produced by a controlled aerobic fermentation process [16].

2.2. Phase 1: tests on mortar

SCC has a lower coarse aggregate content than that of normal concrete; therefore, the properties of the mortar are dominant. Assessing the properties of the mortar is an integral part of many SCC mix design processes; therefore, knowledge of the mortar properties is itself useful [17]. In addition, testing mortar is more convenient than testing concrete. In SCC, the mortar phase provides lubrication between coarse aggregate particles and overall stability to the concrete. The required properties of mortar are similar to those of the concrete itself; that is, a low yield stress to ensure flow under self-weight and a plastic viscosity sufficient to ensure that the concrete (mortar) does not segregate during flow but not so high that the flow is too slow for practical concreting.

Table 2
Grain size distribution of aggregates

Sieve size (mm)	Fine aggregate	Coarse aggregate
20	100	100
12.7	100	67
9.5	100	34
4.75	97.1	0
2.36	87.6	
1.18	76.7	
0.6	52.4	
0.3	16.6	
0.15	4.0	

Flow of fresh paste, mortar and concrete is in the domain of fluid mechanics that deals with mass in motion (i.e., a time-dependent parameter). For this reason, the Bingham model [18] was introduced to characterize the flow behavior of fresh paste, mortar and concrete by measuring the rheology data such as the yield stress, viscosity, shear stress and shear rate. In this study, tests on rheological properties as well as setting time were conducted on mortars with different dosages of VMA.

The tests on mortar were designed to study the performance of novel form of VMAs and to identify the most suitable one that could be employed with optimum efficiency in the design of mixtures for the development of SCC.

2.2.1. Mix proportion and preparation of mortar

Twelve mortar mixes were made to study the effect of type and dosage of VMA on rheological properties and setting time. The proportion of cement and sand was kept approximately at 1:2 by weight. For mortar with VMA (A, B, C, D and COM), W/C and SP content were kept constant at 0.45% and 0.6% by mass of cement, respectively, while VMA contents were kept at 0.025% and 0.075% of cement. Mix 9 with commercial VMA COM had W/C of 0.42, SP content of 0.74% and VMA content of 0.37%, typically used in a commercial SCC using COM as per recommendation from the manufacturing company. The sand and 50% of the water was first mixed for 30 s. Then, cement was added with the remaining water, SP and VMA and mixed for an additional 2 min.

Table 3
Chemical and physical properties of VMA

	VMAs				
	A	B	C	D	COM
Total solids (%)	80.7	80.2–81.4	80.4–81.6	82.1	42.5
pH	4.9	4.9	4.8	4.8	7.0
Specific gravity	1.42	1.42	1.42	1.42	1.21
Viscosity (cP)					
26°C	81,000	81,000	54,000	25,000	–
60°C	2500	2500	1600	1000	–

2.2.2. Rheological properties

The rheological measurements of mortars were conducted by using a commercially available digital Brookfield viscometer (Model RVDV-II) equipped with cylindrical spindles at normal room temperature of about 22–25°C. The test samples were poured into a beaker; then, the spindle of the viscometer was introduced in the beaker for measurement. The tests were executed stepwise at 100, 60, 50, 30, 20, 12 and 5 rpm. At each rotational speed, torque and apparent viscosity data were recorded. The results were then converted into viscosity functions such as shear stress (Pa) and shear rate (1/s) using standard procedure [19]. The linear regression analysis was carried out to determine the viscosity and yield stress as slope and intercept of the regression line drawn through the data points in shear stress versus shear rate plot.

Table 4 shows the effect of VMA content (%) and types on the viscosity and yield stress of mortars. Viscosity of mortar with new VMAs is found to increase and yield stress is generally found to decrease with the increase of VMA content from 0.025% to 0.075% (when SP content is kept constant at 0.6%). The yield stresses of mortars with 0.025% and 0.075% of Types A–D VMAs are lower than those of mortars with COM having similar dosages. In fact, no significant difference in yield stress is found between mortars with 0.025% and 0.075% COM and control mortar (0% VMA). This means that Types A–D VMAs are more sensitive in lowering the yield stress or enhancing the flowability of mortars with such lower dosages (0.025% and 0.075%) than COM.

Fig. 1 compares the typical shear stress versus shear rate relationships for all the mortar mixtures with new VMAs. Apparent viscosities of the mortars with various VMAs including the control mortar are also compared in Fig. 2. Apparent viscosity is found to decrease and shear stress is found to increase with the increase of shear rate. All new

Table 4
Test results of mortar mixes

Mix no.	W/C	VMA types	VMA (% cement)	Viscosity (Pa. s)	Yield stress (Pa)	Setting times (h:min)	
						Initial	Final
1	0.45	A	0.025	0.83	7.33	04:14	05:31
2	0.45	B	0.025	0.83	7.87	03:47	05:10
3	0.45	C	0.025	0.85	7.46	03:37	04:42
4	0.45	D	0.025	0.92	7.72	03:41	04:43
5	0.45	A	0.075	0.86	6.12	06:26	07:40
6	0.45	B	0.075	0.96	5.80	06:43	07:53
7	0.45	C	0.075	0.92	6.42	06:34	07:42
8	0.45	D	0.075	0.99	6.91	06:44	07:51
9	0.45	COM	0.370	2.37	14.92	06:34	07:42
10	0.45	COM	0.025	0.75	8.35	03:20	05:35
11	0.45	COM	0.075	0.75	8.33	03:55	06:05
12	0.45	–	0	0.74	8.43	03:15	04:55

For all mixes: SP 0.6% by weight of cement, except for COM Mix 9: SP 4 l/m^3 or 4.84 kg/m^3 or 0.74% by weight of cement

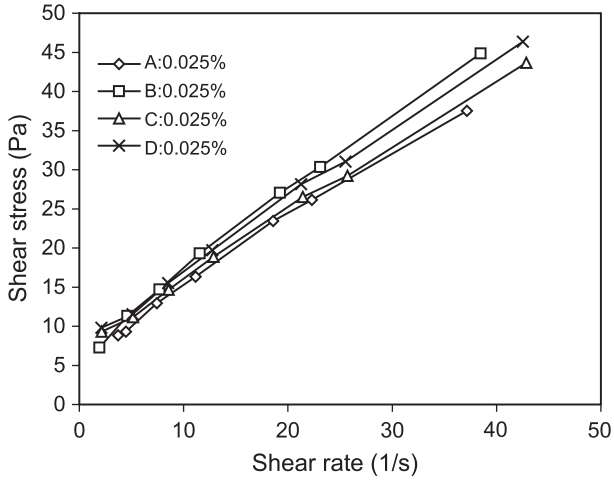

Fig. 1. Variation of shear stress with shear rate for mortar.

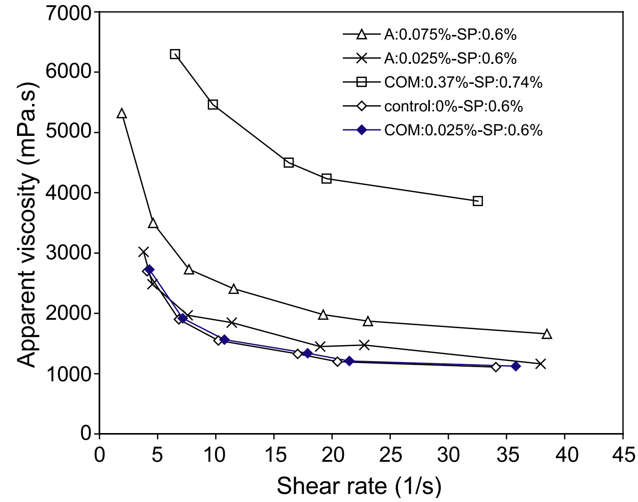

Fig. 3. Effect of VMA content and shear rate on the apparent viscosity of mortar.

VMAs show comparatively similar rheological properties (Fig. 2).

For any given concentration of SP (0.6% in all the mortars, except 0.74% in the COM Mix 9), the increase in VMA content increases the viscosity at both high and low shear rates (Fig. 3). The apparent viscosity of the mortar is increased with the increase of the percentage of VMA in the mixture. The increase in apparent viscosity can be attributed to the fact that the degree of water retention increases with the dosage of VMA, which acts on the aqueous phase. The apparent viscosities of mortars with Types A–D VMAs are higher than the control (0% VMA) and COM VMA mortars (Fig. 3). The development of higher apparent viscosity in COM mortar (Mix 9) is due to the higher percentage of COM VMA. On the other hand, the increase in apparent viscosity of mortars with 0.025% and 0.075% COM VMA is negligible compared with control mortar. The apparent viscosity of mortars with similar dosages of SP (0.6%) and VMA (0.025% and 0.075%) is higher in mortars with Types A–D VMAs than those with COM VMA (Fig. 2). This is an indication of the better performance of Types A–D VMAs compared with COM VMA in enhancing the viscosity of mortars.

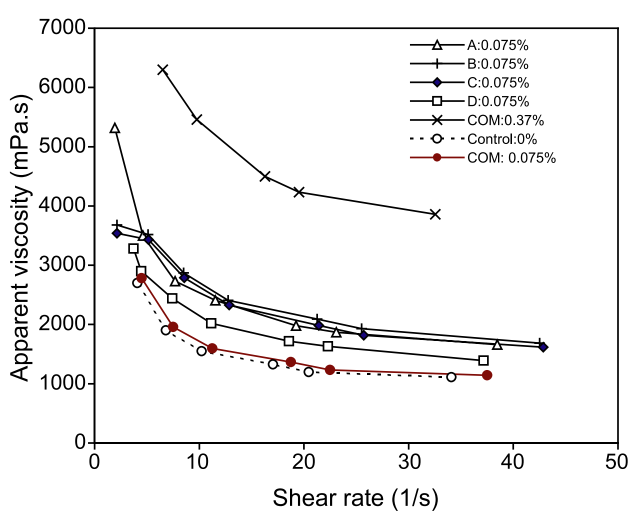

Fig. 2. Variation of apparent viscosity of mortar with shear rate.

2.2.3. Setting time

The test for setting time was carried out following ASTM C403-90 standard penetration test. Regression analysis on the data of penetration resistance versus time was performed to determine initial and final setting times.

The initial and final setting times of all the mixes are summarized in Table 4. Both initial and final setting times of mortar mixes with Types A–D-COM VMAs are increased with the increase of VMA content from 0.025% to 0.075%. This is justifiable because the VMA polymer chains can become adsorbed onto cement grains and interfere with the precipitation of various minerals into solutions that influence the rate of hydration and setting [20]. The increase in initial setting time of cement grout and mortar with the increase of dosages of Welan gum and cellulose-based VMA were reported by Khayat and Yahia [20] and Sogo [21]. The effect of VMA on the setting time depends on the type and concentration of VMA, the type and dosage of SP and the cement composition and W/C. For the same dosage of VMA (as clearly observed at 0.075%), the influence of all the new VMAs on the setting times is similar.

The setting times of mortars with Types A–D-COM VMAs are higher than the control mortar (0% VMA). However, increase in setting times with the increase of the dosage of VMA is higher in mortars with Types A–D VMAs compared with COM VMA (Table 4). The setting times (initial set around 06:30 h while final set around 07:45 h) of mortar with 0.37% of COM VMA can be matched by using only 0.075% of Types A–D VMAs. However, to achieve similar setting time, the new VMAs need five times less VMA (only 0.075%) than commercial VMA COM (0.37%).

2.2.4. Conclusions

The study on mortar suggests that all new VMAs can be used in the development of a SCC with satisfactory rheological properties (better cohesiveness and higher flowability) with less VMA dosage than COM and can prove to be an economical alternative. However, overall performance of Types A and B VMA was better in enhancing rheological and consistency properties of paste [15]. Type A VMA was chosen to develop SCC and the development of SCC is described in Phase 2 of the investigation.

2.3. Phase 2: development of SCC incorporating new Type A VMA

Nine concrete mixes were tested including one mix with COM (Mix 7), one mix with Welan gum (Mix 8), one control mix (Mix 9) and six mixes (Mixes 1–6) with various dosages of Type A VMA. The details of concrete mix proportions are summarized in Table 5.

W/C of all the concrete mixes was kept constant at about 0.45 while the proportion of coarse and fine aggregates was kept at 1:1. The proportion of the COM concrete mix was as per typical mix design recommended by the manufacturing company in Canada.

2.3.1. Tests on fresh SCC properties

The tests were conducted to determine the consistency, workability, stability, bleeding, segregation and setting time of SCC.

2.3.1.1. Slump flow. The slump flow test [14] was used to evaluate the free deformability and flowability of SCC in the absence of obstructions. A standard slump cone was used for the test and the concrete was poured in the cone without consolidation. Slump flow value represented the mean diameter (measured in two perpendicular directions) of concrete after lifting the standard slump cone. Nagataki and Fujiwara [22] suggested a slump flow value ranging from 500 to 700 mm for a concrete to be self-compacted. At >700 mm, the concrete might segregate, and at < 500 mm, the concrete might have insufficient flow to pass through highly congested reinforcement.

The test results of all the concretes are summarized in Table 6. The results show that all SCC mixes with Type A VMA meet the required slump flow value as well as the Welan gum mix. The performance of COM mixes satisfies the requirement and shows comparable flowability to mixes with Type A VMA, with the expense of high dosages of COM, about 5–15 times of Type A VMA. The control concrete (Mix 9) with 0% VMA fails to satisfy the criteria.

2.3.1.2. V-funnel test. The deformability through restricted areas can be evaluated using V-funnel test [23]. In this test, the funnel shown in Fig. 4 was filled completely with concrete and the bottom outlet was opened, allowing the concrete to flow out. The time of flow from the opening of outlet to the seizure of flow was recorded. Flow time can be associated with a low deformability due to high paste viscosity, high interparticle friction or blockage of flow. Flow time should be below 6 s for the concrete to be considered as SCC. All mixes performed well with no significant segregation and jamming of aggregate at the contraction. Test results as shown in Table 6 indicate that all SCC mixes meet the requirements of allowable flow time. Furthermore, SCC mixes with Type A VMA produces shorter flow times than the COM and Welan gum mixes.

2.3.1.3. Segregation and bleeding. Stability is defined as the ability of SCC to resist segregation or to maintain

Table 5
Mix proportions for concrete mixes

Mix no.	W/C	Cement (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	SP (l/m^3)	VMA (kg/m^3)	% VMA
SCC mixes with Type A VMA								
1	0.45	400	180	937	938	3.5	0.122	0.025
2	0.45	400	180	937	938	3.5	0.248	0.050
3	0.45	400	180	937	938	3.5	0.372	0.075
4	0.45	400	180	937	938	4.0	0.122	0.025
5	0.45	400	180	937	938	4.0	0.248	0.050
6	0.45	400	180	937	938	4.0	0.372	0.075
SCC mix using COM VMA								
7	0.42	520	218	855	857	4.0	4.54	0.37
SCC mix with Welan gum as VMA								
8	0.45	400	180	910	910	9.0	0.31	0.078
Control concrete mix without VMA								
9	0.45	400	180	937	938	3.5	0	0.000

Table 6
Fresh and hardened properties of SCC

Mix no.	Slump flow (mm)	V-funnel flow (s)	Air content (%)	SI (%)	Bleeding (ml/cm^2)	Setting times (h:min)		Compressive strength (MPa)			
						Initial	Final	1 day	3 days	7 days	28 days
SCC with Type A VMA											
1	585	4	3.5	0.5	0.05	08:17	09:31	30	–	35	43
2	600	3	1.9	1.7	0.05	07:40	08:58	25	–	39	46
3	610	5	1.9	1.3	0.05	10:16	11:33	–	36	38	42
4	630	5	2.3	3.1	0.05	07:02	08:22	–	36	38	41
5	640	2	2.2	3.6	0.05	08:16	09:44	–	38	40	44
6	645	2	1.5	8.0	0.10	12:09	13:28	22	–	37	44
SCC with COM VMA											
7	660	5	2.7	11.3	0	11:07	13:10	18	–	38	44
SCC with Welan gum as VMA											
8	620	7	2.75	2.0	0	–	–	21	–	33	40
Control concrete without VMA											
9	480	*	3.1	–	0.06	04:53	06:22	20	–	34	40

– Test not performed.
*Blocked.

uniform suspension of solid particles. The stability of a SCC mix can be enhanced by reducing the coarse aggregate content and lowering the maximum size of aggregate. It is also important to increase cohesion of the mix to enhance bond between the mortar and the coarse aggregate that allows uniform deformation around obstacles.

Segregation test method developed by Fujiwara [24] was used. The method includes pouring of 2 l of fresh concrete over a 5-mm mesh and measuring the mass of the mortar passing through the screen after 5 min. The segregation index (SI) is taken as the ratio of the mortar passing to that contained in the original concrete sample. For concrete to be stable, it should have a SI value of $<5\%$ [24]. However, the limit of 5% is considered too severe and a limit of 10% appears more realistic [25]. In the current study, the SI was measured using 1.6 l of concrete on a 4.75-mm sieve. A significant amount of segregation was observed in the COM mix (as shown in Table 6) as it failed to fulfill the required criteria. All other mixes satisfied the requirement including the Welan gum mix.

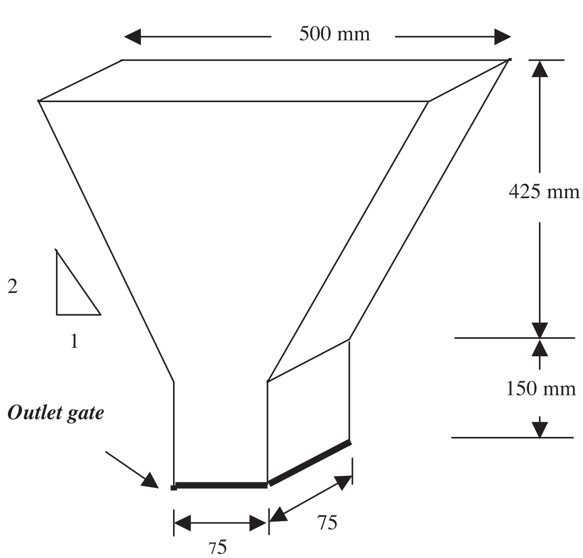

Fig. 4. V-funnel flow apparatus.

Bleeding of concrete was measured as per ASTM C232-99-A by filling a 150×300-mm concrete cylinder to a level 25 mm below the top and then extracting the bleed water with a pipette until bleeding was stopped. The volume of water was then calculated for the surface area of the exposed specimen. Typical range of bleeding in concrete should be 0.01–0.08 ml/cm^2 [26]. All the concrete mixes satisfy the requirement as shown in Table 6, except Type A VMA Mix 6 with 0.075% VMA. The COM and Welan gum mixes showed no sign of bleeding.

2.3.1.4. Air content. Air content was measured by the pressure method and varied from 1.5% to 3.5% (Table 6). All SCC mixtures are non-air-entrained concretes, which explains the low air content of the SCC presented in Table 6.

2.3.1.5. Setting time. Setting time was measured as per ASTM C403-90 using penetration resistance. The results (Table 6) show an increase in setting time with the increase of amount of VMA and SP in the mix. The initial and final setting times vary from 7 to 12 and from 9 to 13 h, respectively, when VMA content varies from 0.025% to 0.075%. The SCC mixes containing 0.075% of Type A VMA exhibit significant increase in setting time comparable with that of COM mix. As expected, the setting times of the

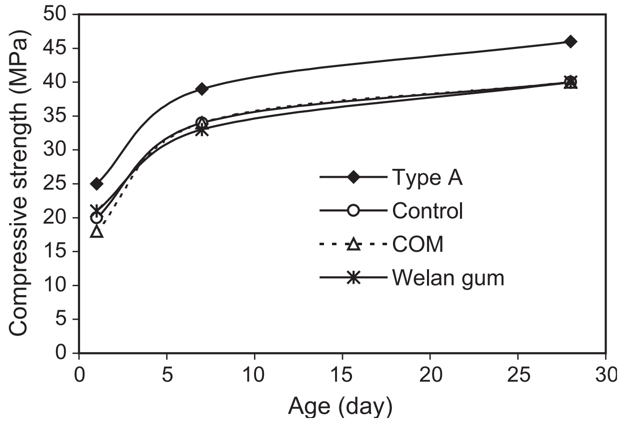

Fig. 5. Strength development in various SCCs.

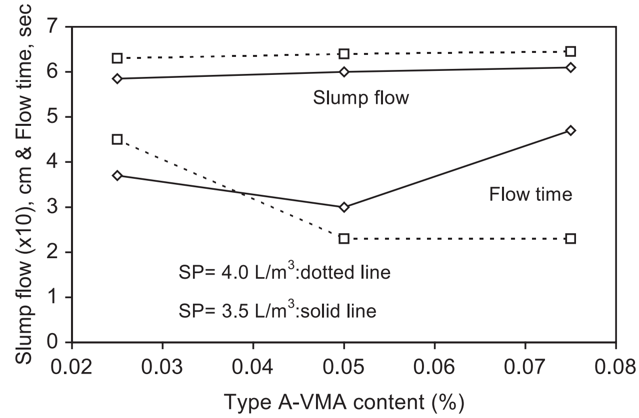

Fig. 6. Effect of VMA content on slump and flow time.

SCCs are 3–6 h longer than those of the control concrete due to the presence of VMA. The setting times of SCC with 0.075% Type A VMA are almost double than those of control mixes. The delay in initial setting time of fluid concrete made with 0.45 W/C and Type II cement containing 0.65% SP and 0.15% Welan gum was reported by Khayat [27].

2.3.2. Properties of hardened concrete

Comparative performance of hardened concrete was investigated by measuring the development of compressive strength with curing age ranging from 1 to 28 days. Three 100×200-mm cylinders were cast, with no rodding or consolidation effort for all the concrete mixes, and stored in a humidity chamber for proper curing.

The SCC mixes in this research were required to meet the compressive strength for normal applications, which was ~ 35 MPa at 28 days. All the mixes (Table 6) with Type A VMA satisfy that requirement within 7 days, with 28-day strength varying from 41 to 46 MPa. The compressive strengths at 7 and 28 days were not affected by the percentage of Type A VMA in the mix although the mixes with 0.05% show higher strength. The Type A VMA mixes generally show high early strength development than control, COM and Welan gum (Fig. 5). The higher setting time in COM mixture leads to a reduction of the early strength development (similar effect is also observed in Type A VMA mix with 0.075% VMA), but 28-day strength is comparable with those of VMA mixes (Table 6).

3. Discussion of results

3.1. Effect of VMA on the fresh properties

The slump flow value (a measure of flowability) is found to slightly increase with the increase of dosages of Type A VMA (from 0.025% to 0.075%) and SP (from 3.5 to 4.0 l/m^3) as shown in Fig. 6. The effect of Type A VMA on V-funnel flow time is also shown in Fig. 6. The flow time is decreased with the increase of VMA content for SCC with 4.0 l/m^3 of SP. On the other hand, lower dosages of SP (3.5 l/m^3) and VMA combinations tend to produce higher flow time (Fig. 6).

The effect of Type A VMA and SP combinations on the SI and bleeding is shown in Fig. 7. SI is found to be higher in mixes with higher SP content. The incorporation of VMA can imbibe some of the free water and increase the viscosity of the paste or mortar that can reduce the risk of segregation and bleeding in SCC [16]. The increase in viscosity of the cement paste and mortar due to the incorporation of VMA is observed in the current study. The enhancement of SCC resistance against bleeding and segregation by incorporating Welan gum VMA was reported by Khayat and Guizani [13]. However, the current study reveals that bleeding and segregation are dependent on the combinations of dosages of SP and VMA and it is important to use an optimum SP-VMA combination dosage to develop better segregation and bleeding resistance in VMA SCC.

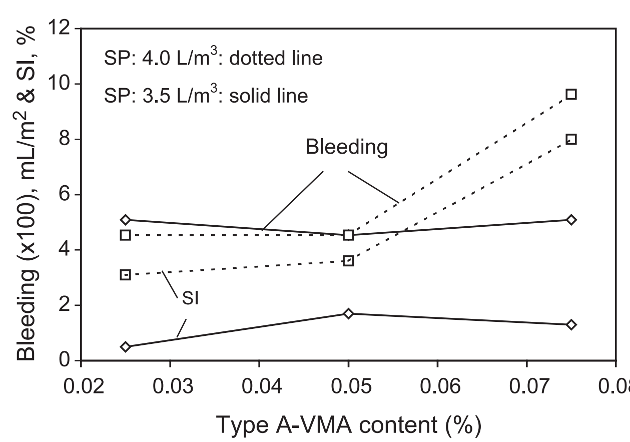

Fig. 7. Effect of VMA content on bleeding and segregation.

The air content seems to decrease (Fig. 8) with the increase of VMA content in the SCC mixes. This suggests that the incorporation of VMA will probably necessitate greater additions of air entraining agents to secure a given air volume. This finding is consistent with that suggested by Khayat [28]. However, air content of 1.9–3.5% in the current mixes produce acceptable properties showing good flowability. This is consistent with the findings of Zain et al. [29] who suggest that air content between 1.5% and 2.3% in non-air-entrained concrete should be adequate to maintain workability and flowability.

3.2. Comparative performance of optimum SCC

The optimum SCC mix with Type A VMA is identified to be the one containing 0.05% VMA and 3.5 l/m^3 of SP on the basis of following test observations.

(1) The COM SCC needs higher VMA and higher SP content. It exhibits higher flow time and higher SI although it shows no bleeding, higher slump and higher air content. It has higher initial setting and final setting time. It also shows lower early age strength development (1-day strength) compared with optimum SCC with Type A VMA.
(2) Welan gum SCC has higher flow time, higher SI and comparable slump. It shows no bleeding and higher air content. It also shows lower early age strength development (1-day strength) and lower 28-day strength compared with optimum SCC with Type A VMA.
(3) The control concrete has shown lower slump flow and failed to meet the criteria for SCC. It has lower initial setting time and lower final setting time. It also shows lower early age strength development (1-day strength) compared with optimum SCC with Type A VMA.

The performance of the optimum Type A VMA SCC is compared with COM, Welan gum and control concrete in Figs. 5, 9 and 10). The optimum SCC with Type A VMA has acceptable slump flow of 600 mm (within the range of 500–700 mm), bleeding value of 0.045 ml/cm^2 (0.01–0.08 ml/cm^2), SI of 1.7% (lower than 5%) and flow time of 3 s (< 6 s). An air content of 1.9% is lower but within the acceptable range of 1.5–2.3% [29]. It has initial and final setting times of 07:40 and 08:58 h, respectively, which are lower than COM SCC. It shows better strength and high early strength development (Fig. 5) than other SCC and has 46 MPa, 28-day strength. It also needs 7.4 and 1.25 times lower VMA than COM and Welan gum mixes, respectively, in achieving comparable and acceptable fresh SCC properties and better strength characteristics.

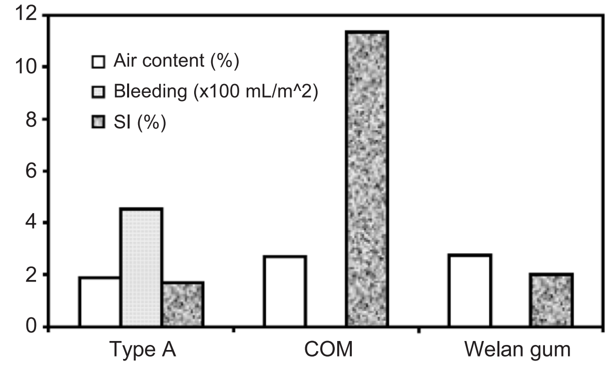

Fig. 9. Comparative performance of various SCCs.

3.3. Cost analysis of VMA SCC

Table 7 presents the pricing of SCCs based on the cost of materials only. The cost was based on local prices used in the typical Canadian market; all figures are in Canadian dollars. The prices used were \$130/t for cement and \$3/l for SP. The cost of SCC with Type A VMA is almost 1.72 and 1.42 times lower than SCC with COM and Welan gum, respectively. However, the mix proportion of the commercial SCC with

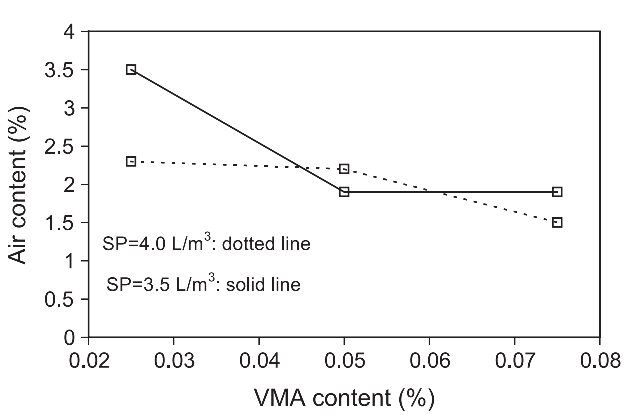

Fig. 8. Effect of percentage of VMA content on the air content.

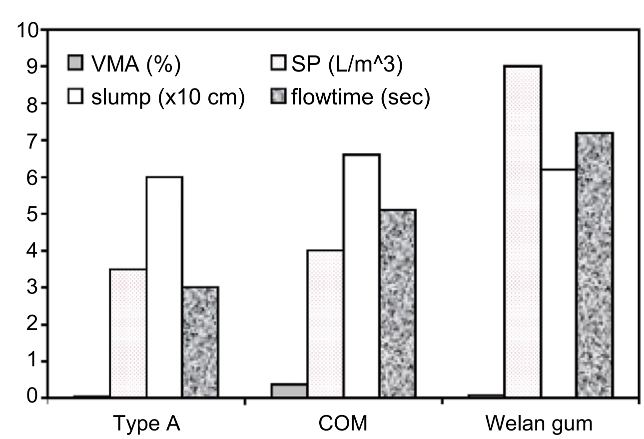

Fig. 10. Comparative performance of various SCCs.

Table 7
Cost analysis of VMA SCC compared with control concrete

Mix no.	Mix design					Mix pricing per cubic meter of concrete			
	W/C	Cement (kg/m^3)	SP (l/m^3)	VMA		Cement at \$130/t	SP at \$3/l	VMA[a]	Total cost (\$)
				kg/m^3	l/m^3				
A	0.45	400	3.5	0.248	–	52.0	10.5	0.1	62.6
Control	0.45	400	3.5	0	0	52.0	10.5	0.0	62.5
COM	0.42	520	4	4.54	3.75	67.6	12.0	31.9	111.5
Welan gum	0.45	400	9	0.31	–	52.0	27.0	6.2	85.2

[a] Type A VMA at \$0.350/kg, COM at \$8.5/l and Welan gum at \$20/kg.

COM is different than the other SCC mixes used in this study. A cost comparison with a commercially available SCC is very important in studying the feasibility of newly developed SCC.

There is virtually no difference between the cost of Type A SCC and the cost of control concrete. It is interesting to note that the production of a SCC satisfying all the required fresh and mechanical properties is possible by incorporating new Type A VMA without adding any extra cost to the control concrete. The reduction in cost of the proposed SCC with new Type A VMA compared with the widely used Welan gum SCC and commercially available COM SCC can boost the future use of such SCC in the construction industry.

4. Conclusions

Tests on mortar including setting time and rheological properties suggest that all new VMAs can be used in the development of a SCC with satisfactory properties and with less VMA dosage than commercial COM.

The study on SCC with Type A VMA produces encouraging results when compared with SCC manufactured by using a known commercial VMA, Welan gum and control mixes. It is possible to produce SCC using Type A VMA having a slump flow in the range of 585–645mm, a flow time ranging from 2.3 to 4.7 s, a SI ranging from 0.5% to 8%, bleed water ranging from 0.045 to 0.096 ml/cm^2, initial setting time ranging from 7 to 12 h and final setting time ranging from 08:22 to 12:28 h.

The rheological characteristics of SCC with Type A VMA in fresh state is improved and better when combining 3.5 l/m^3 of SP and 0.05% of VMA in the mix design. This combination ensures stability of the mix with no segregation and low bleeding in the concrete. A satisfactory SCC can be achieved by using less amount of new VMA than the manufacturer's recommended dosage of commercial VMA COM and Welan gum. The use of new VMA can also produce cost-effective SCC. However, the long-term durability characteristics of such SCC with new Type A VMA and their performance in structural elements are important issues and should be considered in its future application in the construction industry. Further research is currently in progress toward those directions.

References

[1] K. Ozawa, K. Maekawa, H. Kunishima, H. Okamura, Performance of concrete based on the durability design of concrete structures, Proc. Second East Asia-Pacific Conf. Struct. Eng. Const. 1 (1989) 445–456.

[2] A. Skarendahl, Self-compacting concrete for improved productivity, working environment and performance, Swedish Cement and Concrete Research Institute, Stockholm, Paper presented at IREX Meeting, ''Réunion d'information sur les bétons autoplacants, Paris, France, February 23, 1999.

[3] M. Sonebi, P.J.M. Bartos, W. Zhu, J. Gibbs, A. Tamimi, Task 4: properties of hardened concrete, final Report, Advanced Concrete Masonry Centre, University of Paisley, Scotland, UK, 2000. Available: http:/scc.ce.luth.se.

[4] M.J. Campion, P. Jost, Self-compacting concrete, Concr. Int.: Design and Construction 22 (4) (1999) 31–34.

[5] K.H. Khayat, K. Manai, A. Trudel, In situ mechanical properties of wall elements using self-consolidating concrete, ACI Mater. J. 94 (6) (1997) 491–500.

[6] M. Yurugi, Application of self-compacting concrete in Japan, Proceedings 23rd OWICS Conference, CI-Premier Ptc Ltd., Singapore, August 25–26, 1998, pp. 29–42.

[7] O. Petersson, Application of self-compacting concrete for bridge castings, Swed. Cem. Concr. Res. Inst. 54 (2) (1998) (5 pp).

[8] I. Arima, M. Takeguchi, S. Sakurai, J. Hayashi, The quality of superworkable concrete used for the construction of Akashi-Kaikyo Bridge 4A anchorage, Proc. Jpn. Concr. Inst. 16 (1) (1994) 25–30.

[9] K. Sakata, T. Ayano, A. Ogawa, Mixture proportions for highly-flowable concrete incorporating lime stone powder, ACI Mater. J. 1 (1995) 249–268.

[10] N. Bouzoubaâ, M. Lachemi, Self-compacting concrete incorporating high volumes of class F fly ash: preliminary results, Cem. Concr. Res. 31 (2001) 413–420.

[11] M. Sari, E. Prat, J.F. Labastire, High strength self-compacting concrete, original solutions associating organic and inorganic admixtures, Cem. Concr. Res. 29 (6) (1999) 813–818.

[12] S. Rols, S.J. Ambroise, J. Pera, Effects of different viscosity agents on the properties of self-leveling concrete, Cem. Concr. Res. 29 (2) (1999) 261–266.

[13] K.H. Khayat, Z. Guizani, Use of viscosity modifying admixtures to enhance stability of fluid concrete, ACI Mater. J. 94 (4) (1997) 332–340.

[14] N. Sakata, K. Maruyama, M. Minami, in: P.J.M. Bartos, D.L. Marrs, D.J. Cleland (Eds.), Basic Properties and Effects of Welan Gum on Self Consolidating Concrete, Production Methods and Workability of Concrete, E&FN Spon, London, UK, 1996, pp. 237–252. ISBN 0 419 220704).

[15] M. Lachemi, K.M.A. Hossain, V. Lambros, P.-C. Nkinamubanzi, N. Bouzoubaâ, Performance of new viscosity modifying admixtures in enhancing the rheological properties of cement paste, Cem. Concr. Res. 34 (2) (2004) 185–193.

[16] K.H. Khayat, Viscosity-enhancing admixtures for cement-based materials—An overview, Cem. Concr. Compos. 20 (1998) 171–188.

[17] P.L.J. Domone, J. Jin, Properties of mortar for self-compacting concrete, Proceedings of the First International RILEM Symposium on Self-Compacting Concrete, Stockholm, Sweden, RILEM Publications S.A.R.L., September 13–14, 1999, pp. 109–120.

[18] E.C. Bingham, M. Reiner, The rheological properties of cement and cement-mortar-stone, Physics 4 (1933) 88–96.

[19] P. Mitschka, Simple conversion of Brookfield R.V.T. readings into viscosity functions, Rheol. Acta 21 (1982) 207–209.

[20] K.H. Khayat, A. Yahia, Effect of Welan gum-high range water reducer combinations on rheology of cement grout, ACI Mater. J. 94 (5) (1997) 367–372.

[21] S. Sogo, Properties of underwater concrete containing segregation controlling admixtures, Marine Concrete, International Conference on Concrete in the Marine Environment, Concrete Society, London, UK, 1986, pp. 247–256.

[22] S. Nagataki, H. Fujiwara, Self compacting property of highly flowable concrete, ACI SP-154 (1995 June) 301–314.

[23] K. Ozawa, N. Sakata, H. Okamura, Evaluation of self-compactibility of fresh concrete using funnel test, Proc. JSCE 90 (23) (1994) 59–75.

[24] H. Fujiwara, Fundamental study of self-compacting property of high-fluidity concrete, Proc. Jpn. Concr. Inst. 14 (1) (1992) 27–32.

[25] K.H. Khayat, A. Ghezal, M.S. Hadriche, Development of factorial design models for proportioning self-consolidating concrete, in: V.M. Malhotra (Ed.), Nagataki Symposium on Vision of Concrete: 21st Century, 1998 June, pp. 173–197.

[26] S.H. Kosmatka, W.C. Panarese, K.D. Gissing, N.F. MacLeod, Design and control of concrete structures, CPCA, Ottawa, Canada, 6th Canadian Edition, 1995.

[27] K.H. Khayat, Effects of antiwashout admixtures on fresh concrete properties, ACI Mater. J. 92 (2) (1995) 164–171.

[28] K.H. Khayat, Optimization and performance of air-entrained, self-consolidating concrete, ACI Mater. J. 97 (5) (2000) 526–535.

[29] M.F.M. Zain, M. Saifuddin, K.M. Yusof, A study on the properties of freshly mixed high performance concrete, Cem. Concr. Res. 29 (9) (1999) 1427–1432.