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Stability of Self-Consolidating Concrete Containing Different Viscosity Modifiers

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ABSTRACT: The main objective of this paper is to assess the effect of different viscosity-enhancing admixture (VEA) types and concentrations on deformability and stability of self-consolidating concrete (SCC). Two polysaccharide-based VEAs, one cellulose-based VEA, and a modified-startch VEA are used in this investigation. Regardless of polymer type, results showed that the incorporation of VEA leads to reduced passing ability represented by higher difference between the slump flow and J-Ring tests. The rheological properties followed an enhancing trend with VEA additions, given the higher degree of association and entanglement of polymer chains that increase resistance to flow. For given VEA dosage of 0.035%, mixtures made with cellulose VEA showed the highest stability levels including deformability and resistance to bleeding and surface settlement. Series of predictive charts are established to predict the changes in SCC stability as a function of rheological properties.

Keywords: Admixture Compatibility, Rheology, Self-Consolidating Concrete, Stability, Viscosity-Enhancing Admixture.

INTRODUCTION

Self-consolidating concrete (SCC) found wide acceptance in the construction industry, mostly due to its high flowability that eliminated the need for vibration, especially in complex-shaped and congested formworks. Properly proportioned SCC should exhibit adequate stability to avoid blockage of concrete during flow as well as separation of material constituents (Rilem, 2006; Farsani and Keshtegar, 2015; Assaad and Issa, 2017). Lack of static stability manifests itself by high bleeding, aggregate segregation, and surface settlement in the plastic state, causing anisotropy in the direction of casting and weakening the interface between the aggregate and cement paste (Matar and Assaad, 2017; Gökçe and Cakir, 2018). Bleeding can also result in accumulation of porous cement paste under the lower half of horizontally embedded reinforcement, which could reduce the bond strengths. The surface settlement of fresh concrete, which often is related to segregation, can reduce the effective projection of concrete lugs and further contribute to reduction in bond strengths (Khayat et al., 2003; Assaad, 2017).

The incorporation of viscosity-enhancing

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admixtures (VEAs) is common practice to secure adequate stability of SCC mixtures, albeit the efficiency of such additions depends on the type and concentration of polymer used (Üzer and Plank, 2016). For example, VEAs based on polysaccharide and cellulose derivatives are believed to act in three modes including adsorption, association, and intertwining (Issa, and Assaad, 2015; Üzer and Plank, 2016). In the first mode, the long-chain polymers adhere to the periphery of water molecules, thus adsorbing part of the mixing water and increasing the viscosity of interstitial liquid phase. In the case of association, attractive forces are developed between molecules in adjacent polymer chains. This blocks the motion of water, causes gel formation, and increases viscosity of the mixture. In the last mode, polymer chains intertwine and entangle at low shear rates, causing an increase in the SCC apparent viscosity (Sonebi, 2006; Assaad et al., 2014).

The selection of given VEA type and concentration during the development of SCC is concomitant with the intended powder (i.e., cementitious materials) content used in the mix as well as structural conditions during the casting process (ERMCO, 2005; Valcuende et al., 2012; Askarinejad, 2017). In fact, earlier studies have classified SCC in three categories including powder-type, combination-type, and VEA-type whereby the powder content varies between 650-550, 550-450, and 450-350 kg/m^3, respectively (Jawahar et al., 2013; ERMCO, 2005; EFNARC, 2006). The powder-type SCC is typically characterized by low water-to-powder ratio (W/P), making it suitable for casting heavily reinforced high-performance structures. Because of the high powder content and low W/P, the powder-type SCC requires limited or no VEA to secure adequate stability. The combination-type SCC is suitable for a variety of civil engineering and infrastructure applications requiring relatively high strength and durability properties. In such mixes, the W/P is generally selected to secure the targeted strength, while the VEA and high-range water-reducer (HRWR) regulated to secure adequate stability during placement. This type of SCC was reported to have high filling ability and resistance to segregation (EFNARC, 2006; Issa and Assaad, 2017). To the extreme end, the VEA-type SCC made using 350 to 450 kg/m^3 powder relies essentially on mixing water to achieve the required flowability, which thereby entails the addition of increased VEA concentration to maintain proper homogeneity of material constituents. This type of concrete exhibits high flow rates during casting (EFNARC, 2006); it is mostly used for normal-strength (i.e., grade 25 MPa) residential and massive caisson applications (Jawahar et al., 2013; Rahmatabadi et al., 2014).

Considerable efforts have been realized to incorporate readily available powders during proportioning of VEA-type SCC, which could reduce the cement and chemical admixtures content and lead to savings in material cost (Mechaymech, 2008; Valcuende et al., 2012; Shadkam et al., 2017). Jawahar et al. (2013) reported that the SCC material cost may be 10% to 15% higher than conventional concrete, depending on the strength class and availability of supplementary cementitious materials such as silica fume, fly ash, and blast furnace slag. Mechaymech (2008) and Shadkam et al. (2017) found that the incorporation of readily available limestone filler is best suited to optimize SCC cost, while satisfying stringent performance criteria related to slump flow and its retention over time, V-funnel flow time, rheological parameters, surface settlement, and compressive strength at 1 and 28 days. The SCC mixtures contained up to 120 kg/m^3 limestone, 250 to 400 kg/m^3 cement, and W/P varying from 0.38 to 0.72. Fixed volumes of coarse aggregate and welan gum VEA were employed to ensure adequate stability. Mechaymech (2008) reported that the replacement of 100 kg/m^3 of cement with finely ground limestone filler can improve deformability and stability without affecting the 1-day compressive strength. The concrete exhibited up to 10% lower 28-day strength, compared to similar concrete made without filler.

This paper is part of a comprehensive research project undertaken to assess the effect of different VEA and HRWR combinations on stability and strength of VEA-type SCC containing limestone fillers. It mainly seeks on evaluating the compatibility of chemical admixtures, including their effect on stability responses such as rheology, passing ability, bleeding, aggregate segregation, and surface settlement. The VEA-type SCC was prepared using 400 kg/m^3 powder materials (i.e., 280 kg/m^3 cement and 120 kg/m^3 limestone filler) and 0.57 W/P. Two polysaccharide-based VEAs, one cellulose-based VEA, and a modified-startch product are tested to evaluate their efficiency to mitigate the detrimental effects of mixing water on stability responses. Also, the 1- and 28-days compressive strengths are determined. Such data can be of particular interest to researchers and concrete practitioners evaluating the stability and compatibility of chemical admixtures incorporated in VEA-type SCC prepared with relatively high W/P.

EXPERIMENTAL PROGRAM

Materials

ASTM C150 Type I Portland cement along with commercially available finely ground limestone filler were used in this study. Their chemical and physical characteristics are summarized in Table 1. Crushed limestone coarse aggregate with maximum size of 14 and 20 mm were used; their bulk specific gravities are 2.71 and 2.7, respectively, and water absorption are 0.44% and 0.31%, respectively. Well-graded siliceous sand with fineness modulus of 2.5 is used; its bulk specific gravity and absorption capacity are 2.66 and 1.12%, respectively. All fine and coarse aggregates complied with ASTM C33 recommendations.

Four types of powder VEAs were tested. Two anionic microbial polysaccharide gums (diutan and welan gum) having long-chain biopolymers with backbones substituted with sugar side chains. These are produced by controlled aerobic fermentation process, and have high molecular weights of around 0.6 and 2 millions for welan and diutan gums, respectively (Sonebi, 2006; Simonides and Terpstre, 2007).

Table 1. Chemical and physical properties of cement and limestone filler

	Cement	Limestone filler
SiO_2, %	21.0	-
Al_2O_3, %	4.2	-
Fe_2O_3, %	3.1	-
CaO, %	62.0	-
MgO, %	2.9	-
$CaCO_3$, %	-	95
$MgCO_3$, %	-	2
Na_2Oeq, %	0.74	-
C_3S, %	52.0	-
C_2S, %	21.5	-
C_3A, %	5.7	-
C_4AF, %	9.5	-
Blaine surface area, m^2/kg	325	490
Mean particle diameter, µm	17	-
Specific gravity	3.15	2.79
Percent passing 45 µm, %	92	-
LOI, %	2.5	-

The third VEA type was cellulose-based; this water-soluble agent is among the most abundant naturally available polymers. Unlike other types of natural polymers (such as startch and gums), cellulose ethers dissolve less in water, thus offering a variety of functions such as thickening, surface activity, protective colloid, water retention, and shape retention (Lachemi et al., 2004; Assaad et al., 2014; Li et al., 2018).

The fourth VEA type is a modified startch; it is considered as rheology modifying admixture for concrete (Simonides and Terpstre, 2007). This product allows the creation of concrete with high flow, without sacrificing stability. As a result, it becomes easier to make a good quality concrete and formulations become more robust.

Two types of HRWR complying with ASTM C494 specification were used in this study; this includes naphthalene-based (PNS) and polycarboxylate-based (PC). The PNS had a solid content of 41%, specific gravity of 1.21, and contains 42% solid matter. The PC is a polymer with high molecular mass; its pH value is 6.5, specific gravity of 1.07, and contains 30% dry matter. For compatibility reasons (such as rapid drop in workability and excessive air entrainment), the PNS-based HRWR was used in conjunction with welan gum VEA, while the PC HRWR was employed with the diutan gum, cellulose, and startch VEAs (Diamantonis et al., 2010).

Mixture Proportions and Batching

The investigated VEA-type SCC mixtures were prepared with 400 kg/m^3 binder composed of 70% cement (i.e., 280 kg/m^3) and 30% limestone (i.e., 120 kg/m^3), making them suitable for residential applications having ultimate compressive strengths of about 30 MPa (Jawahar et al., 2013; Shadkam et al., 2017). A total of 13 SCC mixtures with initial slump flow consistency of 665 ±15 mm were evaluated. The W/P was kept constant at 0.57, and sand-to-coarse aggregate volume ratio was fixed at 0.45. As earlier noted, the binder type/content including W/P were selected following the recommendations provided by Mechaymech (2008) in a way to achieve adequate compromise between cost, stability, and strength.

Two VEA-free control mixtures incorporating either PC or PNS-based HRWR are considered in this study. Those mixtures had low stable nature manifested by relatively high external bleeding, aggregate segregation, and surface settlement. The VEAs were introduced at successive dosage rates varying from 0.02% to 0.08% of water mass in order to secure moderate to high stability levels. Table 2 summarizes the mixture proportions of tested mixtures, along with the required HRWR dosages to secure slump flow of 665 ±15 mm.

All mixtures were prepared in an open pan mixer of 100-L capacity. The batching sequence consisted of homogenizing the sand and coarse aggregate for 30 sec in the mixer, then adding 75% of mixing water. Following 30 sec of mixing, the cement and limestone filler were added along with rest of water. After 1 min of mixing, the VEA diluted in HRWR (i.e., to facilitate dispersion) was introduced, and the concrete was mixed for two additional minutes. After 1 min of rest, the mixing was resumed for 2 additional minutes. The temperature of fresh mixtures was kept around 22 ±2 ^oC.

Test Methods

Following the end of mixing, the slump flow diameter, time to reach 500 mm flow (T50), and Visual Stability Index (VSI) were determined. The VSI is a numerical rating from 0 to 3, with 0.5 increments, which is assigned to SCC texture after conducting the slump flow test (Matar and Assaad, 2017; Assaad, 2017). A value of 1 reflects slump flow with no mortar halo, while a value of 3 reflects clearly segregating SCC by evidence of large mortar halo (> 10 mm) and thick layer of bleed water. It is to be noted that the slump flow and VSI were determined right after mixing and 35 min later.

The passing ability of SCC was determined using the J-Ring test, using a co-centric ring at the base of the slump cone (Lachemi et al., 2004). The measurements are carried out as the mean diameter of the spread concrete at end of flow. The J-Ring apparatus measured 300 mm diameter and 100 mm height; the gaps between deformed bars were set at 35 mm.

The rheological properties, yield stress (τ_0) and plastic viscosity (μ), were evaluated using a modified two-point workability rheometer similar to the MK III model proposed by Tattersall (Assaad, 2017; Taboada et al., 2017). The adopted protocol consisted on subjecting the fresh concrete to increasing then decreasing ramps of shear rates while measuring the corresponding torque impeller required to shear the material. The Bingham fluid model was used to determine the τ_0 and μ parameters.

The bleeding test covers the determination of the relative quantity of mixing water that has bled from a sample of freshly mixed concrete, as per ASTM C232 (2014). The test required a cylindrical container having 150-mm diameter and 300 mm height. Cumulative bleeding was monitored at set intervals until reaching steady state conditions (i.e., after about 4 hours from initial mixing). Except for the periods corresponding to bleeding measurements, the column was covered to prevent evaporation. The percent of bleeding was determined as the ratio of cumulative bleed water divided by the mixing water existing in the specimen, multiplied by 100.

The coarse aggregate segregation was determined using the column test (Figure 1); this consists of casting concrete in a PVC tube measuring 660 mm height and 200 mm diameter, then measuring the variation in the relative concentration of aggregate at four sections along the concrete sample (Assaad, 2017; Soshiroda, 2004). The PVC tube is divided into four sections of 165 mm height. A leak-free joint is provided between the sections so that they can be easily uncoupled. Before conducting the test, the concrete is vertically consolidated five times using a 20 mm-diameter rodding bar. The concrete is then left to rest for 15 min. After removing each section starting from top, the concrete is weighed, and the mortar is washed out on a 5 mm sieve to retain the coarse aggregates which are dried to obtain a near surface-saturated dry moisture condition. The coefficient of variation (COV) of the aggregate distribution along the column is taken as a segregation index (I_{Seg}).

The surface settlement test is used to measure the settlement of fresh concrete during the plastic stage (Assaad, 2017). This test was assessed by casting concrete in a PVC column measuring 200 mm diameter and 700 mm height. The settlement was monitored using a linear dial gage, or LVDT, fixed on top of a thin plate positioned at the concrete surface that was anchored in the concrete three 40-mm long screws. The test enables one to differentiate between the static stability of various mixtures.

Finally, six cylinders of 100×200 mm were filled from each produced SCC to evaluate the 1- and 28-days compressive strengths, as per ASTM C39 (2018). The early-age measurements would allow determining whether incompatibility between chemical admixtures took place, thereby leading to delayed setting times and drop in 1-day compressive strength (Assaad and Daou, 2017; Shadkam et al., 2017).

TEST RESULTS AND DISCUSSION

Repeatability of Responses

The test results performed on various SCC are summarized in Table 3. It is to be noted that selected mixtures prepared using 0.035%

VEA were tested three times to evaluate repeatability of responses. The coefficient of variation (COV) was determined as the ratio between standard variation and mean values, multiplied by 100. As can be seen in Figure 2, the COV values for slump flow after 30 min, T50, J-Ring, and surface settlement were quite limited (i.e., less than 7.5%), indicting high repeatability of responses. Yet, the COV varied between 6.8% to 13.4% for τ_0, μ, bleeding, and segregation, reflecting increased sensitivity of such responses to variations in test procedures including flowability of SCC. It is to be noted that mixtures prepared with combinations of PC-based HRWR and startch VEA exhibited the highest COV values.

Table 2. Mixture proportions of tested SCC mixtures

		0% VEA	**0.02% VEA**	**0.035% VEA**	**0.05% VEA**	**0.08% VEA**
VEA, g/m³		0	46	80	114	182
W/P				0.57		
Sand/Aggregate (by volume)				0.45		
Cement, kg/m³				280		
Limestone filler, kg/m³				120		
Natural sand, kg/m³				730		
Coarse aggregate	14 mm, kg/m³			635		
	20 mm, kg/m³			274		
PC HRWR (Cellulose VEA), L/m³			0.35	0.35	0.4	-
PC HRWR (Diutan VEA), L/m³		0.3	0.55	0.65	0.8	-
PC HRWR (Startch VEA), L/m³			0.35	0.4	0.5	-
PNS HRWR (Welan VEA), L/m³		2	-	3	-	3.3

Fig. 1. Photo of the column segregation test

Table 3. Properties of SCC mixtures made with different VEA combinations

VEA type + HRWR type	**No VEA + PC**	**Cellulose + PC**			**Diutan + PC**			**Startch + PC**			**No VEA + PNS**	**Welan + PNS**	
VEA dosage, %	0	0.02	0.035	0.05	0.02	0.035	0.05	0.02	0.035	0.05	0	0.035	0.08
Temperature, °C	23.5	23.7	20	22.4	22	20.2	21.6	21.7	21	21.5	20.2	19.7	20.4
Slump flow, mm (10 min)	650	660	680	680	650	650	650	650	675	650	655	670	670
Slump flow, mm (35 min)	520	540	600	490	570	500	390	575	570	470	530	510	440
VSI (10 min)	2	1	1.5	1.5	1	1	1	2	2	1	2	2	1
VSI (35 min)	0	0	1	1	0.5	0	0	0.5	1	0	0	0	0
T50 (10 min), sec	1.71	1.85	2.1	2.14	1.67	1.47	1.52	1.18	1.79	1.38	1.32	0.84	1.58
Air volume, %	1.3	1.5	1.7	3	1.5	1.2	1.4	1.8	1.4	1.5	0.8	0.9	1.4
Unit weight, kg/m³	2310	2282	2310	2256	2291	2319	2316	2289	2314	2301	2323	2294	2310
J-Ring spread, mm	630	620	640	630	610	600	560	590	630	570	630	590	560
Yield stress, Pa	101	138	128	123	139	135	131	126	115	103	112	127	145
Plastic viscosity, Pa.s	9.3	10.5	13.6	15.8	14.8	18.5	18.8	12.5	15.7	18	9.4	14.3	16.1
Bleeding, %	4.53	2.63	2.78	2.49	4.82	3.8	2.05	4.09	3.95	2.92	7.02	8.33	5.56
Segregation index, %	3	3.6	2.73	2.36	1.32	1.46	0.93	1.9	1.38	1.33	2.57	1.83	1.57
Surface settlement, %	0.96	0.9	0.87	0.58	1.03	0.83	0.55	0.89	1.2	1	1.44	0.81	0.7
1-d compression, MPa	6.2	6.6	4.6	5	5.6	4.8	2.2	5.8	4.3	3.1	4.5	5	3.7
28-d compression, MPa	30.1	28.4	29	26.3	28.6	28.3	27.7	29.2	28.8	27.3	31.5	30.2	28.6

Effect of VEA Type on HRWR Demand and Fluidity Loss

The variations in HRWR demand to secure initial slump flow of 665±15 mm for tested SCC are plotted in Figure 3. Clearly, the HRWR dosage increased when mixtures incorporated higher VEA content, given their mode of action (adsorption, association, and intertwining) that cause a decrease in available free mixing water (Zhang and Kong, 2015; Lachemi et al., 2004).

Mixtures made with diutan gum necessitated higher PC-based HRWR necessary to maintain fixed slump flow, as compared to other VEAs combined with the same HRWR. For example, at VEA rate of 0.05%, the HRWR reached 0.8 L/m^3 with the use of diutan gum, while this was 0.4 L/m^3 in the case of cellulose VEA. This can be attributed to the type and characteristics of the polymer in use such as molecular weight, chain length, and solubility in alkaline environment (Sonebi, 2006; Üzer and Plank, 2016).

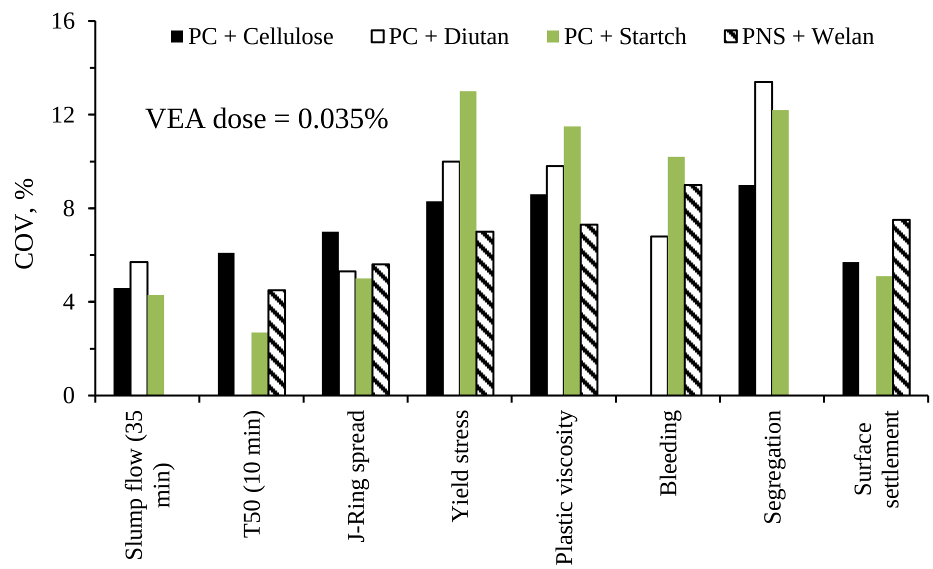

Fig. 2. Repeatability of various stability responses

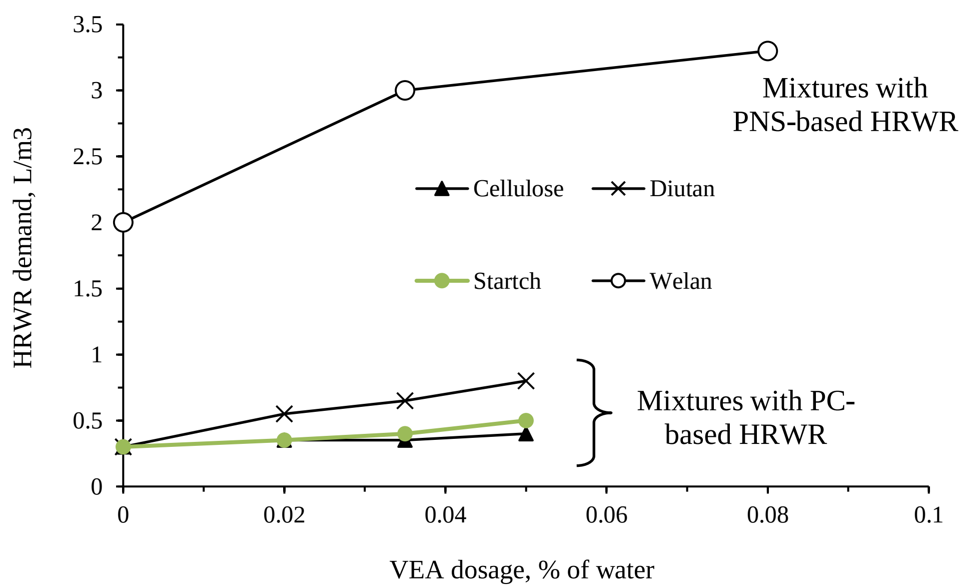

Fig. 3. HRWR demand as a function of VEA type and concentration

Generally speaking, the fluidity loss determined as the difference between initial slump flow (10 min) and the one measured after 35 min was pretty similar for SCC incorporating relatively low VEA rates (Figure 4). At higher concentrations, however, the plastic mixtures exhibited remarkable differences in fluidity loss; for example, this reached 260 mm at 0.05% diutan gum combined with PC-based HRWR. Also, the SCC made with 0.08% welan combined with PNS HRWR showed high slump flow of 230 mm, which is believed to be due to the nature of PNS molecules (Zhang and Kong, 2015; Gökçe and Cakir, 2018). It is to be noted that the VSI measurements varied between 1 and 2 right after the end of mixing, while these become less than 1 after 35 min from mixing, reflecting improved stability of tested SCC.

Effect of VEA Type and Dosage on Passing Ability

The differences between slump flow and J-Ring test results determined right after the end of mixing are plotted in Figure 5. Regardless of VEA type, the incorporation of such molecules led to reduced passing ability, thus resulting in higher differences between the unconfined slump flow test and J-Ring. For example, such difference varied from 20 mm for control mix made with PC-based HRWR to 40 and 80 mm when the diutan gum was incorporated at a rate of 0.02% and 0.05%, respectively. This can be attributed to higher level of matrix cohesiveness due to VEA additions, thus hindering deformability and ease of deformation of the plastic concrete (Sonebi, 2006; Khayat and Assaad, 2008a).

The drop in passing ability was particularly accentuated for SCC made with combinations of PNS-based HRWR and welan gum; the difference between slump flow and J-Ring reached 110 mm at the highest dosage of 0.08%. Also, the mix made with PC HRWR and 0.05% diutan gum exhibited a relatively high difference of 90 mm. It is to be noted that T50 values reflect the ease of SCC deformation, and thereby may sometimes be used to assess the passing ability. However, such values were pretty close to each other in this study, given the relatively high W/P ratio, and therefore not considered for analysis.

Effect of VEA Type and Dosage on Rheological Properties

The shear stress vs. shear rate responses of all concrete were linear following the Bingham fluid model, with correlation coefficients (R^2) greater than 0.96. Hence, τ_0 determined at zero shear rate can be related to the ability of fresh concrete to spread, while the slope of relationship (i.e., μ) can be used to assess the ease of deformation and level of cohesiveness of the plastic mixture (Assaad and Issa, 2014; Khayat and Assaad, 2008b).

The effect of VEA type and dosage on τ_0 and μ parameters are plotted in Figure 6. Generally speaking, the τ_0 values followed an increasing trend with VEA additions; this can naturally be attributed to the high degree of association and entanglement of VEA polymer chains that increase interparticle attraction and resistance to flow (Üzer and Plank, 2016). Curiously, the SCC made with startch VEA exhibited slight reduction in τ_0, which may be attributed to its combination with the PC-based HRWR. From the other hand, the mixture prepared with diutan gum and PC HRWR exhibited the highest increase in τ_0 measurements, which can be related to the high pseudoplastic characteristics of such polymers that lead to increased resistance to flow (Sonebi, 2006; Üzer and Plank, 2016). For example, this increased from 101 Pa for the control mix to 135 and 148 Pa with the addition of 0.035% and 0.05% diutan, respectively. It is to be noted that τ_0 value reached 151 Pa, at 0.08% of welan gum VEA combined with the PNS-based HRWR.

In concordance with τ_0 measurements, the μ values followed an increasing trend with VEA additions (Figure 6). The highest viscosity was obtained for the mix made with PC-based HRWR and diutan gum; hence, this varied from 9.3 Pa.s for the control mix to 14.8 and 18.8 Pa.s with the addition of 0.02% and 0.05% diutan, respectively. In the case of SCC made with PNS HRWR and welan gum, the μ reached 16.1 Pa.s at the highest rate of 0.08%. Generally, it is to be noted that the enhancement of rheological properties due to VEA additions is often associated to improved stability of the plastic mixture, provided the flow rates and filling ability during casting are not detrimentally affected (Lachemi et al., 2004; EFNARC, 2006; Issa and Assaad, 2017).

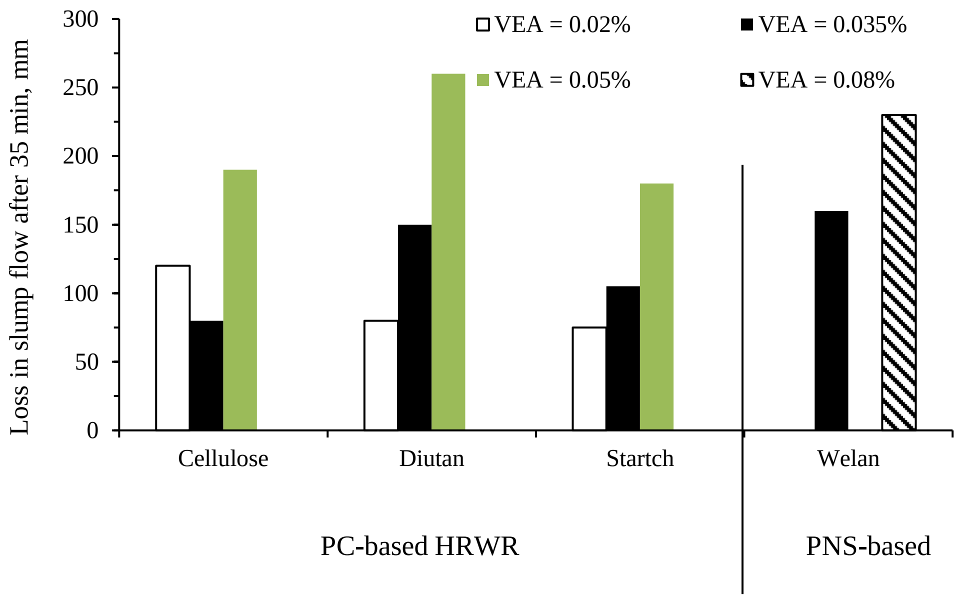

Fig. 4. Loss in slump flow after 35 minutes

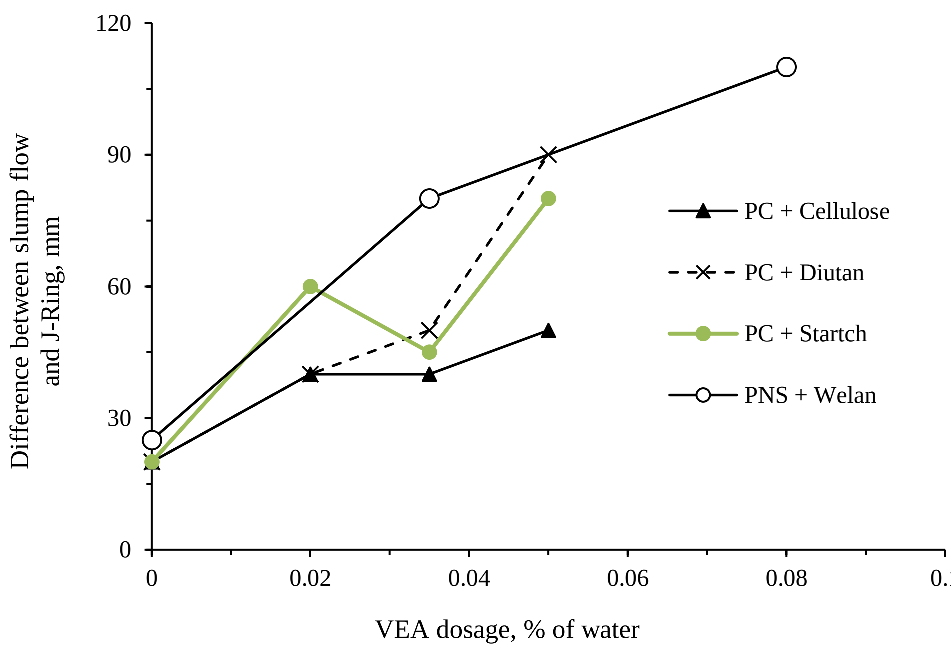

Fig. 5. Effect of VEA type and concentration on passing ability

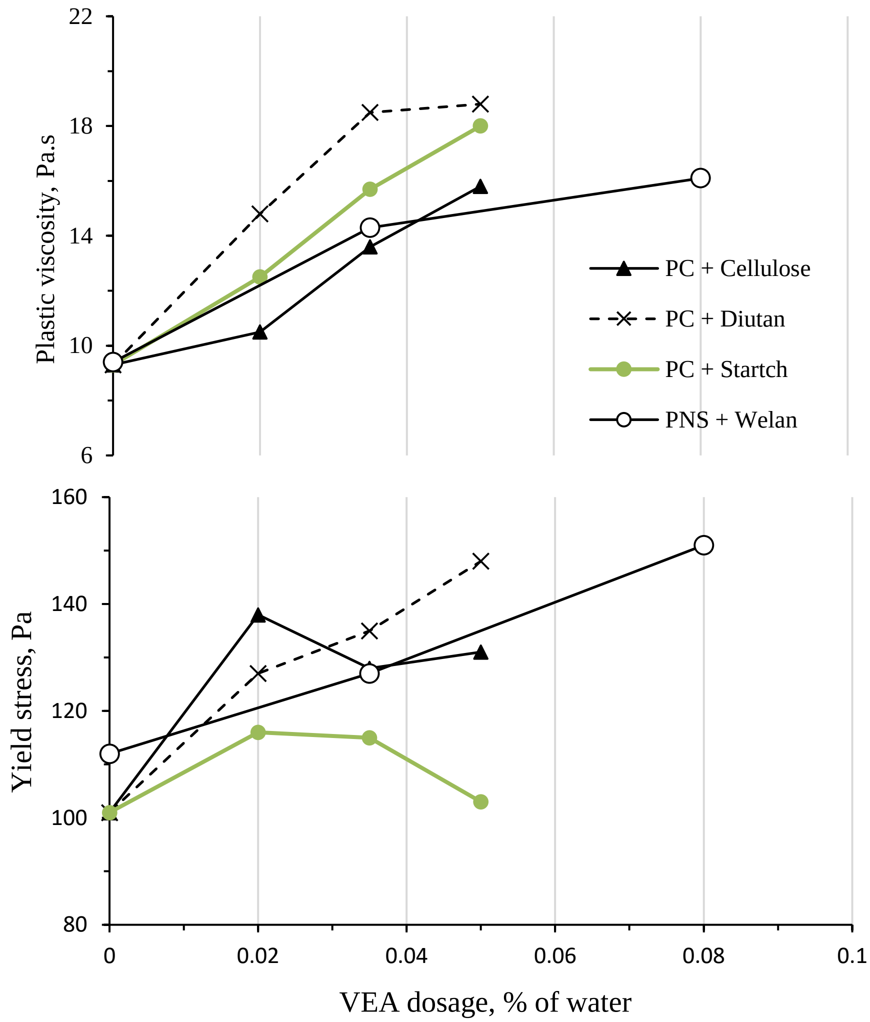

Fig. 6. Effects of VEA type and concentration on rheological properties

Effects of VEA Type and Dosage on SCC Stability

Bleeding

The bleeding responses of various tested SCC are shown in Figure 7. Regardless of polymer type, the effect of VEA on bleeding was not remarkable at low dosage rates of 0.02% and 0.035%. For example, the bleeding of control mix made with PC-based HRWR was 4.53%, and then slightly decreased to 3.8% and 3.95% when the diutan gum or startch VEAs were used, respectively, at a rate of 0.035%. In the case of SCC prepared with PNS-based HRWR, the bleeding of control mix was 7.02%, while increased to 8.33% with the use of welan gum at 0.035%. Given the relatively high W/P of 0.57, this reflects the need to increase the VEA content in order to control the bleeding phenomenon in the plastic SCC.

As shown in Figure 7, the decrease in bleeding becomes significant (i.e., dropped by about two-folds) when mixtures are prepared with PC-based HRWR along with relatively high VEA content of 0.05%. Hence, for example, the bleeding dropped to 2.49%, 2.05%, and 2.92% for mixtures incorporating cellulose, diutan, and startch VEA, respectively (as compared to 4.53% for the control mix). The decrease in bleeding due to VEA is well documented in literature (Sonebi, 2006; Assaad et al., 2014; Üzer and Plank, 2016); this can be attributed to the mode of function of such polymers that trap and absorb part of the free mixing water, thus reducing percolation and migration along the cementitious matrix. It is to be noted that bleeding did not considerably decrease for mixtures made with PNS-based HRWR; at the highest rate of 0.08% welan gum, the bleeding was still 5.56% (as compared to 7.02% for the control mix). This practically highlights the importance of using proper HRWR-VEA combinations to control the SCC stability responses.

Coarse Aggregate Segregation

Figure 8 plots the effects of VEA type and dosage on I_{Seg} measurements. With the exception of one mix, the incorporation of VEA led to decreased I_{Seg}, when compared to equivalent mixtures prepared with similar HRWR. For example, the control SCC made with PC-based HRWR showed the highest I_{Seg} of 3%, while this decreased to 1.9% and 1.33% with the addition of 0.02% and 0.05% startch VEA. In the case of mixtures made with PNS HRWR, the I_{Seg} decreased from 2.57% for the control mix to 1.83% and 1.57% with the addition of 0.035% and 0.08% welan gum, respectively. This can be directly associated to increased cohesiveness of the matrix that reduces sedimentation of coarse particles to the bottom. Several researchers related the improvement in segregation resistance due to increased plastic viscosity and yield value of the aqueous phase as a result of VEA addition (Soshiroda, 2004; Issa and Assaad, 2015; Assaad and Issa, 2017). It is to be noted that the lowest I_{Seg} of 0.93% corresponded to the mix containing 0.05% diutan gum.

Physically speaking, the resistance to segregation reflects the concrete ability to prevent sedimentation of aggregates towards the bottom; this is often linked to the SCC mix design including its plastic viscosity (Sonebi, 2006; Assaad and Issa, 2017). As can be seen in Figure 9, mixtures possessing increased μ values led to reduced I_{Seg} measurements, with moderate R^2 of 0.66. Hence, for example, the segregation dropped by two-folds when μ increased from about 10 to 15 Pa.s; the drop reached three-folds when μ reached 18 Pa.s. This reflects the importance to tailor the viscosity of SCC matrix to control the aggregate segregation phenomenon.

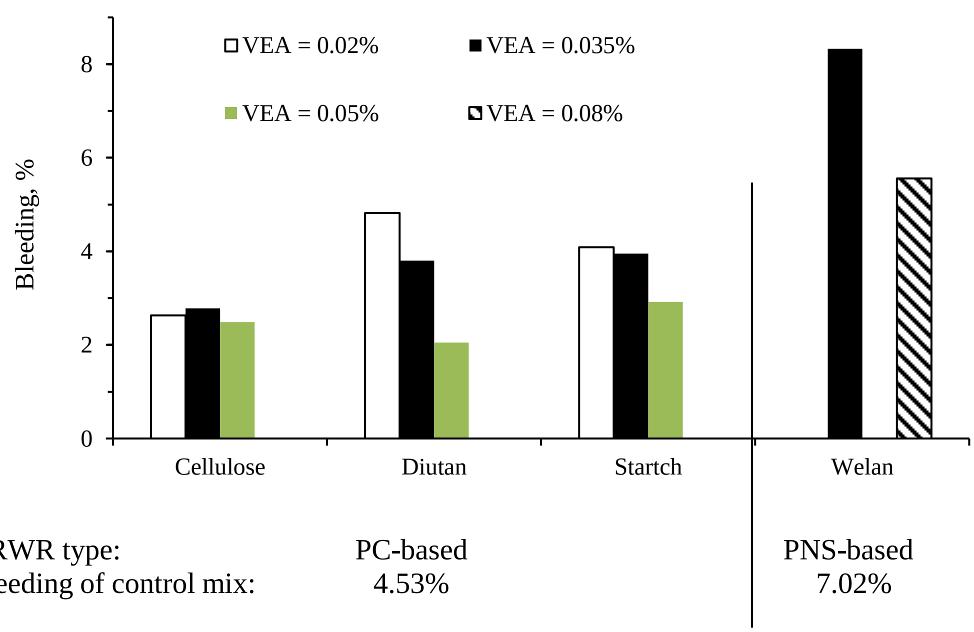

Fig. 7. Effects of VEA type and concentration on bleeding

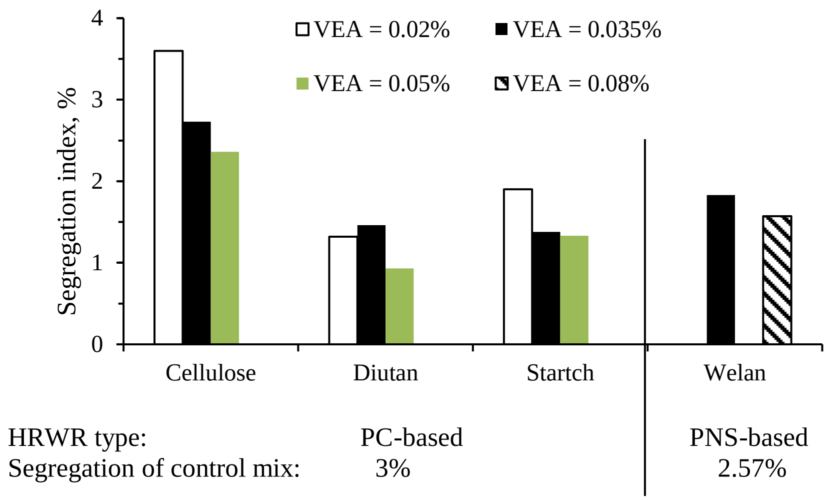

Fig. 8. Effects of VEA type and concentration on segregation index

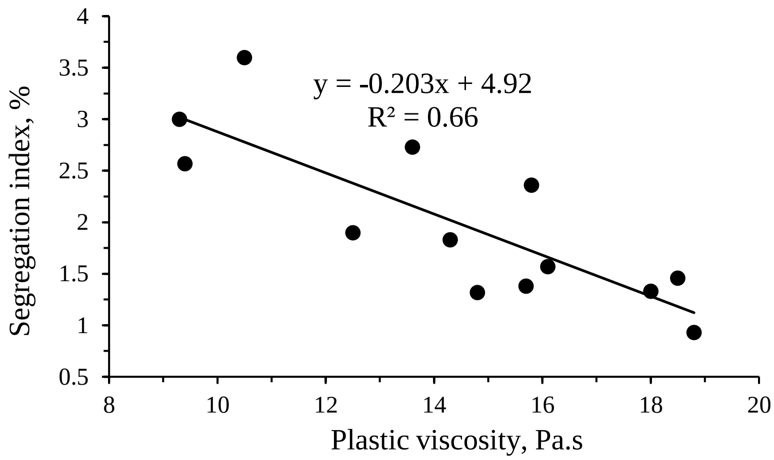

Fig. 9. Relationship between plastic viscosity and segregation index for all tested SCC

Surface Settlement

The variations in surface settlement for various SCC with respect to VEA dosage rates are illustrated in Figure 10. With some exception, the addition of increased polymer content led to reduced surface settlements, implying improved stability and resistance towards separation of material constituents (Assaad, 2017). For example, such decrease was from 0.96% for the control mix to 0.83% and 0.55% with the addition of 0.035% and 0.05% diutan gum, respectively. The surface settlement dropped significantly from 1.44% for the control mix prepared with PNS-based HRWR to 0.81% and 0.7% when the welan gum was incorporated at 0.035% and 0.08%, respectively.

Given the importance of rheological properties to control SCC static stability, a chart is plotted in Figure 11 to predict the changes in bleeding, aggregate segregation, and surface settlement as a function of the changes in plastic viscosity (μ) resulting from given VEA type. The change in any given property is determined as the ratio between the mix containing VEA and the control one, both made with the same HRWR type. Clearly, the higher is the change in μ due to VEA addition, the more SCC becomes stable. It is to be noted here that the weakest correlations were obtained between the change in μ and surface settlement, reflecting the reduced influence of rheological properties on surface settlement responses.

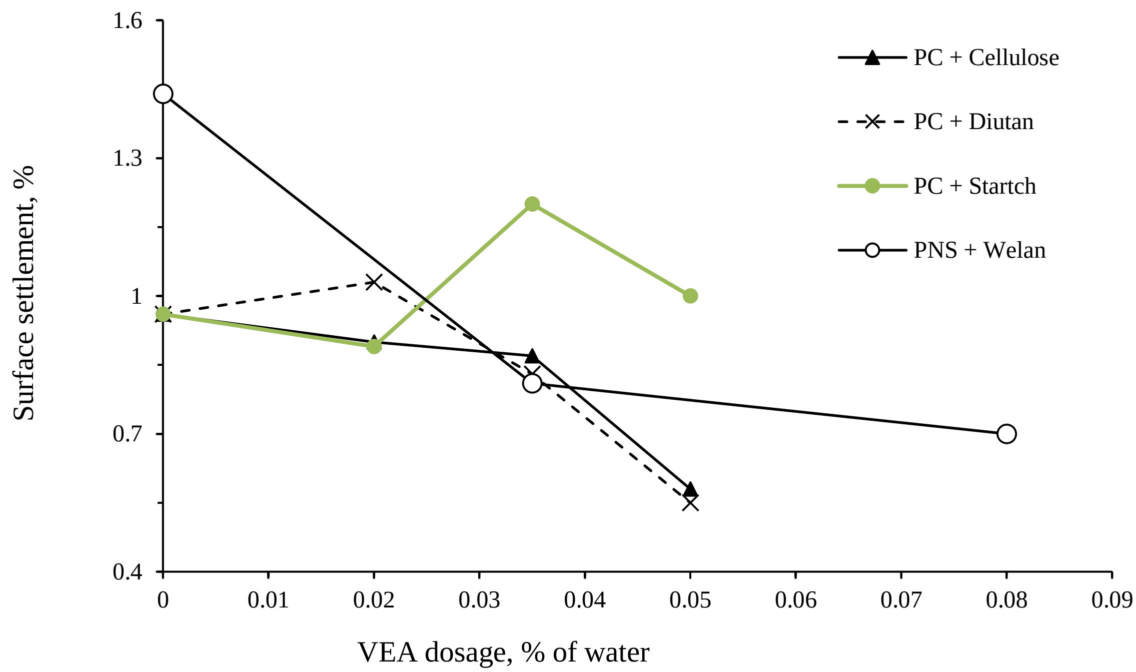

Fig. 10. Effects of VEA type and concentration on surface settlement

Ranking of Different VEA Types

To compare the efficiency of tested VEAs on improving SCC stability, the various responses were scored from 1 to 4 (referring worst to best impact, respectively). Hence, mixtures exhibiting the highest slump flow retention after 35 min, T50 flow times, J-Ring spread, and enhancement in rheological properties were attributed the highest scores. Also, the highest scores were attributed to mixtures possessing reduced bleeding, segregation, and surface settlement responses (i.e., reflecting improved stability).

Table 4 summarizes the ranking process by considering the sum of scores for different VEA types incorporated at fixed concentration of 0.035%. As can be seen, the highest score of 28 corresponded to mixtures prepared with cellulose-based VEA in combination with PC-based HRWR, followed by those incorporating diutan and startch VEAs. To the extreme end, mixtures prepared with welan gum and PNS-based HRWR showed the lowest score of 20, reflecting relatively reduced improvement of SCC stability.

Compressive Strength

The effect of VEA type and dosage on compressive strength determined after 1 and 28-days is presented in Figure 12. Generally, all mixtures incorporating VEA yielded a decrease in 1-day compressive strength, implying that a delay in setting time occurred within the first 24 hours after mixing. The magnitude of strength followed a reduced trend for SCC prepared with successive increases in VEA content. For example, this decreased from 5.6 to 4.8 and 2.2 MPa when the diutan gum was incorporated at 0.02%, 0.035%, and 0.05%, respectively (the control mix had a strength of 6.2 MPa). This can be related to the higher polymer concentration along with HRWR molecules that could be adsorbed onto the cement particles, thus reducing hydration reactions and decrease in early strength. It is important to note that the delay in concrete setting time should generally not exceed 24 hours, so that demoulding and finishing processes are not altered on construction sites (Rilem, 2006; EFNARC, 2006).

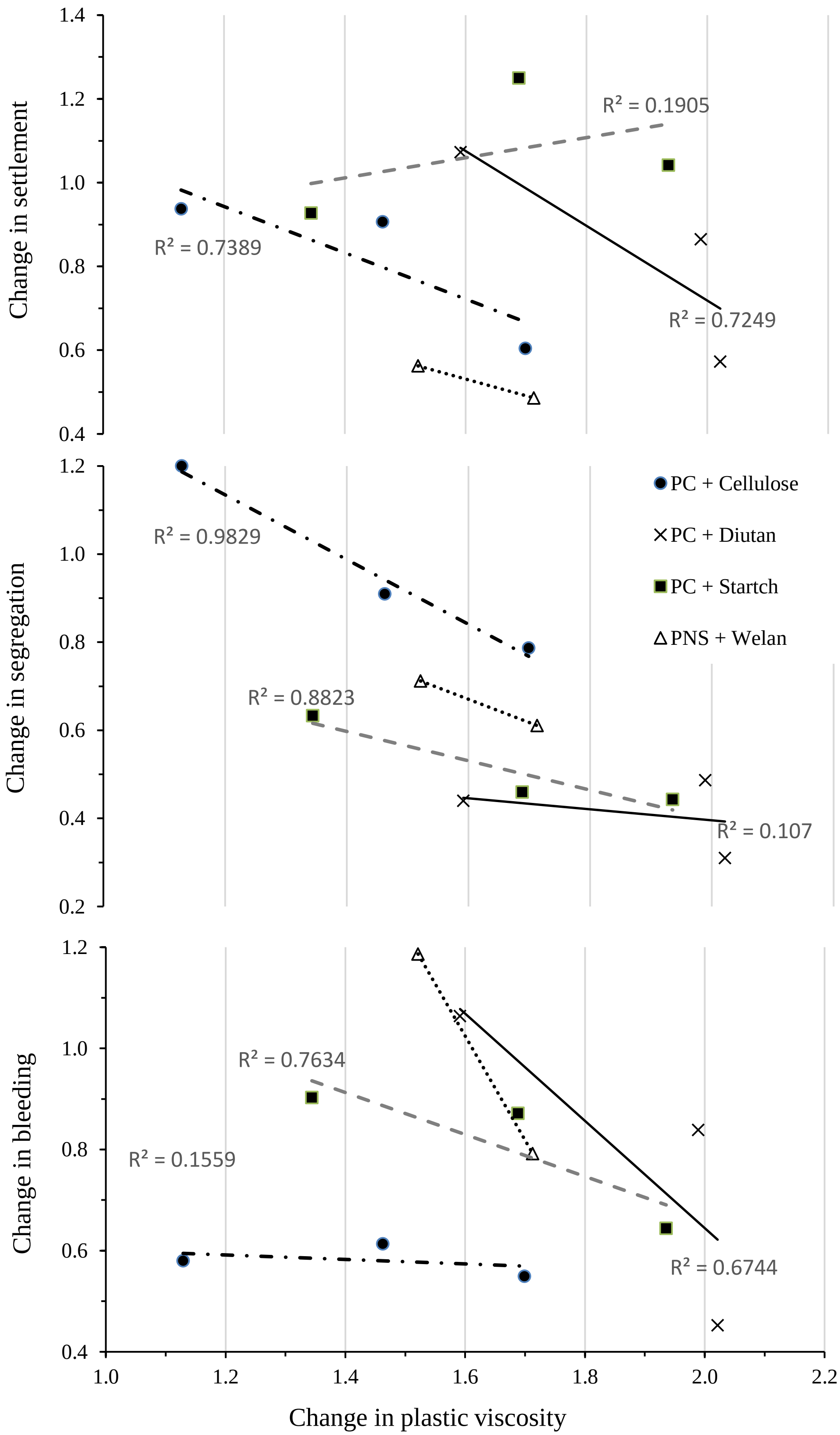

Fig. 11. Prediction of changes in bleeding, segregation, and surface settlement through the determination of the change in plastic viscosity

Table 4. Ranking of different VEA types (for given dosage of 0.035%)

	Cellulose + PC	Diutan + PC	Startch + PC	Welan + PNS
Slump flow, mm (35 min)	4	1	3	2
VSI (35 min)	3	4	3	4
T50 (10 min), sec	4	2	3	1
J-Ring spread, mm	4	2	3	1
Yield stress, Pa	3	4	1	2
Plastic viscosity, Pa.s	2	4	3	1
Bleeding, %	4	3	2	1
Segregation index, %	1	2	3	4
Surface settlement, %	3	4	2	4
Total	28	26	23	20

Scoring is made from 1 (refers to worse) to 4 (refers to best).

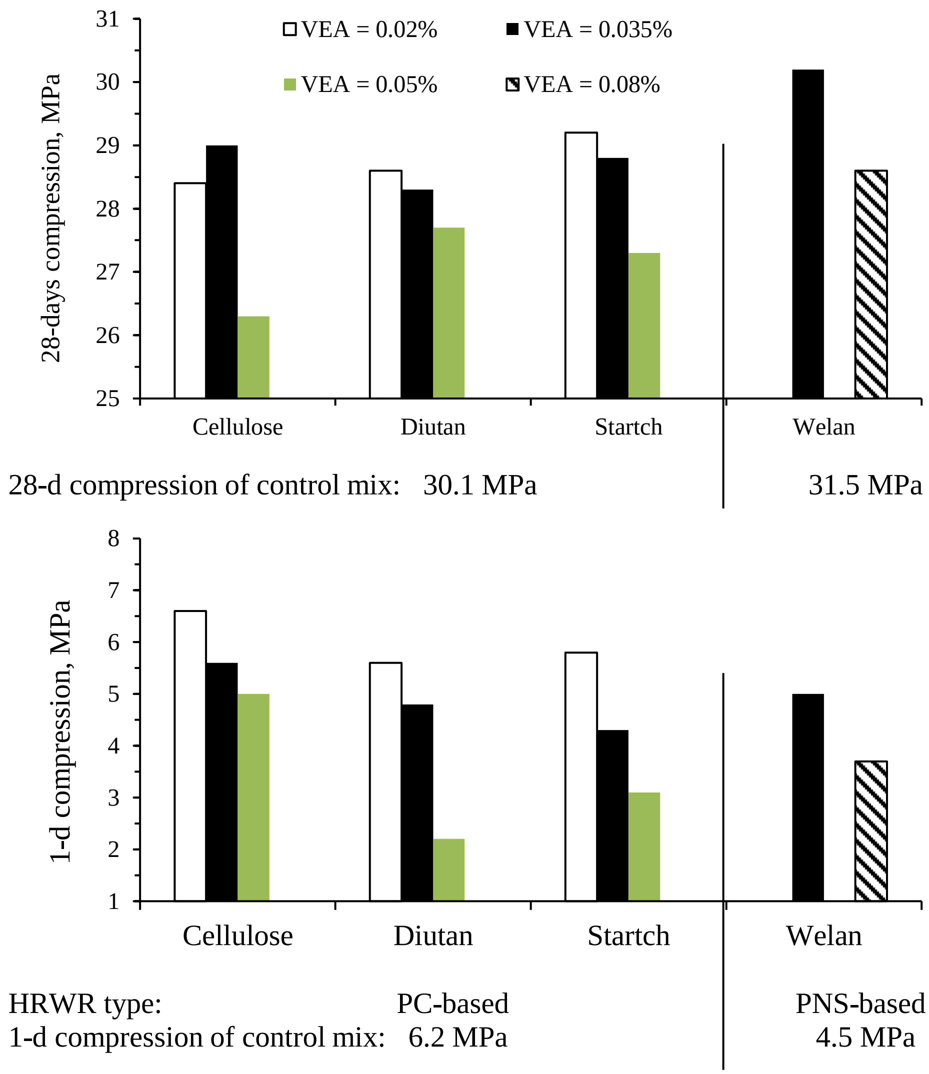

Fig. 12. Effects of VEA type and concentration on 1- and 28-days compressive strength

Concurrent with the results obtained after 1 day, the 28-days compressive strengths were relatively lower than those obtained from the control mixtures (Figure 12). For example, such reduction was from 31.5 MPa for the control mix prepared with PNS-based HRWR to 30.2 and 28.6 MPa with the addition of welan gum at 0.035% and 0.08%

rates, respectively. In literature, the slight decrease in compression (i.e., less than about 10%) due to VEA additions was often attributed to alterations in cement hydrating compounds that create weaker and less stiffer matrix (Sonebi, 2006; Üzer and Plank, 2016; Gökçe and Cakir, 2018).

CONCLUSIONS

The main objective of this research project is to evaluate the effect of different VEA and HRWR combinations on stability of VEA-type SCC prepared with 120 kg/m^3 limestone fillers and relatively high W/P of 0.57. Based on the results obtained, the following conclusions can be warranted:

1. Mixtures made with diutan gum necessitated higher PC-based HRWR demand to maintain fixed slump flow, compared to other VEA employed with the same PC. This was attributed to the type and characteristics of polymer in use such as molecular weight, chain length, and solubility in alkaline environment.
2. Regardless of VEA type, the incorporation of such molecules led to reduced passing ability represented by higher difference between the unconfined slump flow and J-Ring tests. This was related to the higher matrix cohesiveness that hinders deformability and ease of flow of the plastic concrete.
3. The rheological properties (i.e., τ_0 and μ) followed an increasing trend with VEA additions, given the high degree of association and entanglement of VEA polymer chains that increase interparticle attraction and resistance to flow. The SCC prepared with diutan gum and PC-based HRWR exhibited the highest increases in τ_0 and μ measurements, which can be related to the high pseudoplastic characteristics of such polymers that lead to increased resistance to flow.
4. Given the relatively high W/P of 0.57, the effect of VEA on bleeding was not remarkable at low dosage rates of 0.02% and 0.035%. Yet, the decrease in bleeding becomes significant (i.e., dropped by about two-folds) when the VEA rates exceed about 0.05%.
5. The incorporation of VEA led to decreased I_{Seg}, which was associated to increased cohesiveness of the matrix that reduces sedimentation of coarse particles to the bottom. The lowest I_{Seg} of 0.93% corresponded to the mix containing 0.05% diutan gum. Good correlation was established between I_{Seg} and μ measurements for all tested SCC.
6. With some exception, the addition of increased VEA content led to reduced surface settlements, implying improved stability and resistance towards separation of material constituents. The lowest settlement value was obtained for the SCC containing 0.05% diutan gum.
7. SCC mixtures possessing the highest stability levels were prepared with cellulose-based VEA in combination with PC-based HRWR, followed by those incorporating diutan and startch VEAs. Mixtures prepared with welan gum and PNS-based HRWR exhibited the lowest improvement in stability.
8. The 1- and 28-days compressive strengths slightly decreased when SCC mixtures are prepared with successive increases in VEA content.

REFERENCES

Askarinejad, A. (2017). “Using different methods of nanofabrication as a new way to activate supplementary cementitious materials; A review”, *Civil Engineering Infrastructure Journal*, 50(1), 1-19.

Assaad, J. and Issa, C. (2014). “Effect of clinker grinding aids on flow of cement-based materials”, *Cement and Concrete Research*, 63, 1-11.

Assaad, J., Daou, Y. and Harb, J. (2014). “Influence of thixotropy on performance of grouts placed using vacuum injection techniques”, *ACI Materials Journal*, 112(2), 189-198.

Assaad, J.J. (2017). "Influence of recycled aggregates on dynamic/static stability of self-consolidating concrete", *Journal of Sustainable Cement-Based Materials*, 6(6), 345-365.

Assaad, J.J. and Issa, C. (2017). "Mixture optimization of polymer-modified lightweight SCC", *Magazine of Concrete Research*, 14(69), 745-756.

Assaad, J.J. and Daou, Y. (2017). "Behavior of structural polymer-modified concrete containing recycled aggregates", *Journal of Adhesion Science and Technology*, 31(8), 874-896.

ASTM C232 (2014). "Standard test method for bleeding of concrete". West Conshohocken, PA, USA.

ASTM C39 (2018). *Standard test method for compressive strength of cylindrical concrete specimens*, West Conshohocken, PA, USA.

Diamantonis, N., Marinos I., Katsiotis, M.S., Sakellariou, A., Papathanasiou, A., Kaloidas, V. and Katsioti, M. (2010). "Investigations about the influence of fine additives on the viscosity of cement paste for self-compacting concrete", *Construction and Building Materials*, 24, 1518-1522.

ERMCO. (2005). "The European guidelines for self-compacting concrete: Specification, production and use", The SCC European Project Group, 32 p.

EFNARC. (2006). "Guidelines for viscosity modifying admixtures for concrete", www.efnarc.org.

Farsani, A.M. and Keshtegar, B. (2015). "Reliability analysis of corroded reinforced concrete beams using enhanced HL-RF method", *Civil Engineering Infrastructure Journal*, 48(2), 297-304.

Gökçe, H.S. and Cakir, O.A. (2018). "A new method for determination of dynamic stability of self-consolidating concrete: 3-Compartment sieve test", *Construction and Building Materials*, 168, 305-312.

Issa, C. and Assaad, J.J. (2015). "Bond of tension bars in underwater concrete, Effect of bar diameter and cover", *Materials and Structures*, 48(11), 3457-3471.

Issa, C. and Assaad, J. (2017). "Stability and bond properties of polymer-modified self-consolidating concrete for repair applications", *Materials and Structures*, 50(1), 28.

Jawahar, J.G., Sashidhar, C., Ramana, I.V.R. and Annie, P. (2013). "Design of cost-effective M 25 grade of self compacting concrete", *Materials and Design*, 49, 687-692.

Khayat, K.H., and Assaad, J. (2008a). "Measurement systems for determining formwork pressure of highly flowable concrete", *Materials and Structures*, 41(1), 37-46.

Khayat, K.H., and Assaad, J. (2008b). "Use of thixotropy-enhancing agent to reduce formwork pressure exerted by self-consolidating concrete", *ACI Materials Journal*, 105(1), 88-96.

Khayat, K., Trimbak, P., Assaad, J., and Jolicoeur, C. (2003). "Analysis of variations in electrical conductivity to assess stability of cement-based materials", *ACI materials Journal*, 100(4), 302-310.

Lachemi, M., Hossaina, K.M.A., Lambrosa, V., Nkinamubanzib, P.C. and Bouzoubaa, N. (2004). "Self-consolidating concrete incorporating new viscosity modifying admixtures", *Cement and Concrete Research*, 34, 917-926.

Li, C., Miao, L., You, Q., Hu, S. and Fang, H. (2018). "Effects of viscosity modifying admixture (VMA) on workability and compressive strength of structural EPS concrete", *Construction and Building Materials*, 175, 342-350.

Matar, P. and Assaad, J.J. (2017). "Effect of vertical reinforcing bars on formwork pressure of SCC containing recycled aggregates", *Journal of Building Engineering*, 13, 159-168.

Mechaymech, A. (2008). "Development and optimization of cost-effective self-consolidating concrete with limestone filler", Ph.D. Thesis, University of Sherbrooke, Canada, 250 p.

Rahmatabadi, M.A.D., Kazemi, H.H. and Shahabian F. (2014). "Effects of different water and superplasticizer amount, pre-setting and curing regimes on the behavior of reactive powder concrete", *Civil Engineering Infrastructure Journal*, 47(2), 291-304.

RILEM Technical Committee (2006). "Final report of RILEM TC 188-CSC, Casting of self-compacting concrete", *Materials and Structures*, 39, 937-954.

Shadkam, H.R., Dadsetan, S., Tadayon, M., Sanchez, L.F.M. and Zakeri, J.A. (2017). "An investigation of the effects of limestone powder and viscosity modifying agent in durability related parameters of self-consolidating concrete (SCC)", *Construction and Building Materials*, 156, 152-160.

Simonides, H. and Terpstre, J. (2007). "Use of innovative startch ethers for paving blocks and other concrete products", *Concrete Plant and Precast Technology*, 73(9), 38-45.

Sonebi, M. (2006). "Rheological properties of grouts with viscosity modifying agents as diutan gum and welan gum incorporating pulverised fly ash", *Cement and Concrete Research*, 36, 1609-1618.

Soshiroda, T. (2004). "Segregation characteristics of concrete containing a high-range water-reducing admixture", *Proceedings ACI SP 68*, 121-137.

Taboada, I.G., Fonteboa, B.G., Abella, F.M. and Paz, S.S. (2017). "Analysis of rheological behaviour of self-compacting concrete made with recycled aggregates", *Construction and Building Materials*, 157, 18-25.

Üzer, E. and Plank J. (2016). "Impact of welan gum stabilizer on the dispersing performance of polycarboxylate superplasticizers", *Cement and Concrete Research*, 82, 100-106.

Valcuende, M., Marco, E., Parra, C. and Serna, P. (2012). "Influence of limestone filler and viscosity-modifying admixture on the shrinkage of self-compacting concrete", *Cement and Concrete Research*, 42(4), 583-592.

Zhang, Y. and Kong, X. (2015). "Correlations of the dispersing capability of NSF and PCE types of superplasticizer and their impacts on cement hydration with the adsorption in fresh cement pastes", *Cement and Concrete Research*, 69, 1-9.