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Viscosity-Enhancing Admixtures for Cement-Based Materials — An Overview

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Abstract

Viscosity-enhancing admixtures, also known as anti-washout admixtures, are water-soluble polymers that increase the viscosity and cohesion of cement-based materials. Such enhancement of the liquid-phase viscosity is essential in flowable systems in order to reduce the rate of separation of material constituents and improve the homogeneity and performance of the hardened product. Viscosity-enhancing admixtures are mostly used along with a high-range water reducer to obtain a highly fluid, yet cohesive cement-based material that can flow readily into place with minimal separation of the various constituents of different densities and minimal intermixing with the surrounding water whenever cast under water.

This paper reviews the types and modes of action of commonly used viscosity-enhancing admixtures and highlights their influence on the rheological properties of water and cement paste. An overview of the influence of various types of viscosity-enhancing admixture on high-range water reducer demand, resistance to water dilution, static and forced bleeding, segregation, settlement, setting time, and air entrainment is presented. The influence of such admixtures on bond to anchored reinforcing bars, frost durability, mechanical properties, and rapid-chloride permeability is also highlighted. Special applications where such relatively new admixtures can significantly enhance performance are highlighted, including their incorporation in concrete intended for underwater placement and repair, self-consolidating and segregation-free concrete for above-water construction, and structural grout for filling post-tensioning ducts. © 1998 Elsevier Science Ltd. All rights reserved.

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INTRODUCTION

Viscosity-enhancing admixtures (VEAs), also known as anti-washout admixtures, are relatively new admixtures used to enhance the cohesion and stability of cement-based systems. Such VEAs are water-soluble polysaccharides that enhance the water retention capacity of the paste. They are used in concrete intended for underwater repair of marine and hydraulic structures, and tremie concrete for the construction of curtain walls and deep foundation walls, etc. Such admixtures can also reduce the risk of separation of the heterogeneous constituents of concrete during transport, placement, and consolidation and provide added stability to the cast concrete while in a plastic state.

Flowable concrete is commonly used for casting congested structural members that are often encountered in heavily reinforced mat foundations and in reinforced concrete structures in seismic regions. It is also used in restricted areas where the access for placement and consolidation is limited, as in the case of tunnel lining. The use of flowable concrete to facilitate the casting of congested or restricted areas can result in an unstable dispersion of cement paste and aggregate particles since the tendency of the heterogeneous materials to separate increases with the reduction in viscosity. This can be obtained when the consistency of the flowable concrete increases or when the concrete is subjected to high shear rate, such as that encountered in pumping and consolidation. The incorporation of a VEA in flowable concrete can enable the production of a stable and yet highly flowable concrete to facilitate filling congested reinforced members with minimal vibration and segregation. The improved homogeneity of the concrete can enhance bond strength to reinforcement and aggregate, thereby decreasing permeability.

VEAs are also used in shotcrete for the repair of deteriorated structures, since it can enhance the sagging resistance of the concrete and enable the application of thicker lifts. The rheological behavior of specialty cement grouts intended for the underwater sealing of cracks in dams, offshore structures, massive foundations, or fissures in rock can be enhanced by incorporating a VEA. Grouts made with a VEA are also used for filling post-tensioning ducts, where it is important to ensure high resistance to sedimentation and bleeding, hence ensuring corrosion protection of stressed tendons.

A recent review on the use of anti-washout admixtures for underwater concrete placement highlighted the advantages and limitations of such admixtures.[1] The overview presented in this paper discusses the benefits and limitations of incorporating a VEA to modify fresh and hardened concrete properties of cement-based materials intended for underwater and above-water placements. The paper reviews the classification, type, and mode of action of VEAs and discusses the influence of VEAs on improving the rheological properties and cohesiveness of cement-based systems and their effect on fresh and hardened concrete properties. This is intended to provide guidance to engineers considering the use of VEAs to enhance the performance of cement-based systems. The reviewed fresh properties include rheological characteristics, demand of high-range water-reducing admixtures (HRWRs), resistance to water dilution, bleeding, segregation, and surface settlement, as well as the effect of VEAs on setting time, air-entraining admixture (AEA) demand, and air–void-system. The reviewed hardened concrete properties include the effect of VEAs on bond to reinforcing steel, frost durability, compressive, flexural, and splitting tensile strengths, and rapid chloride-ion permeability.

CLASSIFICATION, TYPE, AND MODE OF ACTION OF VEAS

Mailvaganam[2] categorized anti-washout admixtures and pumping aids into five classes according to their physical actions in concrete. These classifications are as follows.

Class A. Water-soluble synthetic and natural organic polymers that increase the viscosity of the mixing water. Class A type materials include cellulose ethers, polyethylene oxides, polyacrylamide, polyvinyl alcohol, etc.

Class B. Organic water-soluble flocculants that become adsorbed onto cement grains and increase viscosity due to enhanced interparticle attraction between cement grains. Class B materials include styrene copolymers with carboxyl groups, synthetic polyelectrolytes, and natural gums.

Class C. Emulsions of various organic materials which enhance interparticle attraction and supply additional superfine particles in the cement paste. Among the materials belonging to Class C are acrylic emulsions and aqueous clay dispersions.

Class D. Water-swellable inorganic materials of high surface area which increase the water retaining capacity of the paste, such as bentonites, silica fume, and milled asbestos.

Class E. Inorganic materials of high surface area that increase the content of fine particles in paste and, thereby, the thixotropy. These materials include fly ash, hydrated lime, kaolin, various rock dusts, and diatomaceous earth, etc.

Kawai[3] classified water-soluble polymers as natural, semi-synthetic, and synthetic polymers. Natural polymers include starches, guar gum, locust bean gum, alginates, agar, gum arabic, welan gum, xanthan gum, rhamsan gum, and gellan gum, as well as plant protein. Semi-synthetic polymers include: decomposed starch and its derivatives; cellulose-ether derivatives, such as hydroxypropyl methyl cellulose (HPMC), hydroxyethyl cellulose (HEC), and carboxy methyl cellulose (CMC); as well as electrolytes, such as sodium alginate and propyleneglycol alginate. Finally, synthetic polymers include polymers based on ethylene, such as polyethylene oxide, polyacrylamide, polyacrylate, and those based on vinyl, such as polyvinyl alcohol.

VEAs were first used in Germany in the mid-1970s and later in Japan in the early 1980s. In North America, such admixtures have been used since the late 1980s in specialty grout and concrete applications. The VEAs that are commonly used in cement-based systems are water-soluble polysaccharides, such as cellulose ether derivatives and microbial-source polysaccharides, such as welan gum, that bind some of the mixing water, thus enhancing viscosity. Acrylic-based polymers, such as partial hydrolysis products of a polyacrylamide copolymer and sodium acrylate, are also employed. Cellulose derivatives often contain non-ionic cellulose ether as the principal component in which different materials are used. The main components of a cellulose-type VEAs are non-ionic cellulose ether, in which different substitutes are introduced into the cellulose. Welan gum is an anionic, high molecular weight (around two million) polysaccharide produced by a controlled aerobic fermentation process. Welan gum is a long-chain biopolymer with sugar backbones (D-glucose) substituted with sugar side chains. The product is calcium compatible and shows good tolerance to increases in temperature.[4]

Viscosity-modifying admixtures can be powder-based or liquid-based products. For example, Kelco-crete is a powder-based product that contains welan gum and is used typically at a concentration ranging between 0.05 and 0.20% by mass of cementitious materials, or 0.10 to 0.40% by mass of water for typical underwater concrete mixtures made with 0.45 W/C. The 81-11 Celbex 208 product is a cellulose-based admixture supplied by Fosroc and used at a recommended dosage of 0.7 to 1.2%, by mass of cementitious materials, for mixtures made with 0.45 W/C. Master Builders' Rheomac UW 450 is a cellulose-based VEA supplied in a liquid form and used at a recommended dosage of 260 to 1300 ml/100 kg of cementitious materials. Another liquid-based VEA is the Sikament 100 SC and 300 SC admixtures that are intended for use in underwater concrete and grouts for post-tensioning applications, respectively.

The mode of action of a VEA depends on the type and concentration of the polymer in use. In the case of welan gum and cellulose derivatives, the mode of action can be classified in three categories, as follows:[4]

(1) Adsorption. The long-chain polymer molecules adhere to the periphery of water molecules, thus adsorbing and fixing part of the mix water and thereby expanding. This increases the viscosity of the mix water and that of the cement-based product.

(2) Association. Molecules in adjacent polymer chains can develop attractive forces, thus further blocking the motion of water, causing a gel formation and an increase in viscosity.

(3) Intertwining. At low rates of shear, and especially at high concentrations, the polymer chains can intertwine and entangle, resulting in an increase in the apparent viscosity. Such entanglement can disaggregate, and the polymer chains can align in the direction of the flow at high shear rates, hence resulting in shear thinning.

Rheological properties and HRWR demand

The various water-soluble VEAs form viscous solutions that bind some of the mixing water in the fresh cement paste, thus increasing viscosity and yield value of the cement-based system. The yield value refers to the minimum shear stress needed to overcome the internal resistance of a fluid to initiate plastic flow. The extent of the increase in water viscosity depends on the type and concentration of the VEA, as well as on the applied shear rate. Figure 1 compares the increased viscosity of aqueous solutions of 0.01 M NaCl at 20°C containing welan gum and HPMC at a low shear rate of 0.1 s^{-1}.[4] The increase in VEA dosage results in a sharp increase in viscosity, especially in the case of welan gum addition. Systems modified with a VEA exhibit a shear thinning (or pseudoplastic) behavior where the apparent viscosity decreases rapidly with the increase in shear rate. As shown in Fig. 2, aqueous solutions containing VEAs exhibit a shear thinning behavior where relatively high viscosity at low shear rate drops significantly with the increase in shear rate.

A cement-based system incorporating a VEA can be sticky and viscous, especially when there is a high concentration of VEA. The incorporation of a VEA increases the yield value, plastic viscosity, and apparent viscosities, both at low and high shear rates, for cement-based materials regardless of the W/C and dosage of HRWR.[5,6] Cement grouts containing a VEA also exhibit high reduction in fluidity over time because of their thixotropic nature. For example, in cement grouts made with 0.45, 0.50, and 0.55 W/C, the apparent viscosities at low shear rates were reported to increase considerably over 35 min after mixing. However, such an increase was easily recovered following some mixing. The recovery rate was especially high in grouts containing an HRWR, and the degree of viscosity recovery was reported to increase with the concentration of the HRWR.[5] Thixotropy and shear recovery with mixing was also reported for concrete mixtures made with welan gum and HRWR.[6]

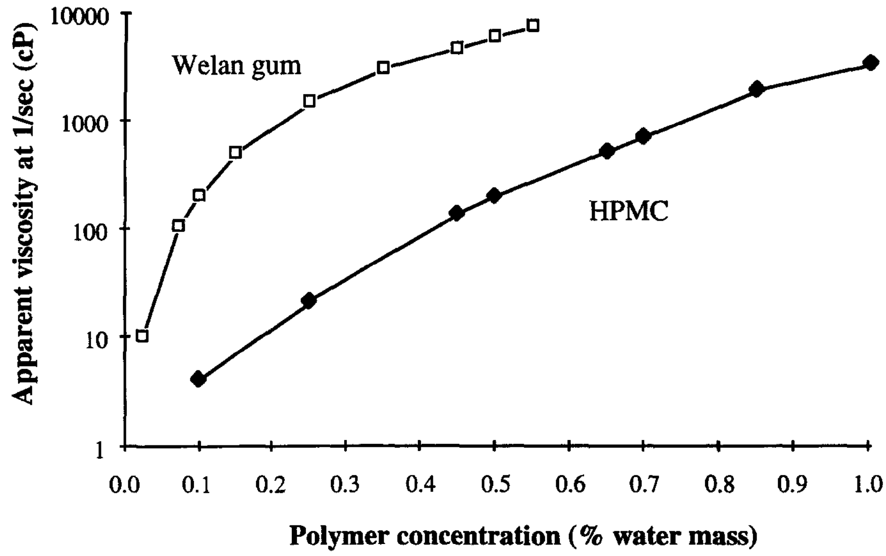

Fig. 1. Variations of apparent viscosity at 0.1 s^{-1} of aqueous solution containing various VEA contents.[4]

An HRWR is often used to reduce the viscosity and yield value of the cement paste, hence avoiding the necessity to increase the W/C to maintain a given consistency. Cellulose derivatives are used in conjunction with melamine-based HRWR because of their incompatibilities with naphthalene-based HRWR.[3,7–9] For example, the use of a polyalkylaryl sulfonate water-reducing admixture in aqueous solutions containing a cellulose VEA was reported to cause abnormal increase in viscosity.[10,11] Kawai & Okada[9] also found that the use of HPMC in an aqueous solution possessing a pH of 13 and containing a naphthalene-based HRWR can result in a sharp increase in viscosity when the HPMC and HRWR contents were respectively greater than 0.8% and 1% by mass of water. This was attributed to the formation of a chemical gel resulting from the incompatibility between the two admixtures. Welan gum does not exhibit an incompatibility with either melamine-based or naphthalene-based HRWRs.[8]

As in the case of aqueous solutions, the incorporation of a VEA results in a significant increase in the apparent viscosity of cement paste at low shear rates, even in the presence of an HRWR.[5,6,12] This is of importance in shotcrete applications where high cohesiveness and good resistance to sagging are required at low shear rate without improving the pumpability of the concrete. The incorporation of a VEA increases the degree of pseudoplasticity of the concrete, hence improving its sag resistance at

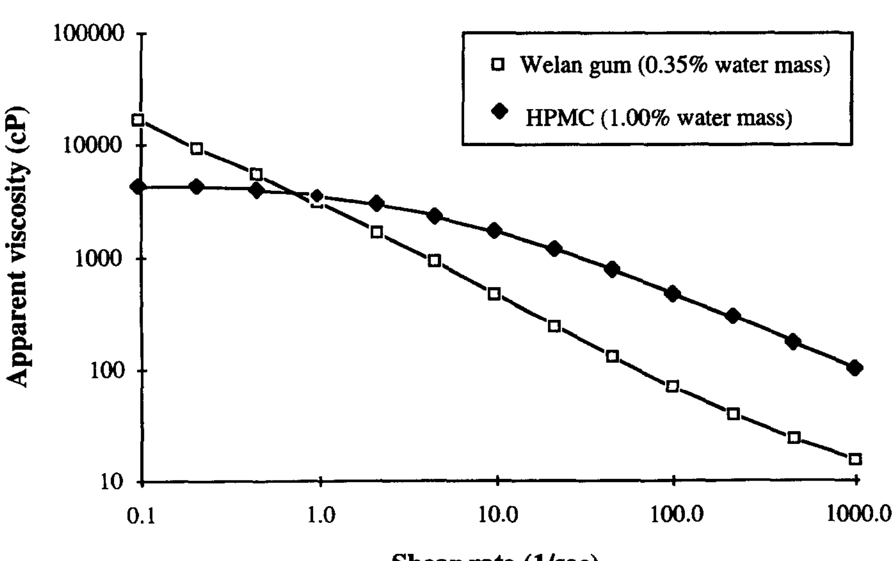

Fig. 2. Variations of apparent viscosity of aqueous solutions with shear rate.[4]

low shear rate while exhibiting a relatively low resistance to flow at high shear rates typically encountered during pumping.[13]

The increase in VEA dosage increases the yield value and apparent viscosity, both at high and low shear rates, in an almost linear fashion regardless of the HRWR content. The demand of the HRWR required to obtain a given fluidity increases with the increase in the VEA dosage and the reduction in the W/C. The introduction of an HRWR results in a significant reduction in yield value, plastic and apparent viscosities, especially in grouts containing low dosages of VEA.[12] In Fig. 3, the viscosity at a low shear rate of a cement grout incorporating various concentrations of welan gum VEA is shown to decrease with the increase in HRWR content. The grouts evaluated incorporated various concentrations of a naphthalene-based HRWR and a fixed W/C of 0.40. For a given decrease in apparent viscosity, the required dosage of additional HRWR is shown to increase with the increased VEA content.[12]

For a given concentration of HRWR, an increase in the dosage of VEA is more effective in increasing the viscosity at low shear rate than at high shear rate.[12] For example, for grouts made with 0.40 W/C and 1% HRWR, an augmentation in the dosage of welan gum from 0 to 0.075% resulted in a sixfold increase in apparent viscosity at 5.1 s^{-1} compared with that evaluated at 510 s^{-1}. This is again due to the pseudoplastic (or shear thinning) behavior of such grouts, where the increase in shear rate reduces the degree of entanglement and association between adjacent polymer chains compared with that at low shear rate. Cement paste systems modified with a cellulose-based VEA also exhibit a highly pseudoplastic behavior, as indicated in Fig. 2.

The increase in the dosage of HRWR disperses cement grains; this can liberate some of the water entrapped between cement grains, hence increasing the amount of free water in the system. The combined use of proper VEA and HRWR contents help secure a highly fluid (yet cohesive) grout, reduce water dilution, and enhance the degree of suspension of various solids. With an increase in the HRWR dosage, the apparent viscosity at low shear rate decreases more dramatically than at high shear rate due to pseudoplastic behavior. As shown in Fig. 4 for cement paste made with 0.40 W/C, grouts containing welan gum as the VEA exhibit high apparent viscosities at low shear rates and significantly lower viscosities at high shear rates. A high apparent viscosity at low shear rate is essential to enhance the suspension capacity of the liquid phase to cement and aggregate particles, hence reducing the rate of sedimentation of fines and segregation of aggregate. On the other hand, because of shear thinning behavior at higher shear rates associated with mixing, pumping, and consolidation, the grout exhibits a lower apparent viscosity that can facilitate the deformability of the mixture. The degree of pseudoplasticity increases with the polysaccharide concentration and the reduction in the HRWR dosage. The increased

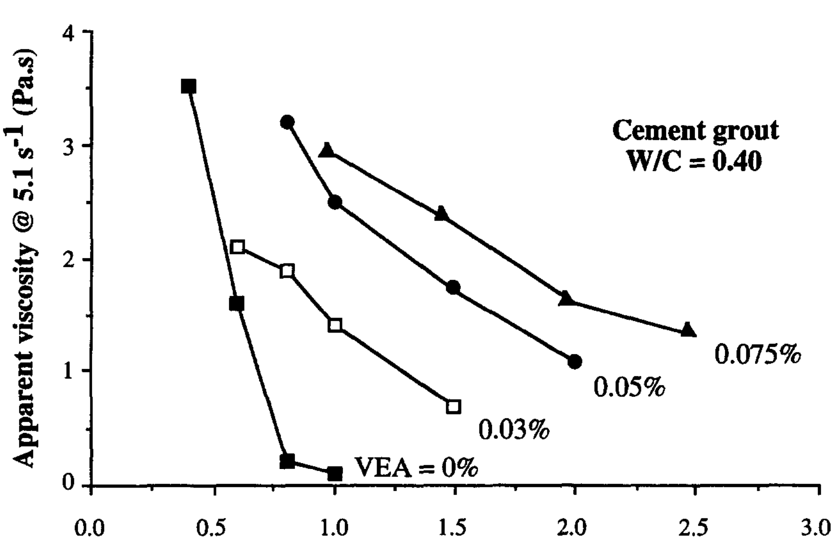

Fig. 3. Variations in apparent viscosity at low shear rate with welan gum–HRWR concentrations.[12]

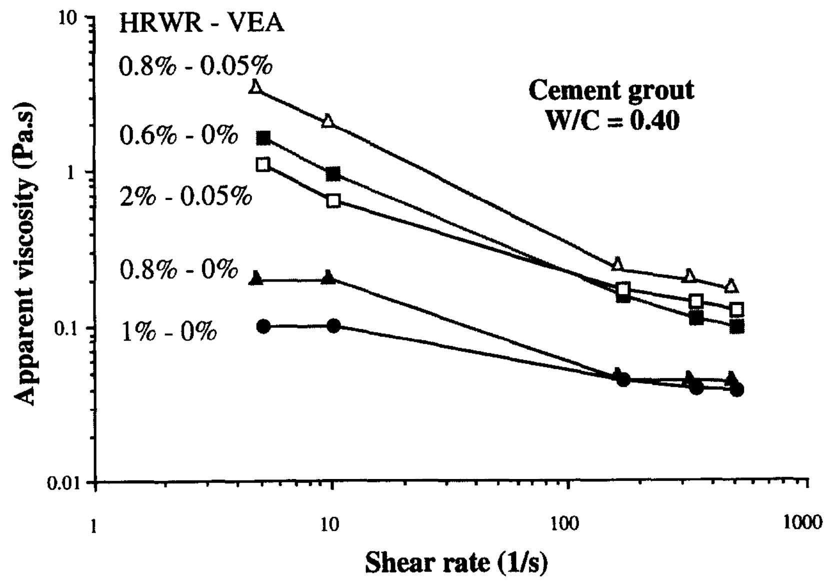

Fig. 4. Variations in apparent viscosity with HRWR and welan gum contents.[12]

pseudoplastic response in the presence of VEA, compared with similar mixtures made without any VEA, is believed to be due to the fact that polymer chains of the VEA entangle or associate, resulting in an increase in apparent viscosity, especially at low shear rates. However, with the increase in shear rate, the entangled chains dislodge and align in the direction of the flow, thus decreasing the resistance of the grout to undergo deformation. The apparent viscosity or resistance to deformation is then decreased with an apparent improvement in flowability and spreadability at high shear rates.

As in the case of cement grout, an increased VEA content results in an increased HRWR demand in concrete. For example, the dosage rate of a naphthalene-based HRWR needed to maintain a slump of 190 ± 5 mm of concrete made with 0.41 W/C and a Type I cement was reported to be approximately 1.0 l/m^3, 3.5 l/m^3, 4.0 l/m^3, and 4.5 l/m^3 when the content of welan gum was respectively 0%, 0.12%, 0.20%, and 0.24% by mass of water. In the case of mixtures made with a liquid-based cellulose VEA, the dosages of a melamine-based HRWR needed to secure an initial slump of 190 ± 5 mm were 3.0 l/m^3, 4.0 l/m^3, and 5.0 l/m^3 when the VEA contents were respectively 600 ml/100 kg, 900 ml/100 kg, and 1200 ml/100 kg of cement.[14]

Resistance to water dilution

The improvement of washout resistance of a cement-based material is advantageous in underwater placements where high strength, good durability, and sound bonding to reinforcing steel and adjacent surfaces are often required. The casting of fluid, yet washout-resistant concrete is especially advantageous in the repair and rehabilitation of existing structures, and can be necessary to improve the constructibility, performance, and cost effectiveness of the repair. The resistance of a cement-based material to water dilution can be enhanced by reducing the fluidity of the mixture. However, this can limit the ability of the cast material to spread readily into place and around various obstacles. By properly selecting an efficient dosage and the type of VEA and HRWR, it is possible to produce a highly fluid and washout-resistant system. Such a system can be cast under water without consolidation and can exhibit minimum intermixing with water.

The washout mass loss can decrease with the increase in VEA concentration, despite the additional HRWR content required to maintain a given fluidity. For example, Fig. 5 shows the cumulative washout mass losses evaluated in accordance to CRD C 61[15] of six concrete mixtures made with W/C ratios of 0.60 and 0.45 and containing no VEA, welan gum, or HPMC. The welan gum was dispersed with the HRWR, whereas the HPMC powder was diluted with part of the cement (1:4 by mass). The dosage of the HRWR was adjusted to obtain approximate initial slump of 185 ± 15 mm. A powder-based deaerating agent incorporated in mixtures made with HPMC was diluted with cement (1:20 by mass) and added to the concrete after the introduction of the HRWR. Despite similar slump

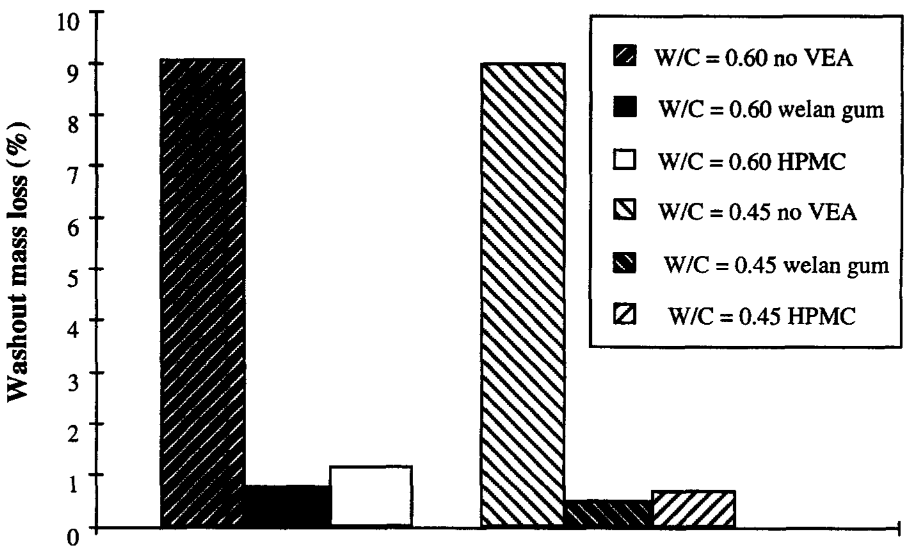

Fig. 5. Cumulative washout mass losses after three drops in water (after Ref. [4]).

values, mixtures containing a VEA had considerably lower washout losses than the corresponding non-VEA mixtures. For example, for the concrete made with 0.45 W/C, the addition of welan gum and HPMC at concentrations corresponding to 0.15% and 0.50% of cement mass reduced the washout mass loss from 9% to 0.5% and 0.7%, respectively.[4]

Regardless of the consistency, the degree of enhancement of washout resistance increases with the dosage of the VEA. For example, for concrete mixtures with a slump of 230 ± 5 mm and W/C of 0.41, the washout mass loss values (CRD C 61[15]) can be 8.3%, 6.4%, 4.0%, and 2.5% when welan gum is incorporated at dosages of respectively 0%, 0.05%, 0.10%, and 0.12% by mass of cement.[14] Such washout mass loss values can be 6.5 and 2.5% when the content of a liquid-based cellulose VEA is increased from 900 to 1200 ml/100 kg of cement.[14]

The improved resistance to water dilution of a cement-based system containing a VEA is due in part to the ability of the polymer to retain some of the mixing water. Such water can be physically adsorbed by hydrogen bonding onto polymer molecules of the VEA. Some of the VEA polymers also become adsorbed onto cement grains along with the imbibed water, resulting in further retention of suspended cement particles. This can then reduce the outflow of water and suspended cement and fines when the concrete is cast in water.[4] Owing to the increased viscosity of the cement paste due to the incorporation of a VEA, the flow of the viscous concrete can proceed at a slower rate than that of a non-VEA concrete of a comparable consistency, or yield value. Such viscous flow reduces the velocity at the water–cement-paste interface, thus decreasing the amount of intermixing of water with the paste. This can then limit the dilution of suspended cement and fines in the surrounding water and any further increase in turbidity and pH.

Several researchers have reported improvement in washout resistance and in situ properties of underwater-cast, cement-based materials.[1,3,7,8,12,14,16–19] For example, welan gum was used to produce a high-performance concrete for the underwater repair of marine piles in California.[17] Marine piles were repaired using a highly flowable concrete with a slump of 230 mm. The repair included a concrete mixture made with a medium dosage of welan gum that incorporated 6% silica fume and 10% fly ash. The concrete had a standard washout mass loss of 5% and a 56 day compressive strength of 62 MPa. The mean in situ compressive strength determined near the upper portion of a 6-m high repair section was only 7% lower than values determined on standard cylinders cast above water. Such a reduction was 40% for concrete made with 11% silica fume replacement and no VEA which had a washout mass loss of 9% and a high slump of 230 mm.[17] A similar concrete was used in the rehabilitation of reinforced concrete velocity caps of an intake structure in Florida. A highly flowable concrete (250 to 275 mm slump) was produced by incorporating a VEA to enable the placement of the concrete in the ocean surf zone without the need to provide a cofferdam for construction in the dry. The concrete was reported to be quite cohesive and resistant to loss of material in water and to segregation.[18]

Resistance to bleeding, segregation, and surface settlement

Bleeding, segregation, and surface settlement can weaken the interface between the aggregate and cement paste, which has a direct implication on permeability and strength. The incorporation of a VEA can imbibe some of the free water in the system and increase the viscosity of the cement paste. As a result, less free water can be available for bleeding. The enhanced viscosity of the cement paste can also improve the capacity of the paste to suspend solid particles which decreases the rate of sedimentation (Stokes' law). Thus, the incorporation of a VEA can enhance the cohesiveness and stability of the cement-based system, hence reducing the risk of bleeding, segregation, and surface settlement.

Khayat & Guizani[20] reported that regardless of the W/C (0.50 to 0.70), slump consistency (140 to 220 mm), casting height (500 to 1100 mm), and mode of consolidation (hand rodding versus excessive external vibration), the incorporation of a medium dosage of welan gum (0.07% by mass of cement) can significantly enhance the resistance of the concrete to bleeding, segregation, and surface settlement compared with concrete of similar slump made without any VEA. Figure 6 shows the maximum cumulative bleeding and surface settlement values of concrete mixtures made with 0.50 W/CM and slumps of 140, 180, and 220 mm that were cast in 700 mm high PVC molds. Regardless of the VEA concentration, the increase in slump resulted in a slight increase in bleeding and settlement, and the incorporation of the VEA caused a significant reduction in bleeding and settlement. Mixtures made with 0.07% welan gum and no silica fume were found to be more stable than those made with 0.035% VEA and 8% silica fume replacement.

Figure 7 shows the variations of bleeding, surface settlement, and segregation coefficients for concrete mixtures with slump values of 220 mm prepared with 0.50 W/CM and made with three dosages of VEA and cast in 500, 700, and 1100 mm high columns.[20] Cumulative bleeding, settlement, and segregation are shown to increase with the reduction in placement height from 1100 to 500 mm and decrease in welan gum concentration from 0.07 to 0%. Regardless of the height of casting, mixtures containing 0.035 and 0.07% VEA had respectively approximately 30% and 50% lower segregation coefficients than the non-VEA concrete. As was the case for bleeding and settlement, the use of 0.07% VEA was more effective in reducing segregation than similar concrete made with 0.035% VEA and 8% blended silica fume cement.

The stability of fluid concrete made with 0.41 W/C and having a constant slump of 230 ± 5 mm can be improved significantly with an increase in the VEA dosage.[14] For example, the maximum bleeding determined according to

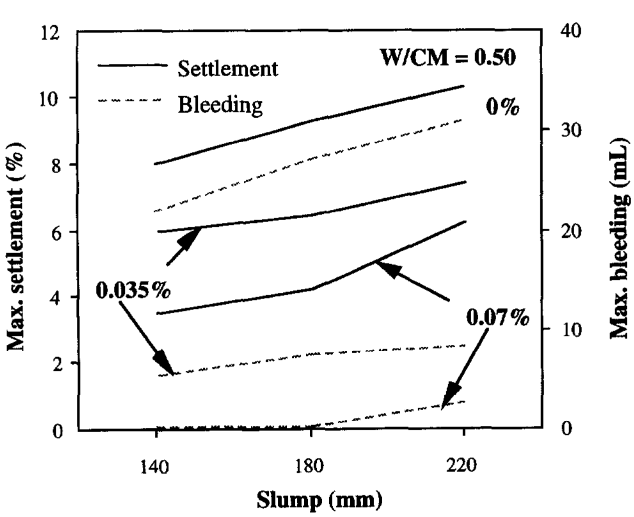

Fig. 6. Effect of welan gum dosage and slump on maximum bleeding and settlement (H = 700 mm).[20]

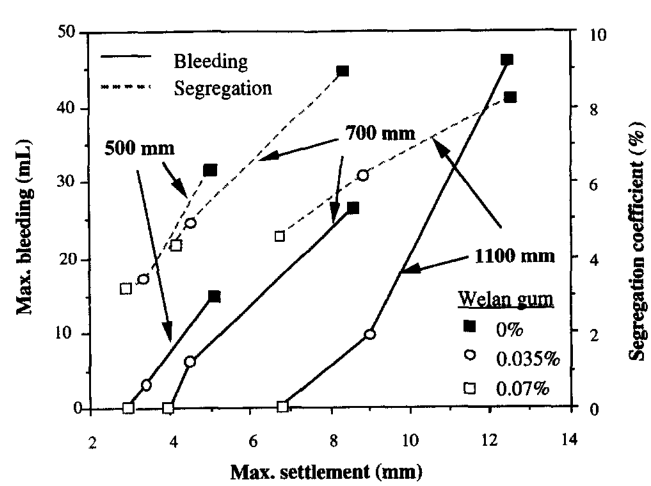

Fig. 7. Relationships between bleeding and settlement, rodded concrete (W/C = 0.50).[20]

ASTM C 232 was found to be approximately 32×10^{-3} ml/cm^2, 9×10^{-3} ml/cm^2, and 4×10^{-3} ml/cm^2 when the concrete incorporated a liquid-based cellulose VEA of 0 ml/100 kg, 600 ml/100 kg, and 1000 ml/100 kg of cement, respectively. Such mixtures had settlements of 6.2 mm, 2.2 mm, and 1.6 mm, respectively, determined on 700 mm high columns, and they had segregation coefficients of 4.6%, 2.6%, and 1.2%, respectively.[14]

It is important to note that because of the reduction of external bleeding, concrete incorporating a VEA has an increased susceptibility to plastic shrinkage cracking. Therefore, special care should be taken to provide proper curing and reduce the rate of evaporation near exposed casting surfaces.

Stability and uniformity of self-consolidating concrete

Owing to the highly flowable nature of self-consolidating concrete (SCC), which is required to facilitate the casting of congested members, it is essential to ensure adequate cohesion and stability of the flowable concrete in order to enhance performance. In general, an SCC is characterized by a low yield value and a relatively high viscosity. The low yield value is essential to enhance spreading of the concrete away from the discharge location, while the viscosity is needed to maintain a homogeneous dispersion of solid particles during the handling and placement as well as once the concrete is cast into place and until the onset of hardening. A highly flowable concrete that does not possess sufficient viscosity can undergo segregation, especially as it flows between closely spaced obstacles such as reinforcing bars. This can lead to blockages that can interfere with the filling of the congested section. The cohesiveness of the concrete is related to the free water content in the mixture, which can be reduced by decreasing the W/C or by incorporating a VEA. Mixtures made with a VEA and a relatively high cement paste content can exhibit less segregation and flow more readily around closely spaced obstacles than mixtures of similar consistencies containing low water and paste volumes and no VEA.

As in the case of fluid concrete, the stability of SCC can be enhanced by incorporating a VEA. For example, as shown in Fig. 8, for an SCC containing 450 kg/m^3 of Portland cement

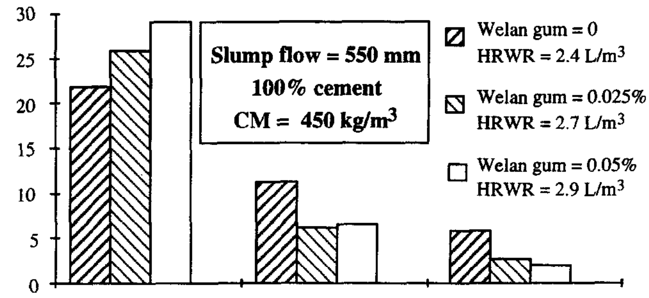

Fig. 8. Effect of welan gum content on properties of SCC made with moderate cement content.

and having a slump flow of 550 mm, the increase in VEA (welan gum) content can result in a reduction of surface settlement and washout mass loss (CRD C 61[15]) and an increase in filling capacity. The slump flow refers to the diameter of the concrete noted at the base following the conclusion of the slump test. This measurement is more sensitive in reflecting small changes in consistency of highly flowable concrete than the slump measurement. The surface settlement was measured using a 700 mm high concrete sample cast in a PVC tube with a diameter of 200 mm. The increase in VEA content from 0 to 0.05%, by mass of cement, resulted in a substantial reduction in settlement and washout mass loss and an increase in the filling capacity. The filling capacity evaluates the ability of the concrete to deform readily and spread among closely spaced reinforcing bars. This test consists of casting concrete in a transparent box with dimensions of $300 \times 500 \times 300$ mm, having 50 mm spaced horizontal bars and determining the amount of concrete that can flow into place between the rebars without consolidation.[21] An increase in VEA content necessitates the addition of a higher concentration of HRWR. However, such additional dosage was limited to 0.5 l/m^3 for mixtures made with 0.05% welan gum compared with no VEA.

The incorporation of a proper dosage of a VEA can enhance the stability of highly flowable SCC. Figure 9 shows the variations of cumulative surface settlements of two highly flowable SCC mixtures having slump flow values of 625 and 650 mm. The concretes had a 0.41 W/CM and contained 585 kg/m^3 of cementitious materials consisting of 3% silica fume, 20% fly ash, and 77% cement, by mass. Again, it can be seen that the increase in VEA content

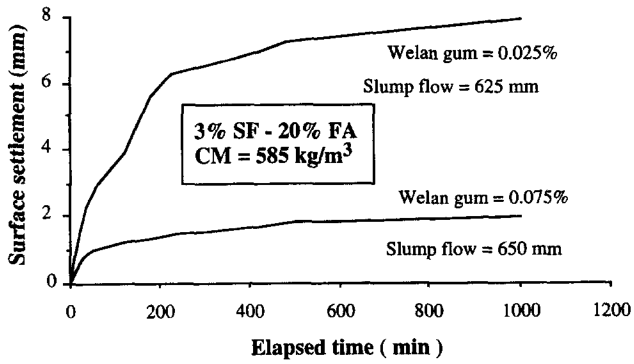

Fig. 9. Effect of welan gum content on surface settlement of SCC.

from 0.025 to 0.075%, by mass of cementitious materials, resulted in a substantial reduction in settlement despite the similar slump flow values. The enhanced stability of the latter concrete led to some increase in filling capacity (61 to 63%).

The flow properties of an optimized SCC can fluctuate greatly with small changes in mixture proportioning, as well as with variations in concrete temperature, sand grading, and cement characteristics and composition. Yurugi *et al.*[22] found that the incorporation of a microbial VEA can be quite beneficial in reducing the sensitivity of flow properties of an SCC to changes in concrete temperature (10 to 30°C), fineness modulus of sand (2.08 to 3.06), and Blaine fineness of the cement (3180 to 3420 cm^2/g) compared with a similar SCC made without any VEA. The SCC mixtures investigated had 0.53 W/C and contained 331 kg/m^3 of Portland cement and 216 kg/m^3 of sand dust. Therefore, the incorporation VEA can contribute to the production of a more uniform SCC at batching plants.

Top-bar effect

Internal bleeding can increase the porosity of the hydrated cement paste near the lower parts of horizontally embedded reinforcement or under the ribs of vertically positioned bars, hence reducing bond strength. The settlement of fresh concrete around the reinforcement reduces the effective projection of the concrete lugs and contributes further to the reduction in bond strength. The inability of rigidly positioned, horizontally embedded bars to settle with fresh concrete can also cause a gap between the lower portions of fixed horizontal reinforcement and the concrete and result in a further reduction in bond strength. The reduction of bond strength to horizontally anchored or overlapped bars located in the upper sections of structural elements as opposed to those located near the bottom is known as the top-bar effect. A high top-bar factor necessitates an increase in the anchorage length and further contributes to the congestion of some structural sections.

As discussed earlier, the incorporation of a VEA can improve the stability of fresh concrete which can reduce the top-bar effect (U_{bot}/U_{top}), as shown in Fig. 10.[23] The anchorage lengths of the reinforcing bars embedded horizontally near the top and bottom of 500 to 1100 mm high specimens were either 2.5 or 5 times the bar diameter. Regardless of the height of the cast specimen, U_{bot}/U_{top} decreases considerably with the incorporation of a VEA. As in the case of bleeding, settlement, and segregation, the top-bar factor was smaller in mixtures containing 0.07% welan gum (by mass of cementitious materials) and no silica fume, compared with those made with 0.035% welan gum and 8% silica fume.

Highly stable SCC mixtures incorporating proper concentrations of VEA to ensure low settlement were also found to secure low top-bar factors.[23,24] The U_{bot}/U_{top} values of the SCC mixtures with slump flow values on the order of 650 mm were quite low considering the highly flowable nature of the concrete. The U_{bot}/U_{top}

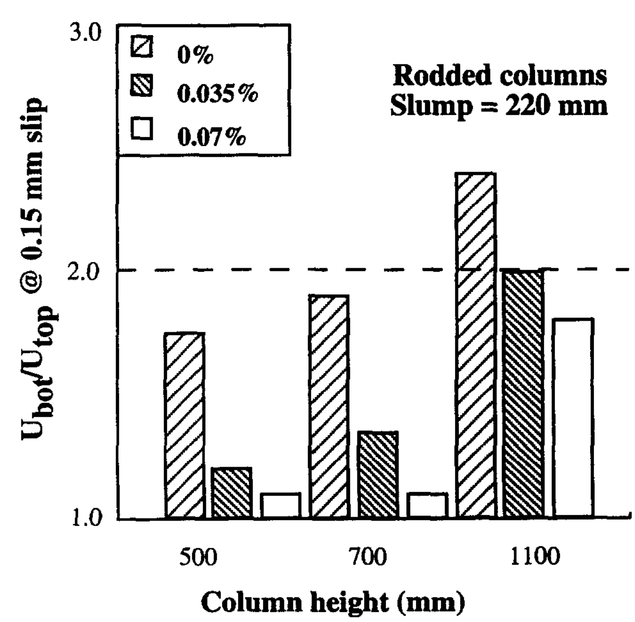

Fig. 10. Effect of welan gum dosage and column height on top-bar effect.[23]

values corresponding to the pull-out load capacity varied between 1.22 and 1.35. These values were comparable with those obtained for rodded concrete samples with slump values of 190 mm (1.25 to 1.40).

As can be expected, a good linear relationship can be derived between the U_{bot}/U_{top} and the extent of surface settlement ($R^2 = 0.87$).[23] Such a relationship demonstrates that, regardless of the fluidity and composition of concrete and the height of concrete cast under the upper reinforcing bar, the top-bar factor is affected significantly by surface settlement. Such settlement was earlier shown to depend closely on the extent of bleeding and segregation, and it can be effectively reduced by the incorporation of a VEA, even in the case of an SCC.

Resistance to forced bleeding and settlement of cement grout

Specialty cement grouts are used in a variety of applications, including sealing rock tendons in tunnel excavation, pressure crack injection of submerged structures and filling bonded post-tensioned ducts for corrosion protection. In such applications, it is essential to control the bleeding of the mix water and settlement of suspended cementitious materials. The incorporation of a VEA can enhance the cohesiveness and reduce the risk of separation of solid constituents. This is advantageous for a cement grout used to fill vertical post-tensioned ducts where differential hydraulic pressure at the lower part of the ducts between the fresh grout and air voids among closely spaced tendons and strands can lead to the seepage of some of the mix water through tight gaps between the tendons and strands. Such water can then move upward by capillary action and become deposited further up in the post-tensioning ducts, hence forming voids that can reduce the corrosion protection of bonded tendons.[12]

The resistance of cement grout to forced bleeding can be evaluated using a special pressure filter vessel in which a fresh grout sample is subjected to a sustained pressure that causes separation of some mix water from the grout. A 200 ml sample of fresh grout is poured inside a sealed steel container, and nitrogen gas is used to provide a sustained pressure of 0.55 MPa for 10 min.[25] As shown in Fig. 11, the incorporation of proper VEA and HRWR dosages can produce fluid grouts with high resistance to water loss due to forced bleeding.[12] The forced bleed water collected over 10 min is expressed as the percentage of the mix water present in the 200 ml grout sample in the above-described test. The grouts tested had a constant W/C of 0.40 and were prepared with Type I cement. Regardless of the concentration of VEA (welan gum), the increase in mini slump spread due to the increase of the HRWR dosage decreased significantly the amount of forced bleeding. The incorporation of an HRWR causes a dispersion of cement particles that enhances the ability of such grains to achieve better packing against

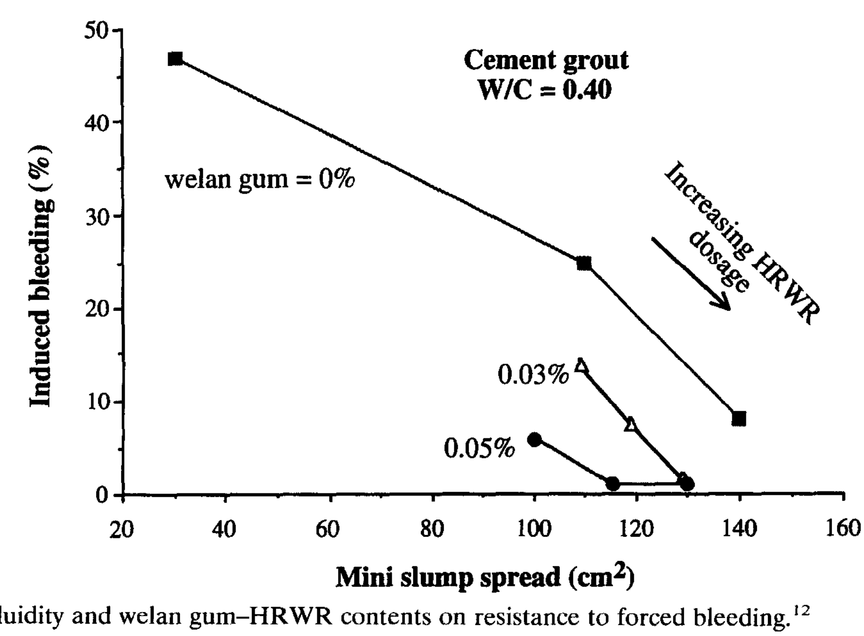

Fig. 11. Effect of fluidity and welan gum–HRWR contents on resistance to forced bleeding.[12]

the filter in the test set-up. This results in a reduction of the permeability of the fresh grout and a decrease in the amount of bleed water penetrating through the filter over time. Furthermore, for a given fluidity, an increase in the dosage of VEA resulted in further reduction in the amount of forced bleeding. The introduction of a VEA increases the viscosity of the mix water and increases the ability of the grout to retain free water.[12]

The incorporation of a VEA can also reduce the rate of sedimentation of suspended cement grains due to the increase in viscosity of the mixing water which reduces the rate of sedimentation of cement grains (Stokes' law) resulting in a highly stable grout.[12,26]

Setting time

The effect of a VEA on the setting time depends on the type and concentration of VEA, the type and dosage of HRWR, as well as on the cement composition and W/C. In general, the incorporation of a VEA can cause some delay in setting time because the VEA polymer chains can become adsorbed onto cement grains and interfere with the precipitation of various minerals into solutions that influence the rate of hydration and setting.[12] In general, mixtures incorporating a cellulose-ether-type VEA can exhibit some delay in setting time, and those made with acrylic-type VEAs do not delay the setting time.

The HRWR used to ensure good fluidity can delay setting time since it disperses cement grains, thus retarding hydration and setting. For example, the increase in the dosage of a naphthalene-based HRWR from 0 to 0.8%, by mass of cement, in a grout made with 0.40 W/C, a Type I cement, and no VEA was shown to increase the initial set from 5.3 to 11.5 h.[12] On the other hand, when a welan gum was incorporated at a low content (0.03% by mass of cement) the increase in the HRWR dosage from 0.4 to 0.8% resulted in a substantial increase in initial setting, from 9.8 to 20.5 h. Further addition of welan gum from 0.03 to 0.05% in grouts containing 1% HRWR resulted in a marginal increase in setting (21.5 to 25 h). Similarly, the increase in VEA dosage from 0.05 to 0.10% in grouts containing 1.5% HRWR resulted in a limited increase in setting (26.5 to 29 h).[12] It is important to note that the delay in setting time due to HRWR and VEA combinations is substantially lower when determined on mortars extracted from concrete mixtures (ASTM C 403) compared with cement grout.

Sogo[19] found that for mortars made with a W/C of 0.55, the increase in the dosage of a cellulose-ether-based VEA from 0 to 1 kg/m^3 and from 1 to 3 kg/m^3 can delay the initial setting by approximately 1.5 h and 2.5 h, respectively. Khayat[4] reported that a fluid concrete made with 0.45 W/C and Type II cement containing 0.65% HRWR and 0.15% welan gum, by mass of cement, can delay initial setting by 80 min over a similar concrete made with 0.33% HRWR and no VEA. The same delay in initial setting was obtained for a similar mixture made with 0.65% HRWR and 0.5% HPMC. The additional delays in final setting compared with non-VEA concrete were 150 min and 90 min for mixtures made with welan gum and HPMC respectively. Regardless of the W/C (0.30, 0.45, and 0.60), concretes containing HPMC and a melamine-based HRWR exhibited some delay in initial setting compared with mixtures made without any VEA (100 ± 20 min). Similar retardation was obtained for mixtures made with welan gum and a naphthalene-based HRWR having W/C ratios of 0.45 and 0.60. Excessive delay in setting was reported in the latter system when the W/C was set to 0.30 because of the high concentration in HRWR needed to maintain a slump of 180 ± 10 mm. In the absence of HRWR, the use of welan gum or HPMC was found to cause only a slight delay in setting.[4]

The delay in initial setting time (ASTM C 403) of fluid concrete made with 0.41 W/C and Type I cement was reported to increase slightly with the increase in the VEA dosage.[14] For example, the initial setting times of superplasticized concretes having slump values of 190 ± 5 mm and 230 ± 5 mm and made without any VEA were approximately 6.1 h and 6.2 h respectively. The approximate delays in initial setting of mixtures with slumps of 190 ± 5 mm and 230 ± 5 mm incorporating 0.08 and 0.10% of welan gum, by mass of cement, were 0.7 and 1.9 h and 1.3 and 2.0 h respectively. Such delays were 0.7 and 1.4 h and 3.7 and 3.7 h respectively when the concrete incorporated 600 and 1200 ml/100 kg of cement of a liquid-based cellulose VEA.[14] Again, some of the increase in setting time is partially due to the additional HRWR dosage required to increase the slump from 190 to 230 ± 5 mm.

Air entrainment and frost durability

Several cellulose derivatives, such as HPMC and HEC, and synthetic polymers, such as polyethylene oxide, can entrap large volumes of air and are used in conjunction with deaerating agents. Owing to the lack of significant hydrophobic constituents, welan gum has little activity at the air–water interface, and thus does not generate foam or entrap large volumes of air.[4]

In general, the incorporation of a VEA can increase sharply the AEA demand for achieving a given air content. However, a proper air–void system can still be produced provided that a proper dosage of AEA is used. The increased VEA content increases the amount of water that can be associated with the polymer. As a result, less free water is available to the AEA, and greater additions of AEA are then needed with increasing VEA contents, even in the case of those containing no deaerating agent.[4] The increased demand for AEA in a concrete containing a VEA may also be due in part to the HRWR that can reduce the sites on cement particles where air bubbles can be attached together. With such reduction in sites on cement grains, it is possible that some of the bubbles become less stable and coalesce, thus necessitating greater additions of AEA.[27]

As shown in Fig. 12, the dosage of AEA required to maintain $7 \pm 1\%$ air content in fresh concrete (ASTM C 231) increases with the increase in welan gum concentration. The evaluated concrete had a fixed W/C of 0.45 and a cement content of 360 kg/m^3. The dosage of naphthalene-based HRWR was adjusted to maintain a constant slump of 210 ± 10 mm in mixtures made with a VEA and 100 mm in the non-VEA concrete. The required dosage of the AEA is shown to increase approximately 3.5 times when the content of welan gum content was varied from 0 to 0.05%, by mass of cement.[4]

The introduction of AEA in relation to the VEA can have an effect on the AEA demand. For example, the incorporation of a highly efficient AEA in concrete after the introduction of welan gum and a naphthalene-based HRWR was shown to result in a more effective air–void system than when the AEA is introduced prior to the VEA–HRWR dispersion.[27] As was the case for the 210 mm slump concrete, the addition of welan gum to an SCC with 630 mm slump flow was found to increase the AEA demand. However, unlike the former concrete, the introduction of the same AEA was more efficient when carried out prior to the addition of the HRWR and welan gum.[28]

The effect of incorporating a VEA and HRWR on the air–void system (ASTM C 457) is presented in Fig. 13 for concrete made with various welan gum contents and two dosages of an efficient AEA. The concentration of HRWR was adjusted to yield an initial slump of 220 ± 20 mm in the VEA concretes.[4] The low AEA dosage of 0.35 ml/kg of cement that was necessary to secure an adequate $\bar{L}$ in the non-VEA concrete resulted in low air volumes and high $\bar{L}$ values when the concrete incorporated 0.05 and 0.10% of welan gum. Such reduction

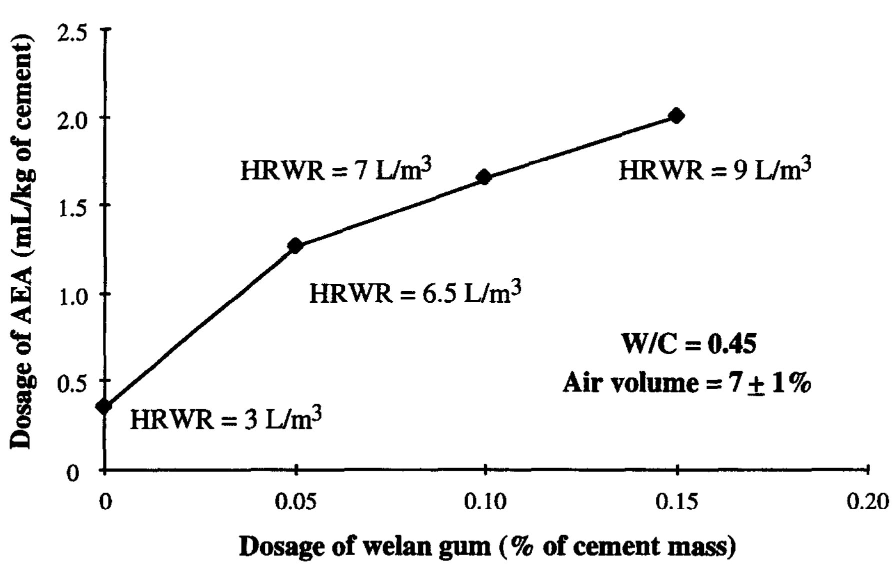

Fig. 12. Effect of dosage of welan gum on demand of AEA in fluid concrete.[4]

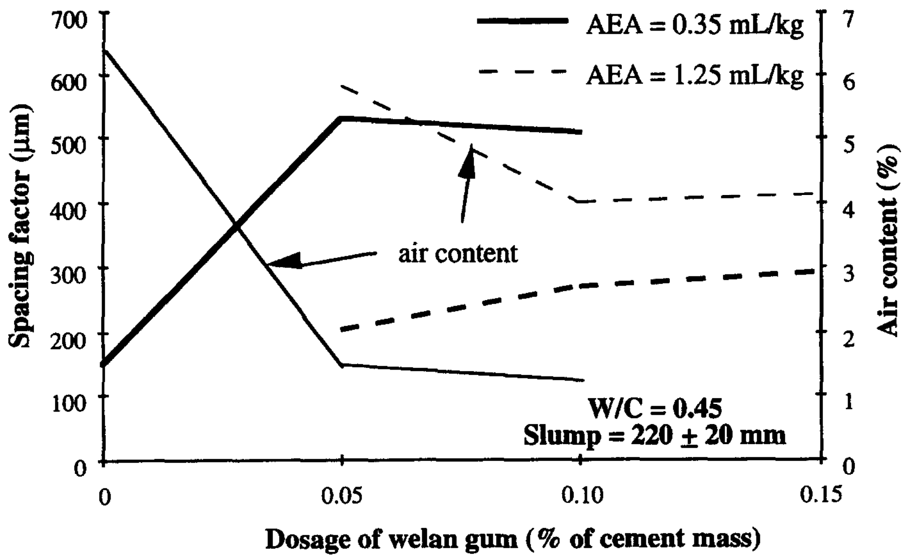

Fig. 13. Effect of welan gum concentration on air content and spacing factor of hardened concrete.[4]

in the quality of the air–void system was less apparent when the dosage of AEA increased to 1.25 ml/kg, which was needed to obtain a proper air–void system in concrete containing 0.05% welan gum.

Yamato *et al.*[29] reported that concrete made with 0.45 W/C and either cellulose-based agents or a polyacrylamide VEA can exhibit poor frost durability (ASTM C 666, Procedure A) compared with concrete made without any VEA. The durability factor of such a VEA concrete was found to vary between 10 and 50% compared with 90% for the non-VEA concrete. Mixtures containing the polyacrylamide-type VEA had better frost durabilities than those made with the cellulose-based VEA. The lack of frost durability was partially attributed to the higher $\bar{L}$ values of the VEA concrete that varied between 120 and 420 μm compared with 250 μm for the non-VEA concrete. The VEA mixtures were reported to have greater capillary porosity than the non-VEA concrete, particularly for pores with apparent diameters larger than 10 nm.[29]

Khayat[27] investigated the impact of incorporating HPMC and welan gum on frost durability of concrete with various W/C (0.32 to 0.50). Small dosages of tri-butyl phosphate were incorporated in mixtures containing HPMC to deaerate any extra entrapped air before introducing the AEA. A naphthalene-sulfonic acid formaldehyde condensate was used in mixtures containing welan gum and those made without any VEA. On the other hand, a melamine-sulfonic acid formaldehyde condensate HRWR was used in mixtures incorporating HPMC. An effective synthetic detergent was used for the AEA. The results clearly showed that, providing an adequate air–void system is secured, concrete made with welan gum or HPMC can exhibit adequate frost durability similar to that of conventional concrete. As shown in Fig. 14, regardless of the presence of a VEA, concrete with 0.45 W/C and $\bar{L}$ less than 400 μm exhibited a frost durability coefficient greater than 75%. Such coefficients were in excess of 100% in the case of similar concrete made with W/C ratios 0.32 and 0.40. Such mixtures had $\bar{L}$ and α values ranging between 150 and 380 μm and 31 and 15 mm^{-1}, respectively.[27]

Mechanical properties

When a VEA is used in a low W/C system (for example 0.30), it may interfere with the degree of cement hydration and reduce the rate of strength development.[30] However, when used in typical mixtures that necessitate the incorporation of a VEA to enhance stability (W/C > 0.40), the VEA does not seem to have a significant effect on strength development. Owing to the increase in stability, the resulting cohesive concrete can develop a denser transition zone between the cement paste and aggregate that can enhance bond strength to embedded reinforcement and impermeability. This can also result in a greater flexural-to-com-

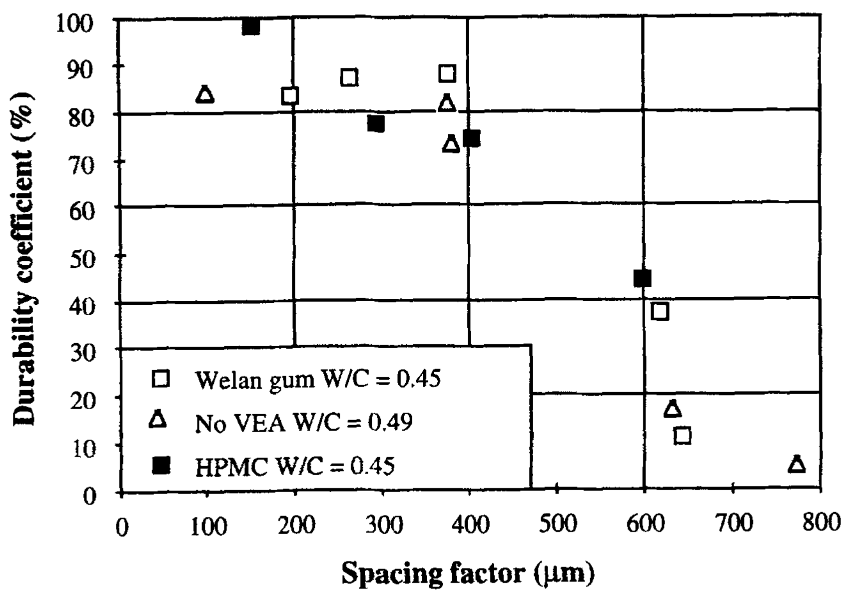

Fig. 14. Relations between spacing factor and durability coefficient.[27]

pressive strength ratio compared with non-VEA concrete of similar consistency.[30]

The effects of incorporating welan gum and HPMC on the developments of compressive strength (ASTM C 39), modulus of elasticity (ASTM C 78), and flexural strength (ASTM C 469) were evaluated for non-air-entrained concrete made with W/C ratios of 0.60, 0.45, and 0.30.[30] The concrete had an approximate slump of 180 mm and was moist cured until the time of testing. Mixtures containing a VEA had 1 to 2.3% higher air contents in the hardened state than non-VEA mixtures, which may result in 5 to 10% compressive strength reduction. Considering the spread in air content, mixtures made with welan gum and W/C ratios of 0.60 and 0.45 were found to develop similar or slightly greater compressive strengths than the corresponding non-VEA concrete. On the other hand, mixtures made with welan gum and 0.30 W/C exhibited up to 10% drop in compressive strength. Such a reduction was 15% in concrete made with HPMC and 0.60 W/C and $20 \pm 10\%$ for HPMC concrete with W/C ratios of 0.45 and 0.30. Compared with non-VEA mixtures, concrete made with welan gum and HPMC and W/C ratios of 0.60 and 0.45 exhibited some reduction in modulus of elasticity corresponding to $8 \pm 8\%$ and $15 \pm 5\%$, respectively. Despite the differences in air contents and compressive strengths, both welan gum and HPMC mixtures made with 0.30 W/C developed moduli of elasticity of $98 \pm 5\%$ of those obtained with the non-VEA concrete.[30] Regardless of the W/C, concrete incorporating welan gum had approximately 10% lower flexural strength at 56 and 84 days than similar mixtures made without any VEA. No reduction in flexural strength was observed in mixtures made with HPMC and 0.60 W/C; however, $12 \pm 4\%$ strength loss was obtained in HPMC mixtures made with 0.30 and 0.45 W/C ratios. Despite the slight lag in compressive strength, the flexural-to-compressive strength ratios of VEA concrete were similar to those obtained for the non-VEA concrete.[30]

Figure 15 compares the compressive strengths measured after 34 days of water curing for air-entrained concretes made with 0.32, 0.40, and 0.45 W/C ratios. The slump values ranged mostly between 160 and 200 mm. The air contents of the hardened concretes, which are indicated on the figure, varied between 4 and 6%.[30] The 34 day compressive strength results indicate that mixtures with W/C ratios of 0.45, 0.40, and 0.32 containing welan gum used at an approximate dosage of 0.20%, by mass of water, had compressive strengths of $100 \pm 5\%$ compared with similar mixtures made without any VEA. The compressive strengths of concretes made with HPMC at W/C ratios of 0.40 and 0.32 were approximately 100% and 90% respectively of those made without any VEA.[30] The contents of HPMC in the medium- and high-strength mixtures were 0.15 and 0.08%, by mass of cement.

The effects of type and concentration of VEA on the development of compressive and

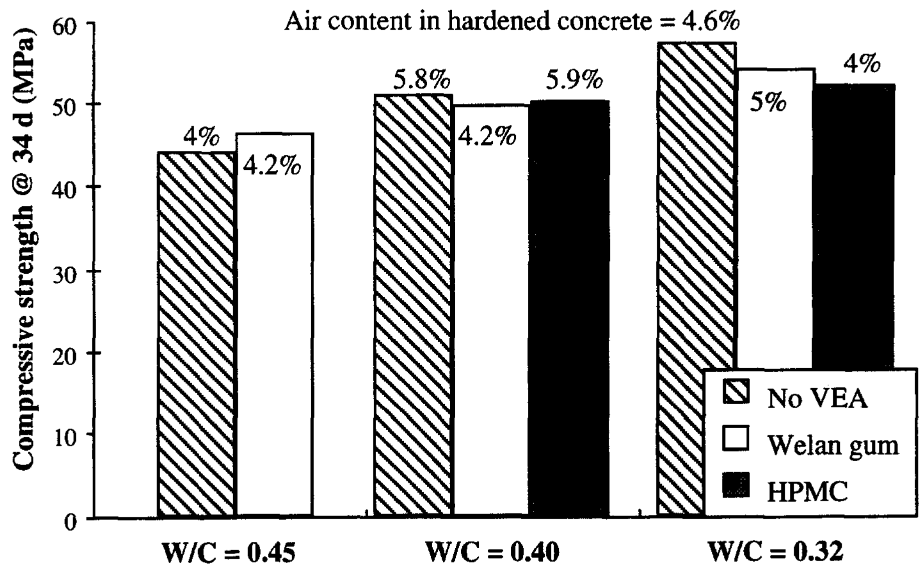

Fig. 15. Compressive strength results at 34 days, * values indicate air volume in hardened concrete (after Ref. [30]).

splitting tensile strengths were investigated for non-air-entrained concrete made with 0.41 W/C.[31] Fluid concrete with 230 mm slump and welan gum dosages of 0.05 to 0.10%, by mass of cement, developed approximately 95±4% compressive strength after 7 days of water curing compared with non-VEA concrete. These values were 94±9% and 98±10% after 28 days and 56 days of water curing, respectively, and they were approximately 5% greater for mixtures made with 190 mm slump. In the case of concrete made with a liquid-based cellulose VEA incorporated at 600 to 1200 ml/100 kg of cement, the relative 7 day, 28 day, and 56 day compressive strengths were 97±7%, 83±5%, and 94±7%, respectively for mixtures of 230 mm slump. These values were 100±4% in the case of mixtures with 190 mm slump.[31]

The incorporation of welan gum or HPMC was shown to reduce the rapid chloride-ion permeability (AASHTO 277, ASTM C 1202) of air-entrained concrete made with 100% Type I cement and W/C ratios of 0.45, 0.40, and 0.32.[30] Despite the similarities in compressive strengths of the VEA and non-VEA mixtures for any given W/C, concretes incorporating a VEA tested up to 40% lower rapid chloride-ion permeability values than corresponding non-VEA mixtures (Fig. 16). All mixtures had slump values of 180±20 mm and hardened air con-

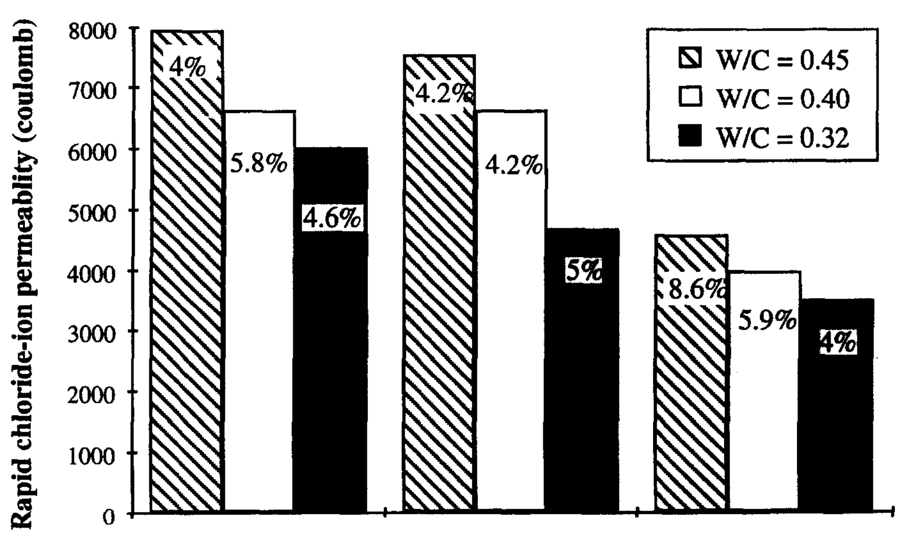

Fig. 16. 33 day rapid chloride-ion permeability, * values indicate air volume in hardened concrete (after Ref. [30]).

tents of $5 \pm 1\%$. The reduction in rapid chloride-ion permeability was especially significant in the case of concrete made with 0.32 W/C incorporating HPMC. Such a reduction could be attributed mainly to the improvement of concrete homogeneity and reduction in the porosity of the transition zone between the bulk cement paste and aggregate.

SUMMARY

The use of a VEA in a cement-based system reduces the amount of free water available for lubrication of the paste and increases its yield value and viscosity. An HRWR is often incorporated to secure a given level of consistency. With the increase in VEA content, the effectiveness of adding HRWR to enhance fluidity is reduced, hence necessitating greater HRWR addition. Combined with an adequate dosage of HRWR, losses in fluidity due to the incorporation of a VEA can be regained without significant effect on cohesion and stability. Cement paste containing a VEA can be highly pseudoplastic and thixotropic, where the viscosity increases with the reduction in shear rate and the elapsed time, respectively. The pseudoplastic behavior can enhance the suspension of solid particles at low shear rates without much interference with the ease of mixing, pumping, and casting that take place at relatively high shear rates where the modified system exhibits a reduction in viscosity.

By adjusting the combination of VEA and HRWR, a fluid, yet washout-resistant, system can be produced. This can then enhance in situ properties of underwater-cast grout, mortar, and concrete and reduce the turbidity and increase in pH of the surrounding water. It is important to note that, despite the enhanced resistance to water dilution and segregation, the free fall of concrete in water should still be minimized to ensure high in situ mechanical properties.

Regardless of slump, W/CM, casting height, or degree of consolidation, the incorporation of a proper combination of VEA and HRWR can significantly reduce bleeding, segregation, and surface settlement. In the case of a highly flowable, yet stable, concrete, the improved homogeneity of aggregate suspension in cement paste can increase the filling capacity of congested structural sections. The resulting stable and homogeneous concrete can develop more uniform in situ mechanical properties and fewer structural defects under embedded reinforcement which increases bond strength and reduces the top-bar effect in deep structural sections. The enhanced interface between the aggregate and hydrated cement paste can also secure greater impermeability.

The combined additions of a VEA and an HRWR can result in some delay in setting time, especially at high HRWR concentrations. However, such delays are limited in concrete mixtures containing normal admixture dosages. The use of a VEA increases the demand for AEA; however, once enough air is entrained, proper air–void parameters needed to ensure good resistance to freezing and thawing can be secured.

In the range of W/C where a VEA is typically employed ($W/C \geq 0.40$), data concerning the effect of VEA on mechanical properties show that, in some cases, the incorporation of welan gum, HPMC, or a liquid-based cellulose VEA in fluid concrete does not affect compressive strength development, whereas in other cases they can result in slight reduction in strength which can be limited to 10% compared with non-VEA concrete. The slightly adverse effect of VEA on mechanical properties can be partially due to the additional entrapment of air in the fluid, yet viscous, cement-based material.

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