

Workability of SCC:

Roles of Its Constituents and Measurement Techniques

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PREFACE

Self-consolidating concrete (SCC) is a highly flowable, yet stable concrete that can spread readily into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation and without undergoing any significant separation of material constituents. SCC has many advantages over conventional concrete, such as: eliminating the need for vibration; decreasing the construction time and labor cost; reducing noise pollution; improving the filling capacity of highly congested structural members; improving the interfacial transitional zone between cement paste and aggregate or reinforcement; decreasing the permeability and improving durability of concrete; and facilitating constructibility and ensuring good structural performance. SCC has been attracting more and more attention worldwide since its introduction in the late 1980s. New applications for SCC are being explored.

To promote and encourage the use of SCC, ACI Committee 236, Material Science of Concrete, and ACI Committee 237, Self-Consolidating Concrete, organized two technical sessions on “Workability of SCC: Roles of Its Constituents and Measurement Techniques” at the ACI Spring 2005 Convention in New York City, New York. Eleven papers were presented covering a wide range of practical case studies and research projects on the design, testing, placement, and performance of SCC. This Special Publication (SP) contains 10 of the papers presented at the sessions. Six of the papers deal with the mixture proportions and the effects of raw materials on workability; two of them deal with the rheometer testing of SCC; one deals with form pressure; and one deals with the structural response of SCC frames under earthquake loading.

On behalf of ACI Committees 236 and 237, the editors would like to thank the authors and presenters for their contributions to the technical sessions and this volume, the reviewers of the original manuscripts for their constructive comments and suggestions, and the ACI staff for their help in organizing the sessions and preparing this SP. It is our hope that the success of these technical sessions and the publication of this SP will encourage and facilitate the use of SCC.

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Getting it Right: Successful SCC Production Practices

by C.R. Cornman, H. Koyata, and A.A. Jeknavorian

Synopsis: The challenge in producing successful self-consolidating concrete (SCC) is based on consistently achieving high flow *and* high stability. The foundation of high quality SCC production is the suitability of the underlying materials and a mixture design that is optimized for those materials and the application. Not all applications require relatively high slump flows in the range of 28-30 inches (700-750mm), where control measures need to be especially well managed. Furthermore, even the best mixture designs can have stability limitations. To assure that SCC applications proceed with minimal difficulties, the concrete producer must anticipate variations in materials and production operations through effective quality control procedures. Changes in cement reactivity, aggregate properties (gradation, shape, and water demand), free moisture, and extra sources of moisture that may be present, for instance, in the truck, and the mixing process need to be carefully monitored. This paper will discuss specific examples that demonstrate best practices in mixture design, QA/QC, and production techniques.

Keywords: admixtures; gradations; mixture proportioning; quality control; rheology; troubleshooting

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Introduction

Self-Consolidating Concrete (SCC) has gained much attention in recent years because the “in place” cost of SCC can be dramatically lower than that of conventionally vibrated concrete. The economic benefits of SCC arise for the most part from the decreased labor associated with placing and finishing the concrete, quicker placement time, and improved form finish requiring fewer repairs. The ACI Committee on SCC, ACI 237, is currently developing a document and defines SCC as follows:

“Self-consolidating concrete (SCC) is highly flowable, yet stable concrete that can spread readily into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation and without undergoing any significant separation of material constituents.”

Due to these performance attributes, SCC has been called *high performance concrete in the plastic state*. As with most *high performance* materials, the quality of SCC is sensitive to the materials and methods of production. Inconsistent quality can lead to inadequate performance, returned trucks, and slow acceptance of this valuable technology. However, by following some simple guidelines, the success rate for SCC production can be very high. Described herein are practices that have proven successful in the commercial production of Self-Consolidating Concrete.

Rheology and SCC

Rheology, the science of the deformation and flow of materials, is important to understanding the performance of SCC. The rheology of SCC is more sensitive than conventional concrete to variability in materials and poor production practices. Figure 1 illustrates how SCC is generally characterized by a lower yield stress and higher plastic viscosity than conventionally vibrated concrete. Since conventional concrete will be consolidated by vibration, the “rheological window” within which the concrete can be successfully placed is relatively large -- if conventional concrete is too stiff for a particular placement, increased vibration can be used for consolidation. However, since vibration is not required as per the definition of SCC, the designed performance window for self-consolidation is confined to a narrower range bordering on segregation at one extreme to inadequate flow at the other end of the rheology spectrum. In the laboratory, rheometers can be used to characterize the rheological properties of SCC. However, field measurements such as slump flow and T20 can also provide insight into the “flow and deformation” of the concrete, and are considered far more practical control measurements for concrete producers (Figure 1, right). Higher flow is generally associated with a lower yield stress and lower viscosity. For any specific set of materials, a shorter T20 generally corresponds to a lower plastic viscosity.

To stay within the rheology window of SCC, good material control and production practices must be followed. As with any production operation, control of the variability in materials and production processes is critical. Pre-job trials to qualify the SCC mixture design, coupled with a quality control program to assure consistent quality of materials, batching operations, and mixing and handling processes will dramatically improve the production, transport, placement, and service life of SCC.

SCC Mixture Proportioning

The details of effective mixture proportioning for SCC is discussed in a separate paper in this symposium. Most importantly, to avoid problems of poor quality SCC, mixture designs should

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be based on “*performance*”, not “*prescription*” concrete. SCC must be designed for specific applications taking into account the required engineering performance, the element characteristics, the placement techniques, and the materials and production process to be used. In general, SCC mixture proportions have a higher paste and mortar content, lower maximum aggregate size, and a higher sand/total aggregate ratio than conventional concrete. A smooth total aggregate gradation curve without gaps generally contributes to SCC mixtures having more consistent and acceptable flow behavior, passing ability, and stability. An appropriate aggregate gradation is most easily achieved by blending two sizes of coarse aggregate with one fine aggregate. Natural, rounded aggregate is preferable to crushed, angular aggregate, and aggregates with a low aspect ratio are preferable to ones with a high aspect ratio. Coarse aggregates should be blended to minimize void volume, *i.e.* maximize dry-rodded unit weight. While higher quality aggregates contribute to SCC with more uniform slump-flow, passing ability, and stability, a wide range of materials and gradations have been successfully used by concrete producers. Figure 2 illustrates a range of aggregate gradations that have been used for commercial SCC production in the Precast/Prestressed (PC/PS) concrete industry. The aggregate gradations used in the North American concrete industry tend to have a slight gap in the region of the Nos. 8, 16, and 30 sieves. Additionally, significant deviations from the average gradation indicate that many different aggregate combinations can be used to produce SCC.

Admixtures for SCC

Polycarboxylate ether-based high range water reducing admixtures (PCE superplasticizers) are most commonly used to achieve the highly fluid properties of SCC. Naphthalene or melamine-based superplasticizers are still used in some cases; however, the “*tunability*” of the PCE polymer structure, especially with regard to concrete viscosity and fluidity retention, has led to their dominance in the market. Figure 3 provides a general depiction of the PCE chemical structure and the so-called “*comb*” polymer architecture wherein the comb backbone adsorbs on to the cement surface and the comb teeth extend into the pore water between cement particles. Teeth length (Z), teeth density ($Y/X+Y$), and backbone length ($X+Y$) are three of the many parameters that can influence performance.

Figure 4 provides data showing the impact of PCE structure on the rheology of SCC. The superplasticizer PCE B was designed to impart increased viscosity to the SCC mixture, and thereby higher stability. Relative to PCE A, superplasticizer PCE B has longer teeth, higher teeth density and longer backbone length. With these differences in comb polymer structure, for any slump flow (or admixture dose) the mixes made with PCE B had a higher viscosity. The mixtures with 20” (500mm) flows have poor passing ability and would probably would not be *self consolidating*. The mix with 27” (635 mm) flow was near segregation.

Hydraulic cement-based materials such as SCC have inherently a limited time for placeability – once water and cement are mixed, the concrete remains in a highly fluid state until the hydration process causes sufficient microstructure to contribute yield stress to the mortar fraction. This limitation is especially important for cast-in-place applications of SCC. Again, the PCE structure can have a dramatic impact. Figure 5 shows the percentage decrease in slump flow over time for three different PCE-based dispersants. While PCE 3 may be suitable for PC/PS concrete production with relatively short transportation times, PCE 1 is much more suitable for a cast-in-place application especially in the case of long transportation time. Given the sensitivity of SCC to materials and processes, mix adjustments (such as retempering) at the job site should be avoided if at all possible.

Viscosity modifying admixtures (VMAs) can be used to improve the segregation resistance of an SCC mixture, and in some instances, provide the added robustness needed for trouble free production. However, in many cases, the mixture design itself – with relatively high powder content, low water-to-cementitious ratio, and/or relatively high paste and mortar fraction – can provide adequate segregation resistance. The function of VMAs is furthered discussed in a separate paper in this symposium.

Materials QA/QC and Batching

All materials and processes used to make concrete have inherent variability that can significantly impact the plastic and hardened performance of the concrete mixtures, which is far more prevalent for SCC versus conventional concrete mixtures. Thus, to produce consistently good quality SCC, one should minimize variability where possible by measuring and tracking key material properties (e.g. gradation), understanding the tolerable limits of variation prior to a performance failure, and be able to proactively adjust for changes where variability is unavoidable (e.g. aggregate moisture level).

The single most important concern with SCC is segregation resistance. The ability to control moisture content dramatically influences SCC segregation resistance. Moisture management includes the water added to a batch, variations in sand moisture, the inadvertent water from a previous load of concrete, and fluctuation in the water demand of the concrete materials. An example of the impact of even “a little” water can be enlightening:

In general, the addition of one gallon of water per cubic yard of concrete can increase the slump flow of SCC by 2-3” (50-75mm). If one considers a mix design with 1500 lbs/yd (890 kg/m³) of sand, 1% sand moisture represents nearly two gallons of water with the potential to increase slump-flow by 4-6” (100-160mm). Thus, if a moisture meter is accurate to +/- 0.5% (which is quite optimal), then the slump flow could vary by as much as 4-6” (100-160mm) from batch-to-batch. If an SCC mixture is designed for a high flow of 28”, then the batch-to-batch variability can lead to slump flows from 25-31” (635-787mm). While the 25” (635mm) batch may have satisfactory stability (not segregating), it is likely that the SCC with a 31” (787mm) flow will be dangerously close to segregation.

Several simple practices can dramatically improve the quality of SCC production:

- Establish *and follow* a Standard Operating Procedure (SOP) that defines the steps taken to minimize, or adjust for, variability. Train everyone that comes in contact with the SCC what good and bad SCC looks like along with cause and effect parameters.
- Control charts should be maintained to confirm the consistency of materials and processes.
- Ensure that all water is backed out of the transport vehicle.
- Use moisture meters and adjust every batch for changes in aggregate moisture. Pay strict attention to the calibration and maintenance of the meters.
- Understand any changes in the water demand of your materials. When qualifying an SCC mixture design, the water demand of the materials should be ascertained (i.e. the water required to produce a 1” (25mm) concrete).
- Remember that aggregate water demand can change even if gradation appears constant. Additional tests such as void volume, slump measurement, and clay content by methylene blue, can be used to further detect reasons for changed water demand.

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- If the concrete is produced with a central mixer, use an accurate amp meter to monitor the moisture content. Identify a target reading for the SCC mixture being made and hold back a little water that can be used to trim the mix.
- SCC may require a slightly longer mixing cycle than conventional concrete. Flow and viscosity may develop at different rates, and this can be materials dependent. Dose high range water-reducing admixtures (and viscosity modifying admixtures) by mix-water or delayed addition according to the supplier's guidelines.
- Polycarboxylate-based superplasticizers especially designed for SCC production should be used per the admixture company recommendations to assure maximum batch-to-batch performance with respect to flow, passing ability, and mixture stability.
- Establish a process for troubleshooting SCC that is based on your knowledge of the materials and process variability of your production operation.

SUMMARY

SCC is high performance concrete in the plastic state. Mixture proportioning and chemical admixtures work in combination to achieve the defining properties of SCC, namely high fluidity, excellent passing ability, and segregation resistance (stability). SCC is performance, not prescription concrete and must be designed with the application in mind. If high fluidity is not needed for the application, a lower fluidity SCC can minimize risks associated with segregation resistance. Adjusting the mixture proportions or using appropriate admixtures (*i.e.* superplasticizers or viscosity modifying agents that increase concrete viscosity) can also decrease the risk of segregation, even with highly fluid mixes. As with all high performance materials, the quality of SCC is sensitive to the inherent variability in materials and production processes. SCC is more sensitive than conventional concrete, and the successful producer will implement processes to minimize variability (*i.e.* SOPs, sufficient training, engineering controls for materials, processes for troubleshooting). Moisture management during material inventory, batching, mixing operations, transport, and placement is critical to assure consistently high quality SCC.

References

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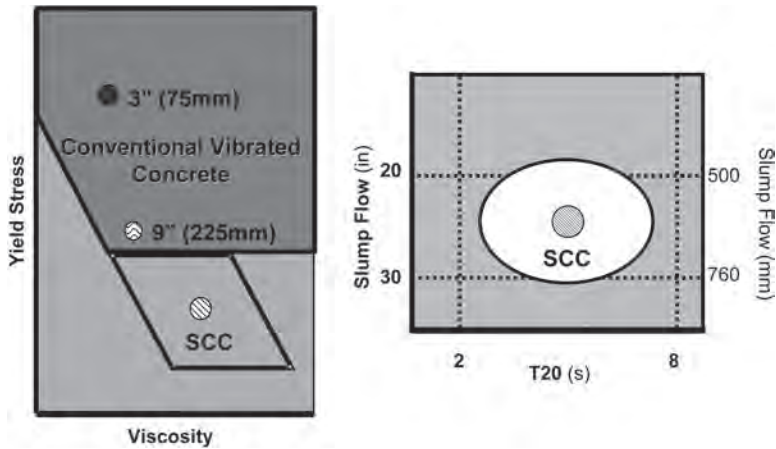


Figure 1. Rheology of SCC using a concrete rheometer (left; yield stress vs. plastic viscosity) or a Slump Cone (right; Slump Flow vs. T20)

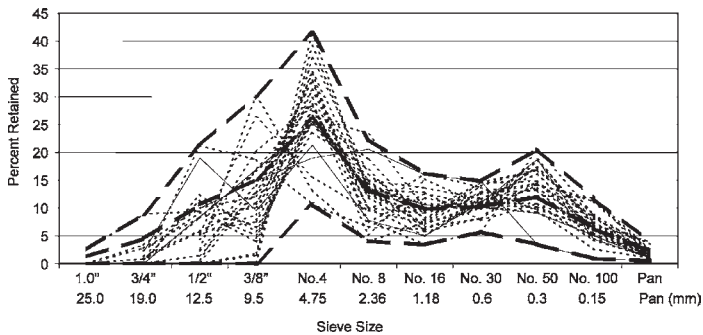


Figure 2. Gradations used in the PC/PS industry (2002 Grace Analysis). Dashed lines represent the upper and lower extremes and the average for each sieve size.

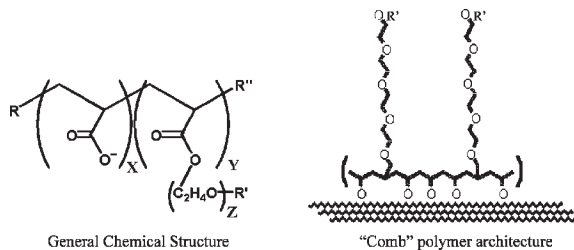


Figure 3. Chemical structure and architecture of PCE superplasticizers.

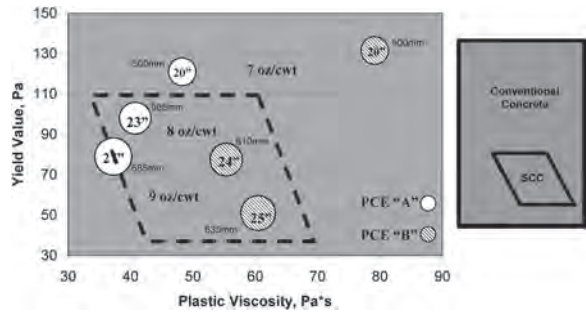


Figure 4. Impact of PCE structure on rheology of SCC. Mixture proportions are identical (750 lb/yd³ (445 kg/m³) cement; w/c = 0.39) except for the type of comb polymer (superplasticizer PCE A vs. PCE B). The dashed trapezoid represents the region of acceptable SCC.

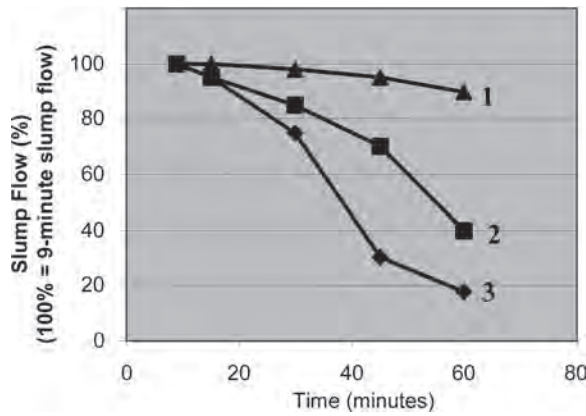


Figure 5. Representation of percentage slump flow decrease over time for different PCE-based dispersants.

The Influence of Viscosity-Modifying Admixture (VMA) on the Performance of Self-Consolidating Concrete (SCC)

by B.J. Christensen and F.S. Ong

Synopsis: The stability of highly fluid self-consolidating concrete (SCC) can be achieved by using a viscosity-modifying admixture (VMA). Currently, there are several types of VMAs available in the market place. Three of the most common ones are based on cellulose-ethers, biopolymers and synthetic polymers. The properties of these three types of VMAs were studied and compared. Specifically, the influence of these three types of VMAs on the properties of self-consolidating concrete (SCC) was studied. Particular attention was placed on the influence of each VMA on the following characteristics of the SCC: 1) dose response of high range water reducer (HRWR), 2) dose response of air entraining agent (AEA), 3) stability of the mixture, 4) effects on time of setting and 5) compressive strength development.

Keywords: air-entraining admixture (AEA); bleeding; compressive strength; high-range water reducer (HRWR); segregation index; self-consolidating concrete (SCC); time of setting; viscosity-modifying admixture (VMA); visual stability index

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1. INTRODUCTION

The application of self-consolidating concrete (SCC) technology has been steadily growing since 1998 (1, 2). The unique properties of SCC in its fresh state are high fluidity and consolidation under self-weight, segregation resistance and non-blocking characteristics when the concrete flows through gaps between reinforcement. Segregation of SCC can be controlled by the careful selection and proportioning of materials, as well as use of a viscosity modifying admixture (VMA) (3). VMAs are typically high molecular weight soluble polymers that change the viscosity of cementitious mixtures by their interaction with the water phase or particle surfaces. These compounds have been used previously to decrease segregation and/or bleeding in cement pastes or mortar (4). Since similar characteristics are desired in highly fluid concretes, such as SCC, they are now finding additional applications.

VMAs are based on a number of different chemistries (5-12). One class is the natural polymers. These include such materials as polysaccharide gums (welan, xanthan, etc.). Welan gum was one of the first biopolymers used as a VMA in SCC applications (13). The effect of welan gum on the hardened concrete properties was further studied (14), and it was concluded that SCC containing welan gum and an air content of 4% could exhibit adequate resistance to freezing and thawing cycles. Recently another biopolymer called diutan gum (3) was introduced. Welan gum

and diutan gum are both high molecular weight, microbial polysaccharides produced by aerobic fermentation. Both welan gum and diutan gum have similar chemical structures, except that diutan gum has generally longer side-chains. A second class is semi-synthetic polymers like cellulose ether-based materials (hydroxy methyl, hydroxyl propyl, carboxymethyl, etc.). A third class is the synthetic polymers like polyethylene glycols, polyvinyl alcohols or polyacrylamides.

Because SCC is relatively new technology, there is only limited information available about the effects of VMAs on the properties of SCC, such as time of setting, strength development, and dose requirement of air entraining agents (AEA) and high range water reducers (HRWR). In particular, there is very little published information available on cellulose-ether based and synthetic polymer based VMAs. Therefore, the performance of the three common VMAs in SCC mixtures has been evaluated under laboratory conditions. The influence of these VMAs on dosage requirement of HRWR and AEA, stability of the SCC, time of setting, and compressive strength development was studied. The stability of the SCC mixtures was evaluated by visual rating, segregation index, and measurement of bleed water content.

2. LAB MATERIALS

Two cements conforming to ASTM C 150 Types I and II (15) were used throughout the laboratory studies. These two cements both had a moderate alkali content with the composition given in Table 1. Two different polycarboxylate HRWRs, varying in side chain length and both meeting the requirements for a ASTM C 494 Type F admixture (16), were used in these studies. Two different AEAs meeting the requirements of ASTM C 260 were used (17); one a blend of synthetic hydrocarbons and natural tall oil derivatives (AEA-1), and the other based on wood rosins/resins (AEA-2). Six different VMA formulations were selected to represent the three common types of VMAs used: VMA-1 (diutan gum), VMA-2 (welan gum), VMA-3 (synthetic glycol polymer 1), VMA-4 (synthetic proprietary polymer 2), VMA-5 (cellulose ether 1), and VMA-6 (cellulose ether 2). Generally, the viscosity of the VMA made with either gum or cellulose was higher than that of synthetic VMA. One fine

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aggregate, consisting of a natural, glacial deposit sand was used and conformed to the requirements of Section 11.2.1 of ASTM C 494. Two different coarse aggregates were used: a crushed limestone and a smooth gravel. Both coarse aggregates conformed to a #57 gradation per ASTM C 33 (20) and had a maximum aggregate size of 37.5 mm (1.5 in.).

3. GENERAL EXPERIMENTAL PROGRAM

Multiple laboratory evaluations are presented in this paper to assess the effects of various VMAs on the performance of SCC. The target slump flow for all these concrete mixes was 600 mm (24 in) or greater. The water to cement ratio (w/c) was generally fixed at 0.35. The slump flow was achieved by delayed addition of the HRWR. A conventional precast concrete mixture design with a sand-to-aggregate (s/a) ratio of 0.43 and a cement factor of 442 kg/m^3 (750 lb/yd^3) were used throughout the current study.

Materials for the evaluations were charged into the mixer in the following order: two-thirds of the total portion of the water, VMA (except for VMA-5, which required addition after 1 minute of mixing), coarse aggregate, cement, fine aggregate, and AEA on top of the sand (when used). After mixing was initiated, the remaining charge of water was added, followed by HRWR to achieve the target slump flow. The concrete was mixed for a total of 5 minutes in a rotary drum mixer turning at 20 rpm. All mixing and testing was executed at room temperature (nominally 21°C).

The air content of freshly mixed concrete was measured according to ASTM C-231 (18). Times of setting were measured using ASTM C 403 (19). Compressive strength of 100 x 200 mm cylinders was determined according to ASTM C 39 (21). All specimens were de-molded at 24 hours from casting and cured in a moist room until the time of testing. Compressive strength cylinders were tested in duplicate and the average value reported.

The rheology of the SCC mixtures was evaluated by use of an IBB Concrete Rheometer using an impeller speed of 250 rpm. The stability of

the fresh SCC was assessed by means of a visual rating system. The rating is referred to as the Visual Stability Index (VSI) and ranges from 0 (stable mix) to 3 (highly segregating). The effect of the VMA on bleeding was studied with mortar specimens. A total mass of approximately 8 kg of mortar was placed in a pail of 150 mm diameter x 150 mm high. The bleeding water on the surface of each mortar mix was collected at 2, 2.5, 3 and 3.5 hours from initial contact of cement and water and reported.

The column segregation test is a relatively new test method to evaluate the stability of SCC. Details of this method can be summarized as follows:

- The segregation column consists of 4 sections of plastic tubes, each with 165 mm height and 200 mm inside diameter.
- The sections are connected and SCC is placed inside the vertical column.
- 15 minutes after placement, the sections are disassembled and the distribution of the coarse aggregate between the top and bottom sections is measured.
- The Segregation Index is calculated according to the following equation:

$$\text{Segregation Index} = 2 \times (W_{t(\text{Bottom})} - W_{t(\text{Top})}) / (W_{t(\text{Bottom})} + W_{t(\text{Top})}) \times 100\%$$

- For stable SCC, the Segregation Index should be less than 15%.

4. RESULTS AND DISCUSSION OF SPECIFIC STUDIES

4.1. Stability of SCC with different VMAs

4.1.1. Stability of SCC measured by visual stability index -- The purpose of the first study was to compare four of the different VMAs in terms of dose efficiency and the effect on HRWR dose. The two main criteria monitored were the slump flow and stability of the fresh SCC. The

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stability of the fresh SCC was assessed by means of the visual stability index.

The four VMAs selected for this study were: VMA-1 (diutan gum), VMA-2 (welan gum), VMA-3 (synthetic polymer 1), and VMA-5 (cellulose-ether 1). Cement A and crushed limestone were used. The slump flow was achieved by delayed addition of HRWR-1. For each VMA, the dosage was successively increased until a stable SCC was achieved, if possible. A total of twenty-six SCC mixes were prepared. The results of the comparison study are summarized in Table 2, which lists the minimum dose of the each VMA required to achieve a stable SCC. Based on the results in Table 2, the following conclusions can be drawn:

- Except for VMA-3 (synthetic polymer 1), all of the VMAs tested together with HRWR-1 can produce stable SCC concrete with a conventional precast design.
- The demand for HRWR-1 in SCC was the highest with VMA-5 (cellulose-ether 1), while the HRWR demand for SCC using VMA-1 (diutan gum) was the lowest (the difference between VMA-1 and VMA-2 was small).
- On an active basis, the dose efficiency of VMA-1 was the highest among these four VMAs tested.

4.1.2. Stability of SCC measured by bleeding characteristics of mortar --

The effect of VMA on bleeding characteristics of mortar was studied and compared among three of the VMAs: VMA-1 (diutan gum), VMA-3 (synthetic polymer 1), and VMA-5 (cellulose-ether 1). Details of this study are listed in Table 3. Cement A was used and the w/c was fixed at 0.53, while the cement/sand ratio was set at 0.38. VMA-1 and VMA-3 were dosed at 265, 530, and 790 mL/100 kg, while VMA-5 was only dosed at 130 and 265 mL/100 kg. Based on the current results in Table 3, the following conclusions can be drawn:

- VMA-1 reduced the bleeding of mortar at a dosage as low as 264 ml per 100 kg of cement. VMA-1 continued to decrease the amount of bleeding with increasing dosage. By using 790 mL/100 kg of VMA-1, more than 30% of the bleed water could be retained in the mortar.

- VMA-3 reduced the bleeding at low dosage (265 mL/100kg), but promoted bleeding at high dosage (above 530 mL/100 kg).
- VMA-5 at 260 mL/100 kg significantly reduced the bleeding, but not at 130 mL/100kg.

4.1.3. Stability of SCC measured by segregation index -- The effectiveness of a VMA in reducing segregation in concrete was studied and compared between VMA-1 (diutan gum) and VMA-4 (synthetic polymer 2). Both VMA-1 and VMA-4 were dosed at 265, 530, and 790 mL/100 kg. For each dose of VMA, the same amount of HRWR-2 was added to the SCC treated with either VMA. Cement B and gravel were used. The details of this study are listed in Table 4. The VMA was added up-front and HRWR was introduced at 1 minute after mixing. For stable SCC, the segregation index should be less than 15%. As shown in Table 4, without VMA the segregation index was high at 22%. In this study, VMA-3 created more cohesive SCC than VMA-1, especially at dosages above 530 mL/100kg.

4.2. Effects of VMAs on time of setting, compressive strength and rheology of SCC

4.2.1. Effect of VMA-1 (diutan gum) -- The effect of VMA-1 on the initial time of setting, compressive strength development, and rheology of SCC was investigated. Cement A, crushed limestone, and HRWR-1 were used. VMA-1 was dosed ranging from 264 to 1320 mL/100 kg. The effect of VMA-1 on time of setting and strength development are shown in Table 5. As shown in Table 2, 395 mL/100kg of VMA-1 was enough to produce stable SCC with this concrete design. To study the effect of VMA-1 on time of setting and strength development, the dosage of VMA-1 was gradually increased from 265 to 1320 mL/100kg. The addition of VMA-1 increased the time of initial setting slightly with increasing dosage. The recommended dose range for VMA-1 is 390 to 910 mL/100kg. Within the recommended dose range, VMA-1 retarded the initial time setting by less than one hour, as shown in Table 5. Up to 28 days, VMA-1 did not significantly influence the compressive strength development, even with an over-dose.

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The effect of VMA-1 on the rheology of fresh concrete was also investigated with dosages ranging from 265 to 1320 mL/100kg using the rheometer. The details of this study are listed in Table 6. The results show that with a constant dosage of HRWR-1, the viscosity of the concrete increased with increasing dose of VMA-1. It should be noted the slump flow data at a fixed dose of HRWR-1 decreased with increasing dose of VMA-1, potentially contributing to the increase in concrete viscosity. Further work at a fixed slump flow is necessary to more clearly understand the rheological behavior.

4.2.2. Effect of VMA-4 (synthetic polymer 2) -- Based on the results of a previous study (Table 2), the dose of VMA-4 should be less than 530 mL/100kg in this SCC design to provide stability. In this study, the VMA-4 was added up-front and dosed at 66, 132, 264, and 396 ml/100kg. HRWR-2 was fixed at 858 ml/100kg and added at 1 minute after mixing. The rheology was investigated by using the IBB Concrete Rheometer. Details of this study are listed in Table 7. The results clearly indicate that VMA-4 at the dosages tested did not significantly alter the plastic air content or time of setting. The compressive strength was not significantly affected by VMA-4 until a dose above 265 mL/100kg was used. VMA-4 did not affect the yield stress of the concrete, but slightly increased the viscosity with increasing dose of VMA-4. The slump flow decreased with increasing dosage of VMA-4.

4.2.3. Effects of VMA-5 (cellulose-ether 1) and VMA-6 (cellulose-ether 2) -- The performance of SCC made with VMA-5 was compared with that of VMA-6 at three dosages of 130, 265, and 530 mL/100kg. In this study, Cement A and crushed limestone were used. The target slump flow for all these concrete mixes was 500 mm or higher.

The results of non-air entrained SCC are listed in Table 8. Except for Mix # 47 (VMA-6 added up-front), the VMA was introduced into the mixture after the addition of HRWR, as recommended by the manufacturer of VMA-5. As compared to VMA-5, the following conclusions can be drawn:

1. VMA-6 can be added up-front in the mixing water, as confirmed in Mix #47.
2. VMA-6 has similar retardation as VMA-5, and the retardation may be up to more than 3 hours at a high dose.
3. The reduction in the slump flow by VMA-6 is less than that by VMA-5.
4. Both VMA-5 and VMA-6 did not have a significant effect on compressive strength development.

4.3. Effect of VMAs on AEA dosage requirement

For the air entrainment study of SCC containing a VMA, again Cement A and crushed limestone were used. The slump flow was achieved by delayed addition of HRWR-1 or HRWR-2. In terms of air entrainment, VMA-1, VMA-2, VMA-3, and VMA-4 were similar, while VMA-5 and VMA-6 were similar. Therefore, only results of VMA-1 (diutan gum) and VMA-5 (cellulose ether 1) are presented here. Details of these studies are listed in Tables 9 and 10 for AEA-1 and AEA-2, respectively. VMA-1 was dosed at 660 mL/100kg, while VMA-5 was dosed at 130 mL/100kg.

When using AEA-1, the dose was slightly increased by addition of VMA-1. This slight increase of AEA dose was likely due to the corresponding increase in dosage of HRWR. On the other hand, the addition of VMA-5 significantly increased the AEA dose requirement by almost 16 times more for HRWR-1 and 33 times more for HRWR-2. Similar effects were observed for SCC containing either of the above VMAs and air entrained by AEA-2.

5. CONCLUSIONS

Based on the results presented, the characteristics of these six VMAs can be summarized as following:

- VMA-1 (diutan gum) has the best dose efficiency on an active basis among the VMAs tested. VMA-1 does not significantly influence the air entraining properties, compressive strength development or time of setting of SCC. The possible problems with VMA-1 are its

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vulnerability to bioactivity and high viscosity (above 500 cps at ambient condition) at relatively low concentrations.

- VMA-2 (welan gum) has a dosage efficiency of four times less than that of VMA-1 on an active basis. VMA-2 suffers from the same vulnerabilities as VMA-1.
- VMA-3 (synthetic polymer 1) is the weakest VMA tested. VMA-3 does not significantly influence the air entraining properties, compressive strength development, or time of setting of SCC. The main deficiency with VMA-3 is its inability to produce stable SCC with conventional precast concrete design.
- VMA-4 (synthetic polymer 2) has the second best dose efficiency on an active basis among the VMAs tested. VMA-4 does not otherwise adversely affect the plastic or hardened properties studied.
- VMA-5 (cellulose ether 1) is the strongest VMA on an as-delivered dose basis. VMA-5 does not significantly influence compressive strength development, but significantly increased the air entraining agent dosage requirement and retarded the time of setting of the SCC. The disadvantages of VMA-5 are numerous, including its very high viscosity (above 1000 cps at ambient condition), significant retardation high cost and necessity to add to the SCC after addition of the HRWR.
- VMA-6 (cellulose ether 2) is the improved version of VMA-5 (much less viscous, and can be added up-front). VMA-6 does not significantly influence strength development, but still retards the time of setting of SCC. The product is also significantly more expensive at the same level of stability as the bio or synthetic polymers tested in this study.

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Table 1. Characteristics of the normal portland cements used in the laboratory concrete evaluations.

Minerals (%)	Cement A	Cement B
SiO ₂	20.86	19.85
Al ₂ O ₃	4.44	4.66
Fe ₂ O ₃	3.25	3.00
CaO	63.46	62.26
SO ₃	2.63	2.76
MgO	2.98	3.51
Na ₂ O	0.13	0.26
K ₂ O	0.59	0.53
Na ₂ O(equiv)	0.52	0.61
LOI	1.37	2.47
IR	0.24	0.33
Bogue potential composition (%)		
C ₃ S	58	59
C ₂ S	16	12
C ₃ A	6	7
C ₄ AF	10	9

Table 2: Minimum dose of the each VMA to achieve stable SCC.

Mix #	1	2	3	4
VMA	VMA-1	VMA-2	VMA-3	VMA-5
VMA (mL/100 kg)	396	924	528	132
% Active of VMA	0.5	1	3	15
VMA (% cwt)	0.002	0.009	0.016	0.024
HRWR-1 (mL/100 kg)	462	495	495	759
HRWR-1 (% cwt)	0.152	0.163	0.163	0.250
Slump Flow (mm)	660	670	670	660
Visual Stability Index	0	0	3	0

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Table 3: The mortar bleeding study with VMA-1 (diutan gum), VMA-3 (synthetic polymer 1), and VMA-5 (cellulose ether 1).

MIX#	6	7	8	9	10	11	12	13	14
Admixture Dosages (ml/100kg)									
VMA-5	264	132	-	-	-	-	-	-	-
VMA-3	-	-	792	528	264	-	-	-	-
VMA-1	-	-	-	-	-	792	528	264	-
Unit Weight (g/mL)	2.16	2.13	2.13	2.17	2.15	2.21	2.19	2.22	2.20
Mortar Flow	47	60	60	69	62	60	64	80	70
Air Content (%)	3.5	4.8	4.9	3.0	3.8	1.5	2.3	0.9	1.6
Bleed Volume (mL)									
2 hours	18.4	36.0	43.4	42.0	26.0	24.0	26.8	33.8	38.4
2.5 hours	3.6	13.0	12.0	8.8	6.8	5.2	6.0	9.4	8.2
3 hours	3.6	11.2	6.4	9.6	3.6	2.8	3.0	7.4	6.6
3.5 hours	2.0	3.6	0.6	3.6	-	-	-	0.4	1.0
TOTAL	27.6	63.8	62.4	64.0	36.4	32.0	35.8	51.0	54.2

Table 4: Reduction in segregation by VMA-1 (diutan gum) and VMA-4 (synthetic polymer 2) added up-front in non-air entrained SCC with cement B.

MIX#	15	16	17	18	19	20	21
Admixture Dosages (mL/100 kg)							
HRWR-2	792	792	858	924	792	858	924
VMA-1	-	264	528	792	-	-	-
VMA-4	-	-	-	-	264	528	792
Slump Flow (mm)	680	650	640	660	600	600	550
Air Content (%)	1.7	1.7	1.5	1.9	1.9	2.2	2.5
Segregation Test							
Top Wt. (g)	5148	5456	5257	5386	5453	5678	5466
Bottom (g)	6444	5896	6036	6094	5917	5721	5855
Segregation Index	22%	8%	14%	12%	8%	1%	7%

Table 5: Effect of VMA-1 (diutan gum) on time of setting and strength development in non-air entrained SCC with cement A.

MIX#	22	23	24	25	26	27	28
Admixture Dosages (mL/100 kg)							
VMA-1	-	264	528	792	1320	-	1320
HRWR-1	528	528	528	528	528	396	660
Slump Flow (mm)	690	660	650	580	570	600	610
Air Content (%)	1.3	2.2	1.8	3.8	3.8	3.2	2.1
Initial Time of Setting (h:min)	4:33	4:37	4:48	4:44	4:47	4:31	5:12
Compressive Strength (MPa)							
1 Day	33	29	29	32	33	34	31
7 Day	52	50	55	47	51	52	52
28 Day	52	60	54	54	61	63	64

Table 6: Effect of VMA-1 (diutan gum) on rheology in non-air entrained SCC with cement A.

MIX#	29	30	31	32	33	34	35
Admixture Dosages (mL/100 kg)							
VMA-1	-	264	528	792	1320	-	1320
HRWR-1	528	528	528	528	528	396	627
Slump Flow (mm)	670	630	570	520	520	440	570
Air Content (%)	1.7	2.8	3.5	4.1	5.2	5.4	3.6
IBB Rheometer Test							
Viscosity (H)	13.5	22.4	25.0	31.8	29.5	29.1	21.4
Yield (G)	0.0	0.0	0.1	0.2	0.9	1.2	0.2

Table 7: Effect of VMA-4 (synthetic polymer 2) added up-front on time of setting, compressive strength and rheology in non-air entrained concrete with cement B.

MIX #	36	37	38	39	40
Admixture Dosages (mL/100 kg)					
HRWR-2	858	858	858	858	858
VMA-4	-	396	264	132	66
Slump Flow (mm)	640	570	580	610	640
Air Content (%)	3.6	3.7	3.5	3.7	3.9
Initial Time of Setting (h:min)	6:10	6:10	6:10	6:20	6:10
IBB Rheometer Test					
Viscosity (H)	2.2	2.7	2.4	2.3	2.0
Yield (G)	0.0	0.0	0.1	0.0	0.2
Compressive Strength (MPa)					
1 Day	19	18	17	19	19
7 Day	40	38	38	41	42
28 Day	48	45	44	47	48

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Table 8: Performance of VMA-5 (cellulose ether 1) and VMA-6 (cellulose ether 2) in non-air entrained concrete with cement A.

MIX #	41	42	43	44	45	46	47
Admixture Dosages (mL/100 kg)							
VMA-5	132	-	264	-	528	-	-
VMA-6	-	132	-	264	-	528	528
HRWR-2	990	990	1122	1122	1584	1584	1584
Slump Flow (mm)	450	580	550	610	520	690	650
Air Content (%)	3.3	3.4	2.3	3.7	2.2	3.4	3.2
Initial Time of Setting (hr:min)	6:41	6:16	7:54	7:41	10:28	9:55	-
Compressive Strengths (MPa)							
1 Day	31	33	31	33	30	31	-
14 Day	54	55	54	54	52	53	-
28 Day	57	57	58	58	57	57	-

Table 9: Air entrainment study with VMA-1 (diutan gum) vs. VMA-5 (cellulose ether 1) in SCC combining different HRWRs and AEA-1.

MIX#	48	49	50	51	52	53
Admixture Dosages (mL/100 kg)						
VMA-1	660	660	-	-	-	-
VMA-5	-	-	132	132	-	-
HRWR-1	429	-	429	-	297	-
HRWR-2	-	528	-	594	-	363
AEA-1	12	7	116	66	7	2
Slump Flow (mm)	690	600	640	620	650	460
Air Content (%)	8.0	8.9	8.7	7.3	8.8	6.6

Table 10: Air entrainment study with VMA-1 (diutan gum) vs. VMA-5 (cellulose ether 1) in SCC combining different HRWRs and AEA-2.

MIX#	54	55	56	57	58	59	60
Admixture Dosages (mL/100 kg)							
VMA-1	660	660	660	-	-	-	660
VMA-5	-	-	-	132	132	-	-
HRWR-1	396	-	396	462	-	-	-
HRWR-2	-	561	-	-	726	-	-
AEA-2	26	20	33	330	330	66	66
Slump Flow (mm)	650	480	610	530	480	200	220
Air Content (%)	5.5	7.0	7.8	5.4	6.0	8.0	7.0

Effect of Various Admixture-Binder Combinations on Workability of Ready-Mix Self-Consolidating Concrete

by S.-D. Hwang and K.H. Khayat

Synopsis: An experimental investigation was carried out to evaluate the effect of high-range water reducing admixture (HRWRA), viscosity-enhancing admixture (VEA), and binder type on key workability characteristics of self-consolidating concrete (SCC), including retention of deformability, passing ability, and stability. Concrete-equivalent mortar (CEM) mixtures were prepared to evaluate the effect of admixture-binder combinations on flow characteristics, including minimum water content (MWC) to initiate flow and relative water demand (RWD) to increase a given fluidity. Four polycarboxylate-based HRWRAs, a polynaphthalene sulfonate-based HRWRA, four types of VEAs, and three blended cements were evaluated. In total, 16 SCC mixtures with initial slump flow consistency of 660 ± 20 mm and air volume of $6.5 \pm 1.5\%$, and 17 CEM mixtures were investigated.

Flow characteristics of SCC and CEM mixtures made with a number of admixture-binder combinations indicate that the efficiency of admixture-binder combination depends on water-to-cementitious material ratio (w/cm), type of binder, and type of admixtures. The CEM approach can be used to evaluate the effect of admixture-binder combination on flow characteristics because the increase in MWC to initiate flow of CEM corresponds to higher demand in HRWRA in SCC mixtures. Binder type was shown to have marked influence on the retention of slump flow, L-box and V-funnel passing ability, filling capacity, and surface settlement characteristics. The binder type also affects HRWRA and air-entraining admixture (AEA) demand. As established from CEMs, B3 quaternary cement with the smallest 50% passing diameter had the highest MWC (lowest packing density) needed to initiate flow and the highest RWD (highest robustness to changes in water). SCCs made with such quaternary cement and polycarboxylate-based HRWRA also exhibited the highest HRWRA demand compared those prepared with other blended cements. Both sets of SCCs made with 0.35 w/cm and 0.42 w/cm plus VEA had similar HRWRA demand and static stability when the polycarboxylate-based HRWRA was used.

Keywords: admixture-binder combination; binder; concrete-equivalent-mortar; rheology; self-consolidating concrete (SCC); workability

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INTRODUCTION

Self-consolidating concrete (SCC) is a new class of high-performance concrete that can flow into place without any mechanical vibration and with limited degree of bleeding and segregation. Such concrete has been used to facilitate construction operations, including cast-in-place concrete in areas presenting special difficulties to casting and vibration. The SCC can also present some added-valued attributes at the hardened state. For example, experience in Sweden indicates that highly stable SCC used in bridge construction can develop superior microstructural characteristics at the transition zone between cement paste and aggregate compared to conventional concrete of normal consistency [1]. A more uniform distribution of bond (lower top-bar effect) and lower risk of corrosion can be secured when using stable SCC, compared to normal concrete subjected to mechanical vibration [2, 3].

Successful placement of SCC requires that the concrete exhibit high deformability and adequate cohesiveness to enhance the filling ability and static stability characteristics. Mix design of ready-mix SCC is often different than that used in precast applications, which includes water-to-cementitious material ratio (w/cm), type and content of cement and supplementary cementitious material, and admixtures. In ready-mix applications including repairs, two mix design approaches can be used to secure adequate dynamic and static stability of plastic concrete. The first involves the reduction in w/cm ranging from 0.33 to 0.37 to secure high stability without viscosity-enhancing admixture (VEA) but needs special care to select binder-admixture combinations to limit the development of compressive strength characteristics to targeted design values of 5 to 10 MPa and 35 to 40 MPa at 1 and 28 days, respectively. Otherwise, given the low w/cm , high mechanical properties could lead to cracking given high degree of restrained shrinkage that can take place in repair applications. The second approach is to maintain the moderate w/cm at a level (0.40 to 0.45) needed to secure adequate strength and durability without the need to reduce the water content and is to incorporate VEA to enhance stability and robustness. The incorporation of VEA increases both the yield value and plastic viscosity and necessitates higher demand of high-range water reducing admixture (HRWRA) compared to SCC made without any VEA. The use of a VEA along with an HRWRA can ensure both high deformability and adequate stability necessary to secure adequate filling capacity and uniformity of in-situ mechanical properties and bond to reinforcement in hardened elements cast with SCC [4, 5].

Khayat [2] compared the deformability, passing ability, and static stability of SCC mixtures proportioned with two mix design approaches: low w/cm of 0.35 without VEA containing the same content of cementitious materials and 0.41 w/cm with moderate VEA content. Two ternary blends of silica fume and fly ash or silica fume and blast furnace slag were used at three different binder contents. For the SCC systems proportioned with 555 and 425 kg/m³ of binder, the use of VEA at moderate dosage was shown to enhance deformability and resistance to surface settlement, despite the greater w/cm . The SCC mixtures made with 0.41 w/cm and a moderate VEA concentration exhibited greater passing ability, filling capacity, and static stability. This is due, in part, to the reduction in coarse aggregate volume of SCC made with the higher w/cm , given its higher paste volume.

In general, SCC is proportioned with high volume of powder materials and involves the replacement of some of the cement with fly ash, blast furnace slag, or limestone filler. This can improve particle-packing density and reduce interparticle friction, given the morphology and particle-size distribution of the powder materials [6, 7, 8, 9]. For example, Billberg [10] investigated the effect of mineral admixtures on fine mortar rheology and found that mortars made with finer cement can develop higher yield stress and plastic viscosity than those made with coarser cement for a given w/cm . This is attributed to the reduction in the mean distance between solid particles in mortars made with finer cement. This can lead to higher inter particle friction when the mortar is sheared.

With the increasing number of chemical admixtures and blended binder types used in SCC, better knowledge of the effect of admixture-binder combinations on workability and rheological properties of SCC is required. The study reported here is part of an extensive investigation carried out at Sherbrooke to develop high-performance SCC for repair applications. This paper discusses the effect of admixture-binder combinations on workability characteristics of SCC mixtures made with a number of mixture parameters, including w/cm , admixture, and binder type. Concrete-equivalent mortar (CEM) mixtures were also tested to evaluate the influence of various admixture-binder combinations on flow characteristics.

EXPERIMENTAL PROGRAM

The experimental program reported here includes two phases. The first phase (Phase I) is to evaluate the effect of HRWRA-binder combinations on flow characteristics of concrete-equivalent mortar (CEM) mixtures. The CEM mixtures are referred to as equivalent rheological properties with concrete [11]. Such CEM is designed to have the same type and content of cement or binder, the same w/cm , the same type and dosage of chemical admixtures, the same type of sand, and additional use of sand to reproduce equivalent surface area of the coarse aggregate in the concrete. The second phase (Phase II) is to assess the influence of admixture-binder combinations on key workability

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characteristics of SCC mixtures, including HRWRA demand, retention of slump flow, passing ability, rheological parameters, and static stability.

Flow characteristics of CEM

In total, 17 CEM mixtures were prepared. At first, five CEM mixtures were prepared with various types and brands of HRWRAs and one blended cement (B1) commercially available in North America to evaluate the effect of HRWRA type on flow characteristics. The HRWRAs included one polynaphthalene sulfonate-based HRWRA (N) and four polycarboxylate-based HRWRAs (C1-C4). Regardless of the HRWRA type, the dosage rate of HRWRA was fixed to 0.2% solid content by mass of cementitious materials to eliminate the effect of different HRWRA dosages on the flow characteristics. The characteristics of these admixtures are given in Table 1.

Additional 12 CEM mixtures were prepared to evaluate the influence of HRWRA-binder combinations on flow characteristics. These mixtures were made with three blended cements (B1, B2, B3) and four types of HRWRAs (N, C1, C3, C4). The CSA GUB-F/SF cement (B1) contains approximately 25% Class F fly ash and 5% silica fume, by mass of cementitious materials. The CSA GUB-S/SF cement (B2) is made with approximately 25% slag and 5% silica fume replacements, and the B3 quaternary cement contains fly ash, slag, and silica fume at unknown proportions. Characteristics of the cementitious materials are given in Table 2. The 12 CEM mixtures are based on the 12 SCC mixtures proportioned with 0.42 w/cm and three binder types presented in Table 3. Regardless of the binder type, the HRWRA dosage was fixed to that of SCC mixture prepared with the B1 cement. Well-graded siliceous sand that has fineness modulus of 2.5 and bulk specific gravities of 2.64 was employed. Its particle-size distributions lie within CSA A23.1 recommendations. All of the tested CEMs were prepared according to NORME C-109 mixing procedure.

The mortar flow test was used to evaluate the flow characteristics of CEM mixtures. As indicated in Figure 1, the test consists of determining the variations of fluidity of a given mortar with changes in water-to-powder ratio, by volume (Wv/Pv). The intercept of the curve with the ordinates axis (Wv/Pv) and the slope of the curve represents the minimum water content (MWC) to initiate flow and the relative water demand (RWD) to increase a given fluidity, respectively. A minimum of four Wv/Pv values was used to evaluate two flow parameters for each CEM.

Workability characteristics of SCC

The evaluated SCC mixtures were prepared with two mix design approaches made with various types and brands of HRWRAs, VEAs, and air-entraining admixtures (AEAs), as presented in Table 1. From each admixture manufacturer, compatible AEAs and liquid-based VEAs were selected to secure stable air-void system and adequate resistance to segregation. For concrete mixtures made with w/cm of 0.35, a CSA Type GU cement, similar to ASTM C 150 Type I cement, was used with 30% Class F fly ash and 5% silica

fume replacements, by mass of cementitious materials. For the other set of mixtures made with 0.42 *w/cm*, three blended cements (B1, B2, B3) were used. A continuously graded crushed limestone with a maximum size aggregate of 10 mm and that has fineness modulus of 6.4 and bulk specific gravities of 2.73 was employed. Its particle-size distributions lie within CSA A23.1 recommendations. Well-graded siliceous sand was employed as in the case of CEM mixtures.

All of the SCC mixtures were prepared with 475 kg/m³ of cementitious materials, which is typically used in SCC targeted for repairs in Canada. The sand-to-coarse aggregate ratio (by volume) was fixed at 1.0. Mixture proportioning of the tested SCC mixtures made with *w/cm* of 0.35 and 0.42 are presented in Table 3. The HRWRA and AEA concentrations were adjusted to secure initial target slump flow consistency of 660 ± 20 mm and air volume of 6.5 ± 1.5%.

Additional experimental work was undertaken to evaluate the effect of admixture-binder combinations on workability of SCC for mixtures with 0.42 *w/cm*. The investigated mixtures were proportioned with three blended cements (B1, B2, B3) and four types of HRWRAs (N, C1, C3, C4). The concentration of VEA determined for the optimized concrete made with the B1 cement was maintained fixed for similar mixtures prepared with the B2 or B3 cement, as indicated in Table 3.

The mixing sequence consisted of homogenizing the sand and coarse aggregate for 30 sec before introducing half of the mixing water. The AEA diluted in half of the water was then added. After 30 sec of mixing, all of the cementitious materials were introduced along with the remaining water that was used to dilute the HRWRA. The concrete was mixed for 3 min and kept at rest for 5 min, before remixing for 3 additional minutes.

Workability test methods

The workability of the concrete was evaluated using the slump flow, V-funnel, L-box, filling capacity, and surface settlement tests. The testing was carried out within 20 min from the end of mixing. The slump flow test was used to evaluate deformation capacity and filling ability of SCC (ASTM C143). The V-funnel apparatus having an outlet of 75 × 75 mm was used, which different from the 65 × 75 mm outlet proposed by Ozawa et al. [12]. The L-box with the 12-mm diameter bars set at clear distance of 35 mm between adjacent bars was used to assess the passing ability [13]. The filling capacity was determined by casting the concrete in a transparent box (caisson) measuring of 300 × 500 × 300 mm containing closely spaced smooth horizontal tubes of 16 mm in diameter and with 34-mm clear spacing in both the horizontal and vertical directions [14]. The column surface settlement test was used to evaluate the stability of concrete and its ability to ensure proper suspension of aggregate and fines [15]. The apparent yield stress (*g*) and torque plastic viscosity (*h*) were evaluated using a modified two-point workability rheometer similar to the MK III model proposed by Tattersall [16].

Effect of admixture-binder combinations on flow characteristics of CEM

In general, concrete made with PNS-based HRWRA exhibits higher HRWRA demand compared to that prepared with PCP-based HRWRA. Similar result was found in flow characteristics of concrete-equivalent mortar (CEM), as shown in Figure 2. Five CEM mixtures were proportioned with the same binder type (B1 cement) and five types of HRWRAs with the dosage rate of 0.2% solid content by mass of cementitious materials. For the given HRWRA dosage, CEM made with PNS-based HRWRA exhibited higher minimum water content to initiate flow (MWC) compared to that prepared with PCP-based HRWRA. It is worthy to note that CEM proportioned with PNS-based HRWRA also developed significantly higher relative water demand (RWD) to increase a given fluidity than other mixtures made with PCP-based HRWRA. Therefore, for a given change in water content, the CEM mixture with PNS-based HRWRA exhibits smaller increase in fluidity, which leads to greater robustness than PCP-based HRWRA. Regardless of the type of HRWRA, CEM mixtures exhibited similar MWC and RWD values when PCP-based HRWRAs were used.

Variations in MWC with binder type are compared in Figure 3. Regardless of the binder type in use, the HRWRA concentration was fixed to that determined for SCC mixtures made with the B1 cement to evaluate the effect of binder type on flow characteristics of CEM. Regardless of the HRWRA type in use, CEMs made with the B2 cement necessitated the lowest MWC value. This can be due to greater packing density and less water adsorption of the B2 cement compared to other blended cements. The same tendency was observed in concrete mixtures. SCC mixtures made with the B2 cement had lower HRWRA demand than those prepared with the B1 cement. This can be partially due to the fact that the slag used in the B2 cement can develop lower water demand than the fly ash in the B1 cement. The B2 cement has lower Al_2O_3 content (5.1%) compared to the B1 cement (8.7%) that can result in lower content of C_3A , which affects the rheology of the mortars at early age. In the case of PCP-based HRWRA, mortars made with the B3 quaternary cement necessitated the highest MWC to initiate flow. This agrees well with the fact that the B3 cement resulted in the highest HRWRA demand for the SCC mixtures as presented in Table 3.

Figure 4 presents the effect of binder type on the relative water demand (RWD) of CEM mixtures. In the case of PCP-based HRWRA, CEM mixtures made with finer B3 quaternary cement exhibited higher RWD. This can lead to relatively small variation in fluidity given a certain increase in water-to-powder ratio, thus leading to greater robustness to changes in water than other blended cements. For example, mixtures made with the C3 HRWRA and the B1, B2, and B3 cements had RWD values of 0.053, 0.058, and 0.073, respectively. The 50% passing diameter (D_{50}) values of these cements are 16, 14, and 12 μm , respectively. Considerably low RWD was obtained for the CEM made with PNS-based HRWRA and B3 cement. Relationships between D_{50} value of cements and RWD values indicate that higher surface fineness leads to higher RWD values, because paste made with finer binder system necessitates more water to increase a certain

thickness of the water film separating adjacent particles and have small variation in fluidity in a given change in water-to-powder ratio [10].

Performance of SCC made with different mix design approaches

As summarized in Table 4, two sets of mixtures prepared with different mix design approaches were compared: the first four mixtures in Table 4 proportioned with low w/cm of 0.35 and no VEA, and the second four with relatively high w/cm of 0.42 and VEA. Regardless of the w/cm and admixture combination, the initial slump flow consistency of 660 ± 20 mm and targeted air volume of 5% to 8% were achieved in all the tested mixtures.

The HRWRA demand of the evaluated concrete varied from 2.4 to 7.0 L/m³, depending on admixture combination. This corresponds to 0.16% to 0.72% of solid content of HRWRA, by mass of binder. Regardless of the w/cm and use of VEA, similar HRWRA demands were obtained for mixtures prepared with PCP-based HRWRA (0.16% to 0.24%). Concrete made with PNS-based HRWRA had significantly high HRWRA demand of 0.72%. The incorporation of VEA increased also the AEA demand, especially in mixtures containing relatively high VEA dosage (VEA1, VEA2); The AEA concentrations were 375 and 400 mL/m³ for the 42-C1-B1 and 42-N-B1 mixtures, respectively. For the remaining SCC mixtures, these values ranged from 10 to 90 mL/m³.

Regardless of the HRWRA type, SCC mixtures proportioned with 0.42 w/cm were less viscous than those made with 0.35 w/cm , in terms of torque plastic viscosity (h) values. The h values ranged from 4.0 to 6.0 N.m.s for mixtures proportioned with 0.42 w/cm and VEA and from 8.0 and 10.7 N.m.s for those made with 0.35 w/cm . This, however, can be due to the decrease in coarse aggregate content in the former mixtures compared to the latter. The decrease in coarse aggregate content from 842 to 800 kg/m³ (Table 3) can reduce internal friction and collision among solid particles, thus leading to lower torque plastic viscosity (h) and faster V-funnel flow time. As shown in Figure 5, the V-funnel flow time values ranged from 2.7 to 4.0 sec for SCC made with 0.42 w/cm and from 3.8 to 5.5 sec for those prepared with 0.35 w/cm . Despite the different V-funnel flow time and h values, SCC mixtures made with 0.42 w/cm exhibited similar static stability as those prepared with 0.35 w/cm , for selected HRWRA-VEA combinations. For the C3 and C4 HRWRAs, the mixtures made with 0.42 w/cm had surface settlement values of 0.16 and 0.21, respectively. These values were 0.19 and 0.16 for the mixtures prepared with 0.35 w/cm and the C3 and C4 HRWRAs, respectively (Table 4). Furthermore, SCC mixtures prepared with 0.42 w/cm and VEA exhibited excellent filling capacity values of 85% to 99% and L-box blocking ratio (h_2/h_1) values of 78% to 90%.

Effect of admixture-binder combinations on workability of SCC

The HRWRA demand of mixtures made with three blended cements is compared in Figure 6. Mixtures made with the B3 quaternary cement necessitated the highest HRWRA concentration when PCP-based HRWRAs were used. This can be in part due to

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the relatively finer nature of this cement (D50 of 12 μm versus 14 and 16 μm for the B1 and B2 cements, respectively). Both the yield stress and plastic viscosity can increase with the increase in specific surface area of solid particles in mixtures of a given solid content [17]. SCC mixtures made with the B3 cement had higher paste volume compared to those prepared with the B1 and B2 cements, given the relatively lower density of the B3 binder. Regardless of the HRWRA type in use, mixtures made with the B2 cement exhibited the lowest HRWRA demand, and concrete-equivalent mortar (CEM) mixtures made with this cement also necessitated the lowest minimum water content (MWC) value. As already mentioned, this can be due to greater packing density and less water adsorption of the B2 cement compared to other blended cements. This can be partially due to the fact that the slag used in the B2 cement can develop lower water demand than the fly ash in the B1 cement. Concrete made with PNS-based HRWRA exhibited significantly higher HRWRA demand ranging between 0.52% and 0.72%, by mass of binder, compared to 0.13% and 0.30% for those made with PCP-based HRWRA.

Mixtures made with the B3 quaternary cement necessitated significantly higher AEA dosage to secure $6.5 \pm 1.5\%$ air content. In particular, the 42-C3-B3 concrete necessitated approximately ten times higher AEA demand compared to the 42-C3-B1 and 42-C3-B2 mixtures. Mixtures made with PCP-based HRWRA necessitated significantly lower AEA dosage to secure $6.5 \pm 1.5\%$ air content compared to that with PNS-based HRWRA. The use of PCP-based HRWRA could cause entrapment of relatively large air bubbles compared to PNS-based HRWRA, depending on the type and content of the de-foamer in use. Special care should be taken to optimize fresh air content to have stable air-void system in the hardened state needed to secure high frost durability.

The effect of binder type on workability retention varied with the HRWRA in use. Regardless of the binder type, mixtures made with PNS-based HRWRA exhibited relatively lower losses in slump flow compared to those made with PCP-based HRWRAs. This is attributed to the retarding effect of the PNS when used at relatively high concentration. As shown in Figure 7, concretes made with PNS-based HRWRA did not exhibit any significant increase in yield stress (g) after 1 hour. These values are in parenthesis in Figure 7. The great workability retention in mixtures made with PNS-based HRWRA also led to excellent retention in passing ability and filling capacity, including V-funnel flow time, L-box blocking ratio (h_2/h_1), and caisson filling capacity, regardless of the cement type in use. On the other hand, mixtures made with PCP-based HRWRA and the B2 cement had significantly greater slump flow loss (105 to 240 mm) and increase in g values (0.4 to 0.8 N.m), compared to similar mixtures prepared with the B1 and B3 cements. The high loss in workability found in mixtures made with the B2 cement and PCP-based HRWRA can be in part due to relatively lower HRWRA concentration than mixtures made with the B1 and B3 cements. Furthermore, mixtures made with the B2 cement exhibited higher losses in filling capacity and L-box blocking ratio (h_2/h_1) compared to those prepared with other blended cements when PCP-based HRWRA was used (Table 5).

Mixtures made with PNS-based HRWRA exhibited higher settlement values ranging from 0.44% to 0.70% compared to 0.16% to 0.45% for those prepared with PCP-based

HRWRA. Again, this is attributed to the retarding effect of the PNS at relatively high concentration. For mixtures made with PCP-based HRWRA, the highest settlement values were obtained when the B3 quaternary cement was used (0.24% to 0.45%). This can be due to the slow hydration characteristics of this cement.

The values of the minimum water content (MWC) established with concrete-equivalent mortar (CEM) mixtures are compared in Figure 8 to the HRWRA demand obtained from SCC mixtures. For a given HRWRA-VEA combination, good correlation can be made between the MWC and HRWRA demand, regardless of the cement type. For a given MWC value, SCC made with PNS-based HRWRA exhibited higher HRWRA demand than mixtures made with PCP-based HRWRA. Regardless of the cement type, concretes made with PNS-based HRWRA necessitated significantly higher demand of HRWRA. The slopes of the four lines representing relationships between HRWRA demand of SCC and MWC of CEM are similar, regardless of the HRWRA type and HRWRA-VEA combination in use. The increase in MWC values of CEM corresponds to higher demand in HRWRA in SCC. The CEM approach can be used to evaluate the effect of binder-admixture combination on flow characteristics of SCC.

CONCLUSIONS

Given the results presented in this paper, the following conclusions are warranted:

1. Efficiency of binder-admixture combination depends on w/cm , type of binder, and type of admixtures.
2. Good correlation can be made between the minimum water content (MWC) and HRWRA demand, regardless of the cement type. The increase in MWC values of concrete-equivalent mortar (CEM) corresponds to higher demand in HRWRA in SCC. CEM approach can be used to evaluate the effect of binder-admixture combination on flow characteristics of SCC.
3. As established from the evaluation of flow characteristics of CEM, the B3 quaternary cement had the highest MWC (lowest packing density) needed to initiate flow and the highest relative water demand (highest robustness to changes in water).
4. The B2 cement had the lowest MWC regardless of HRWRA in use. SCC mixtures made with the B2 cement also exhibited the lowest HRWRA demand. This can be due to greater packing density and less water adsorption of the B2 cement compared to other blended cements.
5. Workability retention of SCC depends on the HRWRA type. Great workability retention in mixtures made with PNS-based HRWRA can lead to excellent retention in V-funnel flow time, L-box blocking ratio (h_2/h_1), and caisson filling capacity. The retarding effect of the PNS-based HRWRA at relatively high concentration leads to relatively high settlement values (0.44% to 0.70%), compared to mixtures prepared with PCP-based HRWRA (0.16% to 0.45%).

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6. Binder type has considerable influence on workability of SCC. Higher loss in workability found in mixtures made with the B2 cement and PCP-based HRWRA led to higher losses in filling capacity and L-box blocking ratio (h_2/h_1) compared to those prepared with other blended cements.
7. SCC mixtures made with 0.42 w/cm was less viscous than those prepared with 0.35 w/cm in terms of torque plastic viscosity (h) values. This, however, can be due to the decrease in coarse aggregate content (from 842 to 800 kg/m³) in the former mixtures compared to the latter. For selected HRWRA-VEA combinations, SCC mixtures made with 0.42 w/cm exhibited similar static stability as those prepared with 0.35 w/cm.
8. Regardless of the mix design approaches, all the SCC mixtures exhibited excellent dynamic stability, including V-funnel flow time, L-box blocking ratio (h_2/h_1), and filling capacity values.

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Table 1: Characteristics of chemical admixtures

Admixture codification	Solid content (%)	Specific gravity	Manufacturer recommended range of additions
C1	39	1.09	250 – 650 mL / 100 kg of binder
VEA1	100	0.95	0.5 – 2.0%, by mass of binder
AEA1	10	1.01	35 – 395 mL / 100 kg of binder
C2	32	1.07	200 – 2000 mL / 100 kg of binder
N	40.5	1.21	400 – 4000 mL / 100 kg of binder
VEA2	42.5	1.21	1100 – 2700 mL/100 L of water
AEA2	10.5	1.00	30 – 100 mL/100 kg of cement
WRA*	28.5	1.15	Up to 200 mL / 100 kg of binder
C3	20	1.06	325 – 1300 mL/100 kg of binder
VEA3	50	1.35	Unknown
AEA3	19.3	1.02	30 – 320 mL/100 kg of cement
SRA**	49.3	1.23	130 – 520 mL / 100 kg of binder
C4	27.1	1.09	260 – 780 mL/ 100 kg of binder
VEA4	39.1	1.12	130 – 920 mL / 100 kg of binder
AEA4	10	1.01	8 – 98 mL/ 100 kg of cement

*WRA = Water-reducing admixture, ** SRA = Set-retarding agent

Table 2: Chemical and physical characteristics of cementitious materials

	T-GU	FA	SF	B1	B2	B3
SiO ₂ , %	21.0	43.6	92.4	32.3	26.5	-
Al ₂ O ₃ , %	4.2	23.6	0.42	8.7	5.1	-
Fe ₂ O ₃ , %	3.1	21.4	0.52	5.0	2.7	-
CaO, %	62.0	4.06	1.93	45.5	55.8	-
MgO, %	2.9	0.33	-	1.4	4.0	-
Na ₂ O eq., %	0.74	1.39	0.77	0.6	0.79	-
50% passing diameter (D ₅₀), µm	17	19	-	16	14	12
Blaine surface area, m ² /kg	420	310	17,500	530	645	690
B.E.T., m ² /kg	-	-	20,250	-	-	-
Percent passing 45 µm	95	91	100	96	95	94
Specific gravity	3.17	2.43	2.22	2.91	3.05	2.87
LOI, %	2.5	2.2	2.8	1.4	0.8	-

T-GU = CSA Type GU cement; FA = fly ash; SF = silica fume

BFS = blast-furnace slag

B1 = CSA Type GUB-F/SF (FA/SF); B2 = CSA Type GUB-S/SF (BFS/SF)

B3 = quaternary cement (FA/BFS/SF)

Table 3: Mixture proportioning of tested SCC mixtures (kg/m³)

Codification*	w/cm	B	W	CA	S	HRWRA		VEA		AEA		WRA	SRA
						Type	L/m ³	Type	L/m ³	Type	mL/m ³	mL/m ³	mL/m ³
35-C1-BC	0.35	475 (1)	166	842	814	C1	2.38	VEA1	-	AEA1	50	-	-
35-C2-BC	0.35	475 (1)	166	842	814	C2	3.30	VEA2	-	AEA2	10	-	-
35-C3-BC	0.35	475 (1)	166	842	814	C3	3.65	VEA3	-	AEA3	40	-	500
35-C4-BC	0.35	475 (1)	166	842	814	C4	3.15	VEA4	-	AEA4	30	-	-
42-C1-B1	0.42	475 (2)	200	800	774	C1	2.63	VEA1	1.31	AEA1	375	-	-
42-N-B1	0.42	475 (2)	200	800	774	N	7.00	VEA2	3.69	AEA2	400	475	-
42-C3-B1	0.42	475 (2)	200	800	774	C3	3.75	VEA3	0.22	AEA3	20	-	120
42-C4-B1	0.42	475 (2)	200	800	774	C4	2.89	VEA4	1.60	AEA4	90	-	-
42-C1-B2	0.42	475 (3)	200	811	785	C1	2.35	VEA1	1.31	AEA1	375	-	-
42-N-B2	0.42	475 (3)	200	811	785	N	5.00	VEA2	3.69	AEA2	350	475	-
42-C3-B2	0.42	475 (3)	200	811	785	C3	3.20	VEA3	0.22	AEA3	30	-	120
42-C4-B2	0.42	475 (3)	200	811	785	C4	2.13	VEA4	1.60	AEA4	60	-	-
42-C1-B3	0.42	475 (4)	200	789	763	C1	3.40	VEA1	1.31	AEA1	650	-	-
42-N-B3	0.42	475 (4)	200	789	763	N	5.50	VEA2	3.69	AEA2	780	475	-
42-C3-B3	0.42	475 (4)	200	789	763	C3	5.25	VEA3	0.22	AEA3	348	-	120
42-C4-B3	0.42	475 (4)	200	789	763	C4	3.20	VEA4	1.60	AEA4	130	-	-

* Codification = w/cm-HRWRA-binder type (C and N refer to PCP-based and PNS-based HRWRA, respectively)

(1) Blended Cement (BC) = CSA Type GU + 30% Class F FA + 5% SF; (2) B1 cement; (3) B2 cement; (4) B3 cement

B, W, CA, and S refer to binder, water, coarse aggregate, and sand, respectively

Table 4: Test results of optimized SCC mixtures

		w/cm	0.35				0.42			
		Codification	35-C1-BC	35-C2-BC	35-C3-BC	35-C4-BC	42-C1-B1	42-N-B1	42-C3-B1	42-C4-B1
Solid content, by mass of binder (%)		HRWRA	0.21	0.24	0.16	0.20	0.24	0.72	0.16	0.18
		VEA	-	-	-	-	0.26	0.40	0.03	0.15
Slump flow, mm		Initial	670	665	675	675	670	650	665	670
		After 1 hr	620	635	665	670	68	600	650	640
Filling capacity, %		Initial	88	98	95	93	99	94	91	88
		After 1 hr	81	90	93	96	97	85	96	94
V-funnel flow time, sec		Initial	4.6	3.8	5.5	4.2	3.9	4.0	3.0	2.7
		After 1 hr	4.2	4.1	5.7	4.4	4.7	4.3	3.2	2.8
L-box blocking ratio, h ₂ /h ₁ , %		Initial	67	86	84	77	90	83	80	78
		After 1 hr	58	80	83	76	81	72	74	87
Rheological parameters	g, N.m	Initial	0.4	0.2	0.6	0.2	0.6	0.6	0.2	0.4
		After 1 hr	0.8	0.4	0.8	0.4	0.5	0.6	0.3	0.4
	h, N.m.s	Initial	8.2	10.6	10.7	8.0	5.2	6.0	5.2	4.0
		After 1 hr	8.5	11.6	11.6	5.6	7.1	7.3	4.9	4.6
Air volume, %		Initial	5.5	8.0	6.5	6.5	5.7	6.2	6.4	7.2
		After 1 hr	4.8	7.0	6.2	8.0	5.9	5.0	5.7	7.0
Surface settlement, %			0.16	0.15	0.19	0.16	0.33	0.44	0.16	0.21
Rate of settlement at 30 min, %/hr			0.08	0.07	0.06	0.06	0.12	0.14	0.07	0.08

Table 5: Test results of SCC mixtures made with 0.42 w/cm and three blended cements

Codi.		42-N-B1	42-N-B2	42-N-B3	42-C1-B1	42-C1-B2	42-C1-B3	42-C3-B1	42-C3-B2	42-C3-B3	42-C4-B1	42-C4-B2	42-C4-B3	
Binder*		B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	
HRWRA		N			C1			C3			C4			
Solid content, by mass of binder (%)	HRWRA	0.72	2.45	2.70	1.12	1.00	1.45	0.80	0.68	1.11	0.85	0.63	0.95	
	VEA	0.40	0.40	0.40	0.26	0.26	0.26	0.03	0.03	0.03	0.15	0.15	0.15	
Slump flow, mm	Initial	650	670	645	670	675	665	665	660	670	670	665	675	
	After 1 hr	600	670	610	680	570	628	650	420	600	640	500	625	
Filling capacity, %	Initial	94	96	93	99	88	91	91	71	94	88	85	93	
	After 1 hr	85	94	88	97	60	86	97	14	86	94	41	83	
V-funnel flow time, sec	Initial	4.0	4.7	5.4	3.9	3.3	3.8	3.0	3.1	2.8	2.7	2.8	2.5	
	After 1 hr	4.4	4.3	5.7	4.7	3.4	3.9	3.2	5.3	3.4	2.8	3.4	2.7	
L-box blocking ratio, h ₂ /h ₁ %	Initial	83	75	85	90	80	83	80	56	89	78	78	92	
	After 1 hr	72	81	80	81	54	73	74	8	68	87	44	70	
Rheological parameters	g (N.m)	Initial	0.6	0.7	0.7	0.6	0.7	0.9	0.2	1.0	0.9	0.4	0.8	0.6
		After 1 hr	0.6	0.6	0.6	0.5	1.3	1.0	0.3	1.8	1.2	0.4	1.2	0.6
	h (N.m.s)	Initial	6.0	6.6	7.8	5.2	6.2	8.8	5.2	5.4	4.7	4.0	5.0	5.0
		After 1 hr	7.3	8.2	11.2	7.1	5.9	11.2	4.9	6.8	5.8	4.6	5.4	5.7
Air volume, %	Initial	6.2	8.0	7.0	5.7	7.9	7.0	6.4	7.0	8.5	7.2	7.4	5.6	
	After 1 hr	5.0	6.4	5.7	5.9	9.7	6.0	5.7	7.3	9.0	7.0	8.0	6.0	
Surface settlement, %		0.44	0.70	0.54	0.33	0.25	0.38	0.16	0.21	0.24	0.21	0.20	0.45	
Rate of settlement at 30 min, %/hr		0.14	0.17	0.14	0.13	0.13	0.17	0.07	0.08	0.11	0.08	0.12	0.18	

*B1 = CSA GU_b-F/SF (FA/SF); B2 = CSA GU_b-S/SF (BFS/SF); B3 = quaternary cement (FA/BFS/SF)

*B1 = CSA GUb-F/SF (FA/SF); B2 = CSA GUb-S/SF (BFS/SF); B3 = quaternary cement (FA/BFS/SF)

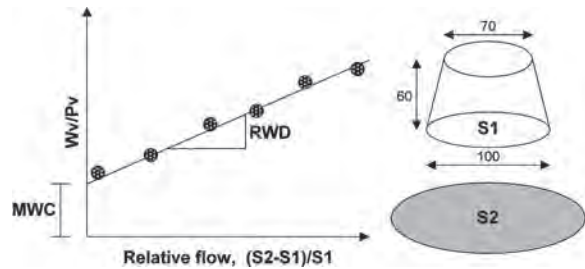


Figure 1: Definition of MWC and RWD parameters from mortar flow test

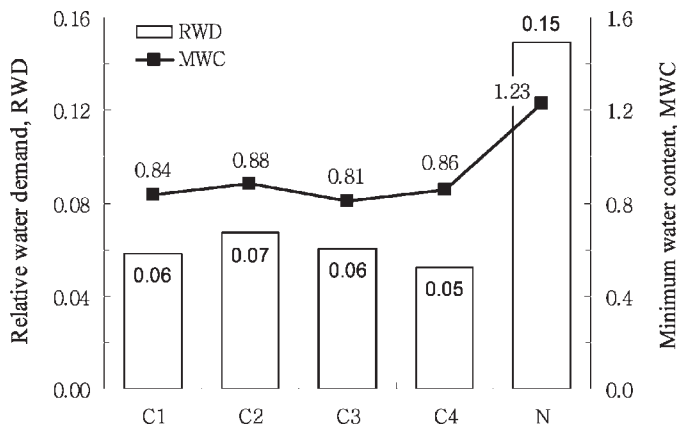


Figure 2: Effect of HRWRA type on flow characteristics of CEM

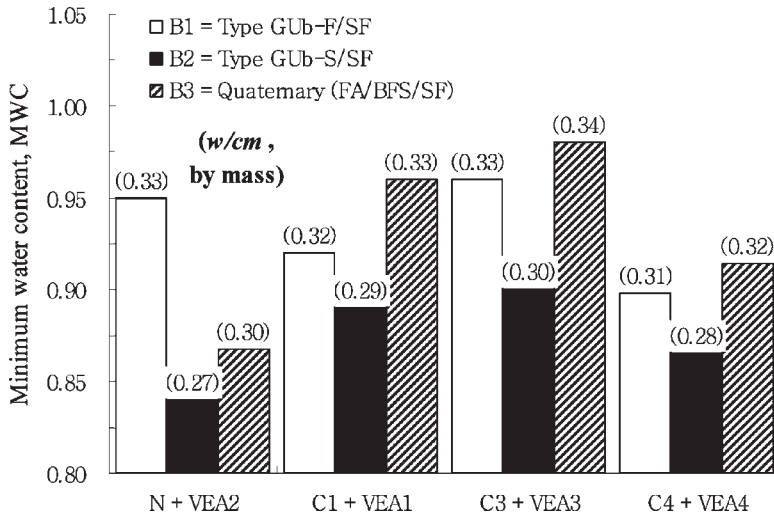


Figure 3: Effect binder type on minimum water content for CEM mixtures (w/cm , by mass)

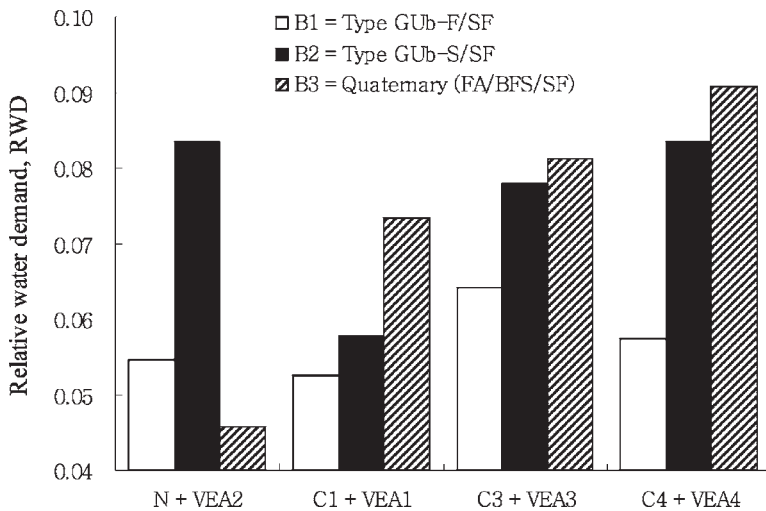


Figure 4: Effect of binder type on relative water demand for CEM mixtures

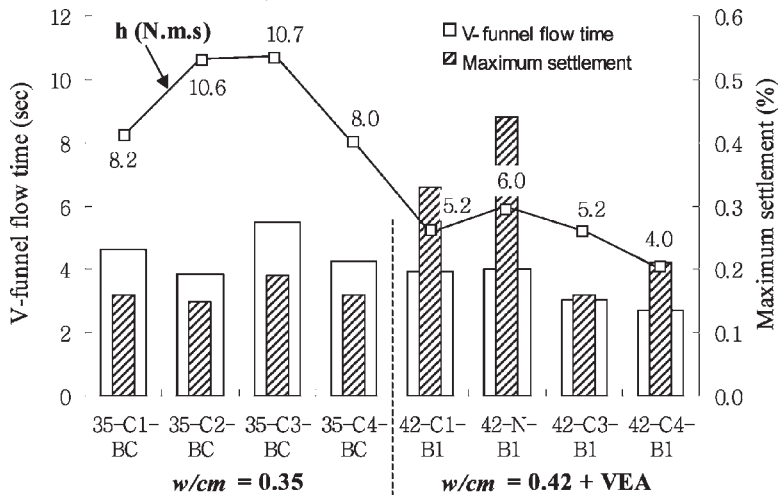


Figure 5: Comparison of stability determined by V-funnel flow time and maximum settlement

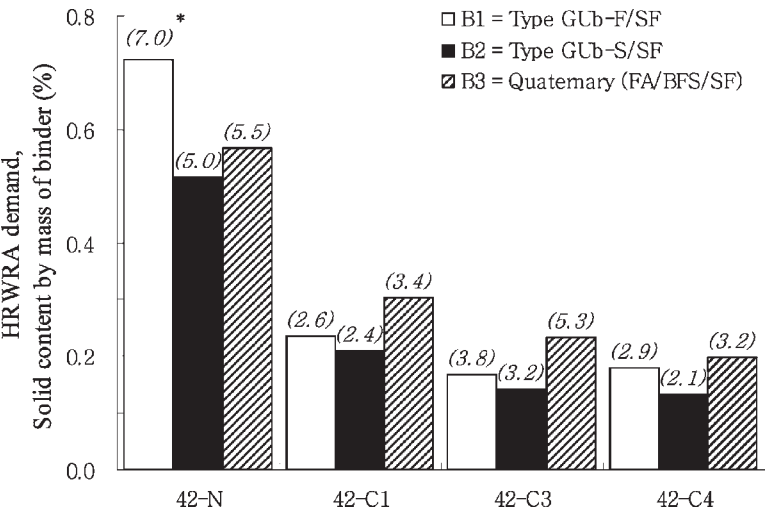


Figure 6: Effect of binder on HRWRA with 0.42 w/cm (*dosage in L/m^3)

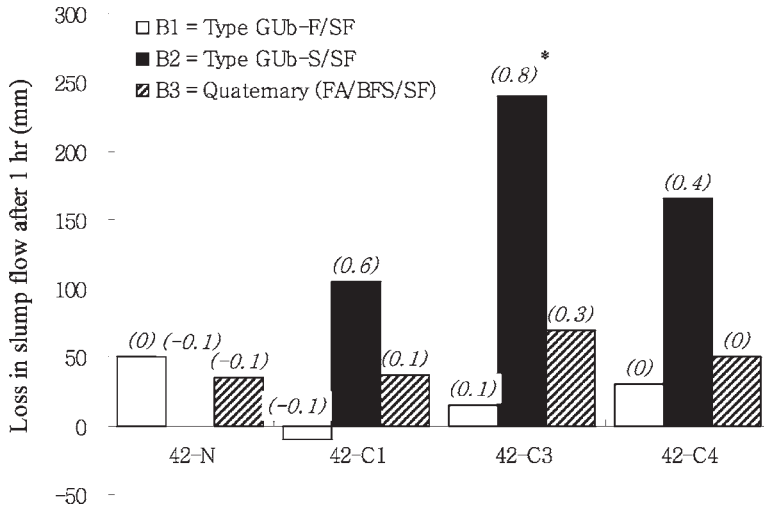


Figure 7: Effect of binder type on loss in slump flow for SCC made with w/cm of 0.42
 (*Values on parenthesis refer to increase in $g, N.m.$, after 1 hr)

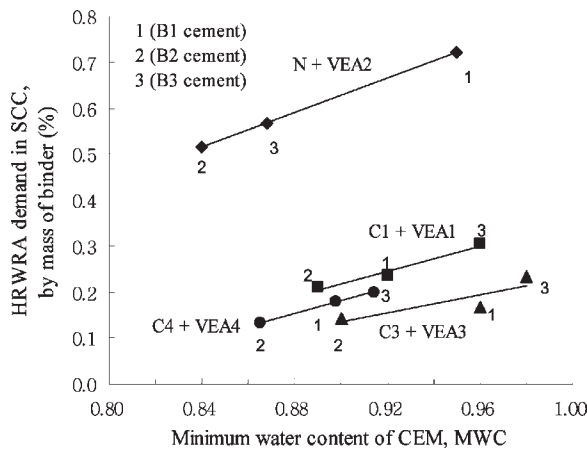


Figure 8: Relationship between HRWRA demand of SCC and MWC index of CEM

Properties of Self-Consolidating Concrete Containing Class F Fly Ash: With a Verification of the Minimum Paste Volume Method

by R.P. Douglas, V.K. Bui, Y. Akkaya, and S.P. Shah

SYNOPSIS:

An experimental program which aimed at investigating the behavior of SCC containing Class F fly ash has been carried out. The fresh state properties of the concrete were assessed using methods of segregation and flow. The rheology of the paste matrix was also characterized and compared with a previously developed paste rheology model. In addition, compressive strength, chloride permeability, and mold-finish were evaluated

The results indicate that it is possible to develop a SCC containing Class F fly ash that is high performing in its fresh state. Furthermore, the addition of fly ash was shown to reduce superplasticizer dosage, increase workability, and increase overall chloride permeability resistance. In addition, it was determined that the difference of densities between the aggregate and matrix influence the results of a previously developed paste rheology model.

Keywords: fly ash; permeability; rheology; self-consolidating concrete (SCC)

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1. INTRODUCTION

The usage of SCC is rapidly growing in the United States, however, there is a need to decrease the material cost, develop globally agreed upon test methods, and gain a deeper understanding of SCC technology. One way to reduce the material cost of SCC is through adequate mix proportioning and the addition of supplementary powder materials, such as fly ash. However, not all fly ash is suitable for concrete, and because the chemical composition of fly ash widely varies ASTM C 618 provides a classification system based on its coal source. Class C fly ashes are produced from the burning of lignitic or subbituminous coals and are primarily found in western states. Class F fly ashes are produced from the burning of bituminous and anthracite coals and are primarily found in states east of the Mississippi River [1]. Class F fly ash have a higher carbon content and lower calcium oxide (lime) content than Class C fly ash, and only exhibits pozzolanic properties when it is introduced to water. However, due to its high calcium oxide content, Class C fly ash exhibits pozzolanic and cementitious properties when introduced to water. The most common coals found in the Illinois region are high volatile bituminous coals [2] however, Class C fly ash is more often used in construction by the Illinois Department of

Transportation. Therefore, the properties of SCC containing Illinois fly ash should be evaluated in order to determine if it is possible to produce a good quality SCC with fly ash from the Illinois region.

The objective of this project was to investigate the fresh properties of SCC containing Illinois Class F fly ash. In addition, the permeability and compressive strength were also evaluated. The rheological properties of the cement paste were evaluated and compared with the results from a previously developed paste rheological model. The results of this project should provide information that will help reduce the material cost of SCC, further sustainable development in the concrete industry, and contribute to the development and usage of SCC in the United States and the global community.

2. BACKGROUND

2.1. Previously developed rheological models

A rheological model for self-consolidating concrete was developed by Bui, Akkaya, and Shah [3]. This model, which takes into account aggregate particle interaction, is based on the assumption that there is a minimum flow, minimum apparent viscosity, and optimum flow-viscosity ratio needed in order to produce a good quality SCC with satisfactory deformability and resistance to segregation. Therefore, there is a “window of opportunity” or satisfactory zone for obtaining a good performing SCC. It has been shown that segregation resistance is affected by aggregate diameter. Hence the average aggregate diameter (D_{av}) and average aggregate spacing (D_{ss}) were used as parameters to account for aggregate influence. See Reference 3 for an in depth discussion of these two parameters.

It was proposed that this model would be valid for concrete mixes with different aggregate ratios, cement contents, fly ash types and content, and water/binder ratios. The model was developed with concrete mixes with water/binder (W/B) ratios ranging from 0.31 to 0.39 (only one mix was tested with a W/B = 0.31, most mixes had a W/B = 0.38) and paste volumes ranging from 335 to 487 L/m³. For high water to binder ratios (greater than 0.40), there is a high potential for sedimentation [4, 5], slippage [6, 7], and centrifugal separation [4], when centric cylinder rheometers are used. Also, it is believed that the difference between the densities of paste and aggregates affects the requirement of rheology for SCC paste [3, 6]. However, in the recently developed rheological model [3], this factor was neglected because the range of W/B used in test program was small. Therefore, in the study presented in this paper, the application of the rheological model will be examined for mixes with high water to binder ratio (W/B = 0.45), for which the difference between densities of paste and aggregates is significant and may affect the correlation of paste rheology with SCC's properties.

2.2. Permeability

The RCPT test, also known as the electrical resistance test, is a six hour test provides a rapid indication of concrete's resistance to the penetration of chloride ions by monitoring electric current across the specimen. A voltage of 60V DC is maintained across the ends of the sample throughout the test. If a concrete is very permeable, then more chloride ions will migrate and the current will be increase. The total charge is obtained by integrating

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the area under the current versus time plot, hence $Q = \int Idt$. The concretes are qualitatively using the criteria in ASTM C-1202 [8].

Numerous studies have shown that a linear correlation exists between the total charge and initial current measured for the RCPT method. In 1996, Wang et.al [9] showed that this relationship existed independently of the W/C ratio. In 1999, McGrath and Hooton [10] conducted a study in which the RCPT test was shortened to 30 minutes in order to eliminate the effects of specimen heating. Results from this study showed that the 30 minute test and the full 6 hour test yielded values within 10% at low charge values; however, larger differences occurred at higher charge values. At the same time, Shane et.al [11] reported the trend of deviation in the plot of initial current versus total charge from a theoretical line at values above 2000-4000 Coulombs. This theoretical line was obtained from the slope of the plot of the initial current versus total charge.

3. EXPERIMENTAL PROGRAM

3.1. Materials

Ordinary (Type 1) Portland Cement (OPC) and Vermillion (Type F) Fly Ash were used. The physical and chemical properties of the fly ash are listed in Table 3.1. Fine river sand and 19mm diameter gravel were used as the aggregates. The physical properties and particle size distributions are provided in Tables 3.2 and 3.3. A polycarboxylate-based superplasticizer (Axim Catexol-Superfluc 2000 PC) was used.

3.2. Concrete program

3.2.1. Concrete mix proportions--A total of six concrete mixes were tested. The proportions of the concrete mixes are summarized in Table 3.4. The mixes were prepared by varying the water/binder ratio (W/B) while keeping the paste volume constant and gravel/total aggregate ratio (Nga) constant. A W/B of 0.35 and 0.45 were used. The paste volume for all mixes was 365 L/m^3 with an Nga = 0.52. Fly ash replacement was conducted on a mass basis. Fly ash replacements of 0%, 20%, and 30% were tested.

3.2.2. Concrete mixing and test methods--All mixes were prepared by mixing aggregates (fine and coarse), fly ash, and cement for one minute. Then the mixing water was added, and the batch was mixed again for one minute. After waiting 30 seconds, the batch was mixed for two minutes, and then the superplasticizer was added and the batch was mixed for an additional two minutes. The inverted slump-flow test was conducted and the T_{50} and the final diameter of the concrete were recorded. Next, the penetration test [12] and the L-box test {Bartos} were conducted. The concrete's mold surface quality was observed after concrete filled into the vertical portion of the L-Box, which was made of plexi-glass. Then the passing ability test with an L-box was undertaken, and the H2/H1 ratio was calculated (higher H2/H1 ratio indicates greater passing ability of SCC). The concrete was also poured into 100 x 200mm cylindrical plastic molds and covered with a plastic sheet in order to prevent water evaporation. The cylinders were demolded after one day and placed in a curing room at 100% relative humidity until the compressive strength tests and permeability tests were performed.