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Rheology of Grouts Containing Ground Granulated Blastfurnace Slag and Viscosity Enhancing Admixture

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ABSTRACT

This paper describes the rheological parameters and the fluidity of mixes containing viscosity enhancing admixture (VEA) diutan gum and compare it to welan gum. This investigation was undertaken to evaluate the influence of the dosages of diutan gum and the superplasticizer (SP) on fresh properties of cement-based materials paste with 0.40 water-to-binder ratio (W/B). The fresh properties of reference grouts made without any VEA and with SP were compared to those of mixes made with 0.02%, 0.04%, 0.06%, 0.08%, and 0.10% diutan gum by mass of cement. The effect of replacement of cement by sustainable by-product such as ground granulated blast slag (GGBS) at 20%, 30% and 40% was also investigated with different various dosages of diutan gum. The results indicate that for any given dosage of SP, the increase in the dosages of diutan and welan gum led to an increase in yield stress, apparent and plastic viscosities, and to a reduction of fluidity.

INTRODUCTION

The cement-based grouts may find use in sealing hydraulically active fracture zones and faults, cracks in dams, rock-concrete interfaces, offshore structures, and, possibly, excavation-disturbed zones. New constructions or repair of existing structures dealing with grouting techniques poses certain challenges that require special placement techniques, and more specially, specialized mix proportions. The viscosity enhancing admixture (VEA) enhances the performance of grouts and can provide an additional measure of protection against bleeding, segregation and washout of fines particles by increasing the plastic viscosity of the paste phase, resulting in increased cohesiveness of the mix. The paste phase rheology modifications provided by VEAs have resulted in their expanded use in other cementitious mixes for various applications. The polymer network and gel structure is responsible for increased viscosity of the paste phase and increased mix cohesiveness. In addition, mixes containing these polymers typically display increased thixotropic and pseudoplastic characteristics [Ghio et al. 1994, Khayat 1998, Sonebi 2001, Sonebi 2006, Sonebi 2007, Sonebi et al. 2004].

Grouts incorporating VEA can be highly pseudoplastic, despite the presence of superplasticizer (SP), making it possible to secure rheological profiles that are difficult to achieve without SP [Sonebi 2002, Sonebi 2006]. Pseudoplastic behaviour can further stabilize solid particles at low shear rates, with limited interference with the ease mixing, pumping, and casting that take place at relatively high shear rates where the modified system exhibits a reduction in viscosity.

Both VEAs, diutan gum (DG) and welan gum (WG), are high molecular weight and microbial polysaccharides. They are anionic polymers and are produced by aerobic fermentation. Their performance is influenced by the presence of superplasticizer (SP). The chain structure of diutan gum is different to the welan gum. Diutan gum had two-rhamnose side chain compare to welan gum, which had only one or one mannose. The molecular length of diutan gum is up to 3 times longer than of welan gum, while the molecular weights of diutan and welan gum are about 2.88 to 5.18 and 0.66 to 0.97 million Daltons for diutan and analogous for welan gum [Phyfferoen et al., 2002, Sonebi, 2006, Sonebi, 2007]. Welan gum is a long-chain biopolymer with sugar backbones substituted with sugar side chain. It is efficient in maintaining high viscosity in alkaline solution with a high concentration of calcium ions even at high temperature [Phyfferoen et al., 2002].

The objective of this study consisted of evaluating the effect of dosage of diutan gum and welan gum on the rheological parameters and the fluidity of grouts. The effect of the replacement of cement by 20%, 30%, and 40% of ground granulated blastfurnace slag (GGBS) is also investigated with the variation of the dosages of both VEAs. All grouts were prepared with 0.40 water-to-binder ratio (W/B), corresponding of high-performance cement-based materials where VEA is typically incorporated. Similar reference mixes without any VEA and made with 100% cement (100%C) and different percentage of GGBS were evaluated in order to compare the fluidity and the rheological parameters.

MATERIALS, MIX PROPORTIONS AND TESTING PROCEDURES

Materials and mix proportions

The grout mixes were prepared with Standard 42.5N grade portland cement and GGBS. The cement and GGBS used conformed to BS EN197-1 CEM1, BS 6699:1992. The density of GGBS was 2.90. Modified polycarboxylic ether (SP) was used with a solid content of 30% and specific gravity of 1.05. SP was used from 0.8% to 1.56% (by mass binder). Diutan gum (DG) and welan gum (WG) were supplied in a powder gum and were used from 0.02% to 0.08% (by mass of binder).

Test methods

All grout mixes were prepared in a 5-litre planar-action high-shear mixer. The mixing tap water had a temperature of 16 ± 1ºC, which was measured before mixing started. The VEA was mixed with cement. The SP was added to the water and mixed together. All components were mixed for seven minutes from beginning. The grout temperature following the end of mixing was maintained at 20 ± 2ºC. Following the end of mixing, the mini-slump test was carried out first (1-2 min), and the viscometer test was performed next (4 -10 min).

The mini-slump test is based on the measurement of the spread of paste placed into a cone-shaped mould. A PVC plate and a cone, which has a lower inner diameter of 38.1 mm, an upper inner diameter of 19 mm, and a height of 52.7 mm, were used in the flow test of paste. The cone is placed on the centre of the glass plate, and, immediately after mixing, the cone is filled with the sample. The cone is then vertically lifted to let the paste flow freely. Finally, the diameters at four right-angle positions are measured when the paste stops flowing and the average diameter of four measurements is recorded.

The viscosity of cement grout is determined using a coaxial rotating cylinder viscometer Fann (smooth cylinders, no serration) that enabled the determination of apparent viscosity at different shear rates [Sonebi et al., 2006]. The viscometer is contained in the annular space between an outer cylinder (rotor) with radius of 18.4 mm and a bob with radius of 17.2 mm and height of 3.80 cm. The rotor and the bob are plunged into a cup which contains 350 ml of sample [8]. The measurement is made for 12 speeds of rotor, from 0.9 rpm to 600 rpm, when the values of viscometer reading (θ) are recorded. The reading of θ was taken when the needle in the viscometer was stabilised, or 30 s after the change of speed in cases when the needle has not stabilised. The upwards flow curve was chosen for the description of rheological behaviour of the grouts. The values of yield stress and plastic viscosity are obtained from modified Bingham model [Yahia et al., 2001].

RESULTS AND DISCUSSION

Comparison of the apparent viscosity of diutan and welan gums with OPC mix

Figure 1 presents the comparison of the apparent viscosity of diutan gum and welan gum at different dosages of VEA ranging from 0.04% to 0.08% with fixed dosage of SP of 1.4% (by mass of CM), and mix without VEA of 100% C mix (made only with OPC). The curves show that the effect of the dosage of diutan and welan gums on increasing the pseudoplastic behaviour or shear thinning compared to no-VEA mix; which can be considered almost Newtonian at the same dosage of SP. Both VEAs exhibited high apparent viscosity values at low shear rates which were attributed to the entanglement and intertwining of VEA polymer chains at low shear rate and association of water between adjacent chains. Reduction in the viscosity of VEA grouts was observed when the shear rate increased and due to a partial realignment of the polymer chains in the direction of flow and the intertwined chains dislodge [Khayat, 1998, Sonebi, 2006], thus the resistance of the mix is decreased to undergo deformation. The apparent viscosity was then reduced with an apparent enhancement of the fluidity at high shear rate.

Diutan gum was more pseudoplastic and exhibited greater viscosity at low shear rate than welan gum at the same dosages of VEA and SP. This difference can be attributed to diutan's gum molecular weight and molecular length which diutan gum is longer up to 3 times than welan gum. It may be attributed to higher water retention of diutan gum. These results confirm some results obtained on water solutions [Phyfferoen et al., 2002]. The higher weight molecular of VEA is the higher water retention will be obtained [Pouchez et al. 2006]. It can be seen that at low rate of shear, the viscosity could be similar to welan gum grout by using lower dosage of diutan gum.

Effect of dosages of VEAs and SP on mini-slump of mix made with OPC

The variation of mini-slump of mixes made with OPC (100% C) and incorporating diutan gum and welan gum is presented in Figure 2. As expected Figure 2 shows that increasing the dosage of SP led to an increase in fluidity for similar dosage of VEA, and the increase of VEA resulted in a significant reduction of fluidity for any given dosage of SP. For all dosages of VEAs, it was observed that the grouts containing diutan gum had better fluidity than those containing welan gums. For example, to secure a mini-slump of 88 mm with 0.04% VEA, diutan gum mix required only 1% SP, whereas welan gum mix required 1.3% SP. Thus, to assure similar fluidity, mixes containing diutan gum necessitated less dosage of SP compared to mixes containing welan gum. This is due to the lower charge density of diutan gum which resulted in a reduction tendency to adsorb out onto the hydration cement products compared to welan gum [Phyfferoen et al., 2002].

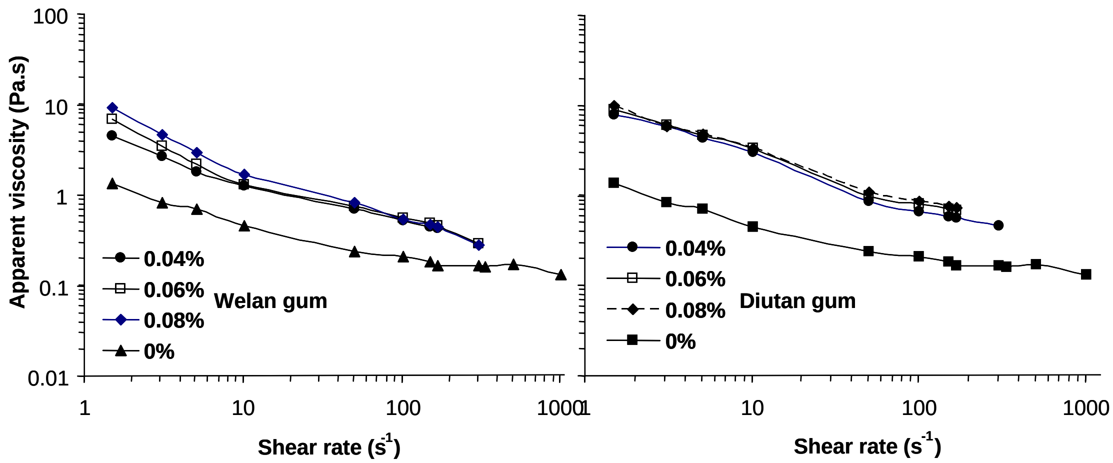

Fig. 1. Variations of Apparent Viscosity with Shear Rate of Welan Gum and Diutan Gum Grouts at Different % of VEA (100% C, SP = 1.4%

Effect of GGBS and dosage of VEA on the mini-slump

Figure 3 presents the results of mini-slump of mixes made with 20%, 30%, and 40% GGBS with various dosages of diutan gum and welan. For any given percentage of GGBS, the mixes made with low and medium dosage of VEA (0.02% and 0.04%, respectively) exhibited better fluidity with welan gum than the diutan gum. However, at 0.06% of VEA, it was observed that the mini-slump values of welan gum mixes were lower than those containing diutan gums. With mixes containing diutan gum or welan gum, the incorporation of GGBS enhanced the fluidity due to the improvement of packing density and lower hydration rate of GGBS to react. For example, for mixes made with 0.04% diutan gum and welan gum and 1% SP, the mini-slump of mixes containing 20% GGBS were 95 mm and 94 mm, respectively (vs. 88 mm and 81 mm for 100% C mixes).

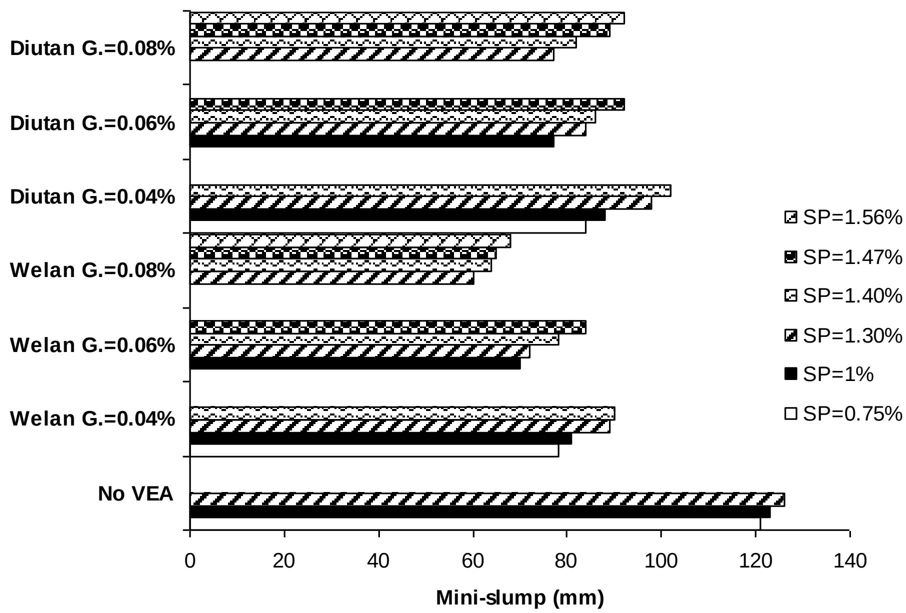

Fig. 2. Variations of Mini-Slump with % of Diutan and Welan Gum Mixes (100% C) with Various Combination of VEA-SP

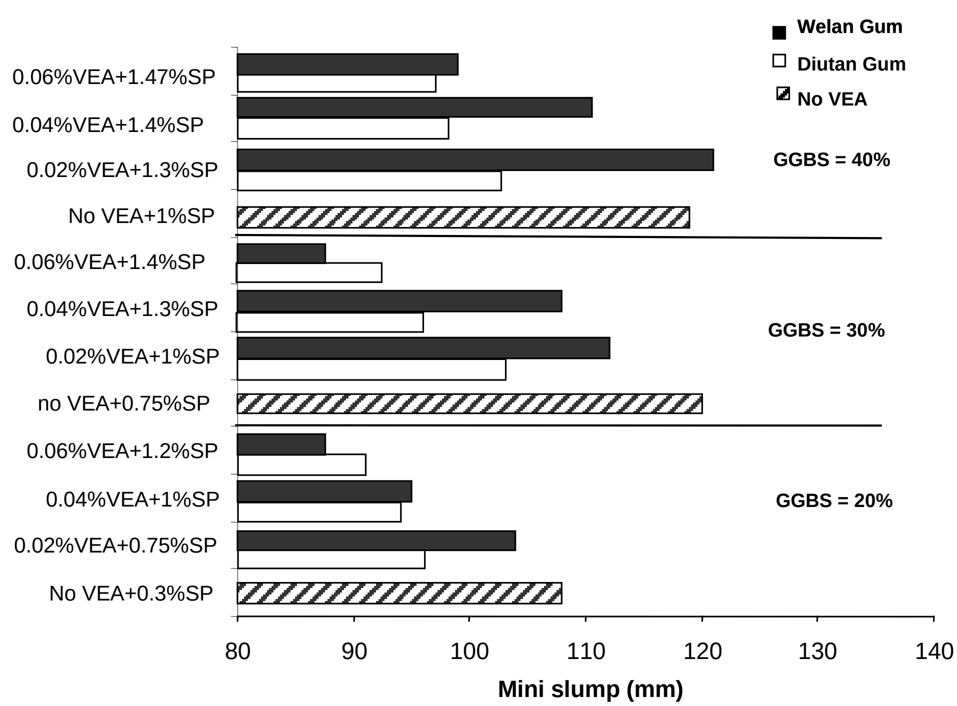

Fig. 3. Comparison of Mini Slump between Diutan Gum and Welan Gum for Mixes Containing 20%, 30% and 40% GGBS with Different Combination of VEA-SP

Effect of VEA and SP on the apparent viscosity at 5.1 s^{-1} of GGBS mixes

Figure 4 and Figure 5 present the influence of the dosages diutan gum and welan gum and SP on the apparent viscosity at low shear rate of 5.1 s^{-1} for mixes made with 100%C, 20% GGBS, 30% GGBS and 40% GGBS. The incorporation of GGBS led to a reduction of the apparent viscosity at low shear rate. The increase in the dosage of SP led to a reduction of the apparent viscosity for all mixes considered in this study. It was observed that the apparent viscosities at low shear rate of all mixes containing diutan gum and GGBS were higher than those made with welan gum. Similar observation was made for mix made only with OPC.

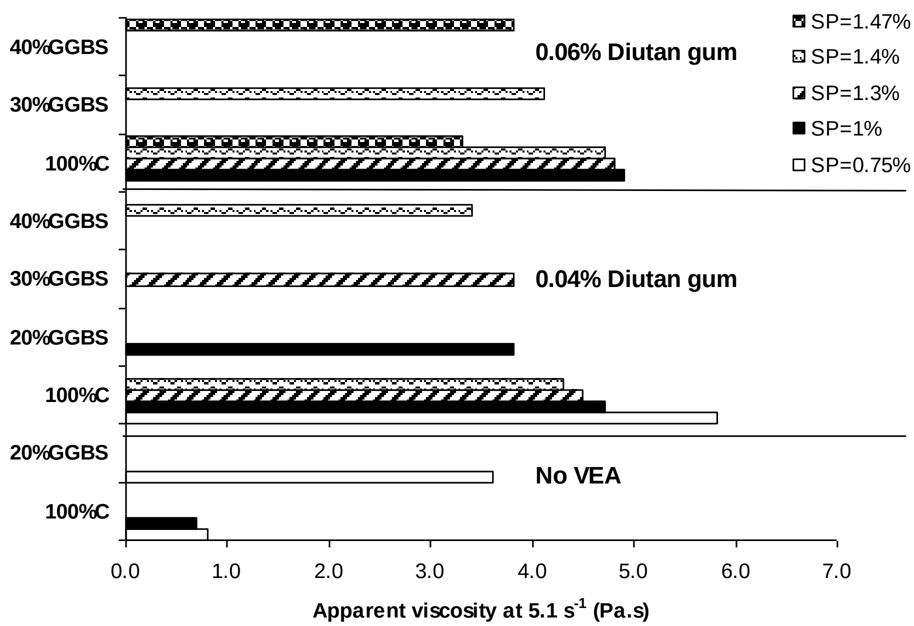

Fig. 4. Apparent Viscosity at Low Shear Rate of 5.1 s^{-1} with % Diutan Gum and % GGBS

Yield stress and plastic viscosity of mix made with 100% C and VEAs

The variations of yield stress and plastic viscosity of grouts made with 100% C and VEAs were shown in Figure 6 and Figure 7, respectively. For any given dosage of diutan gum or welan gum, the increase in the dosage of SP resulted in a reduction of yield stress and plastic viscosity due to the action of dispersion of SP by limiting or reducing agglomeration among the cement particles. Similarly for no VEA mix, the increase in the dosage of SP led to a reduction of the rheological parameters. For any given dosage of SP, the incorporation of VEAs (diutan gum or welan gum) resulted in a significant increase in yield stress and plastic viscosity.

It can be concluded that the rheological parameters of diutan gum mixes were higher that those of welan gum mixes, which due to the diutan's molecular weight and high pseudoplasticity. Higher molecular weight of diutan gum may lead to higher water retention [Pouchez et al., 2002]. The highest viscosity of diutan gum was reported in the literature [Phyfferoen et al., 2002]. Therefore, diutan gum required lower dosage than that of welan gum to achieve similar rheological characteristics.

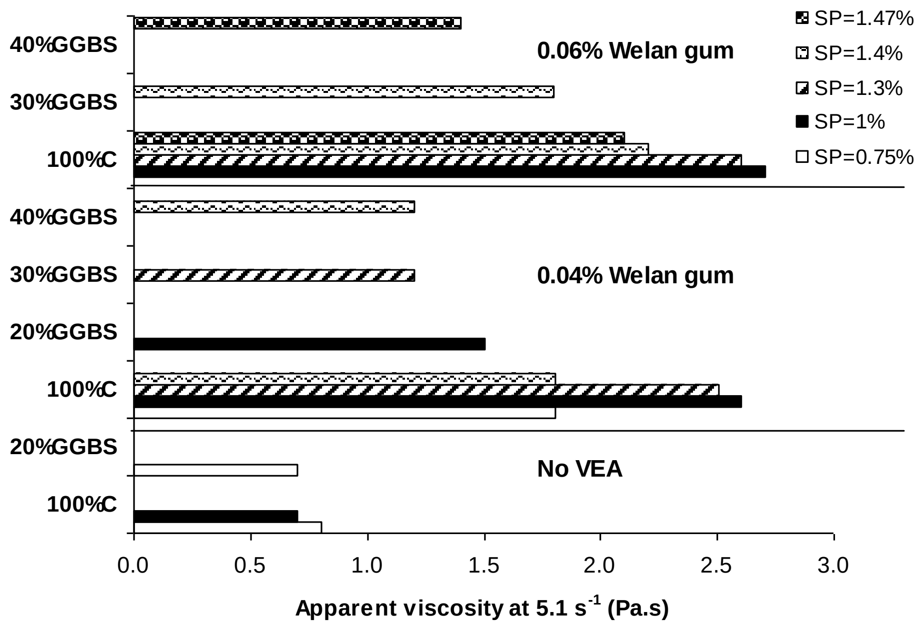

Fig. 5. Apparent Viscosity at Low Shear Rate of 5.1 s^{-1} with % Welan Gum and % GGBS

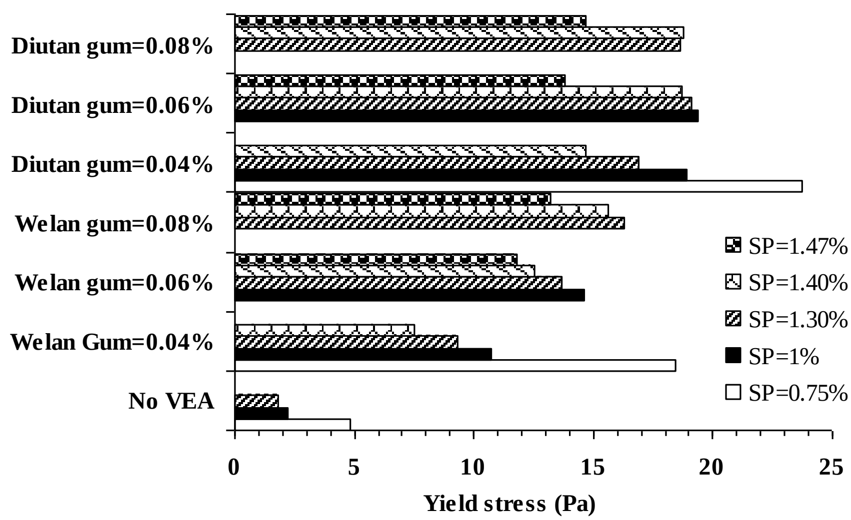

Fig. 6. Variation of Yield Stress of Cement Grout (100% C) with % of Diutan and Welan Gums & SP

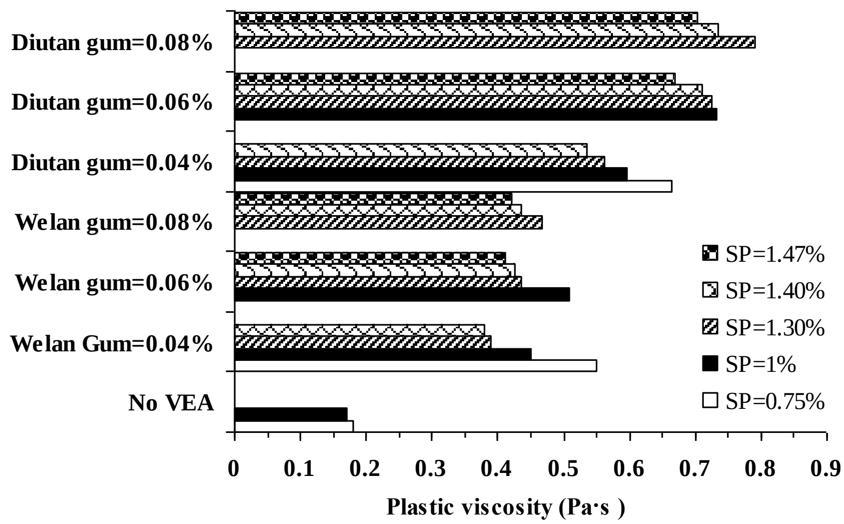

Fig. 7. Variation of Plastic Viscosity of 100% C mix vs. % of DG,WG & SP

Effect of GGBS on yield stress and plastic viscosity for both VEAs

The results of yield stress and plastic viscosity for diutan gum and welan gum grouts containing GGBS are compared in Figures 8 and 9, respectively. The use of GGBS led to reduction of yield stress for any given dosages of VEA and SP. As can be seen, the reduction of yield stress was more pronounced for mixes made with welan gum. These results confirm the data of the effect of the replacement of cement by GGBS in grouts made with welan gum on the reduction of the rheological parameters [Yahia et al., 2001]. GGBS had a higher specific area (460 m^2/kg vs. 385 m^2/kg for cement), lower average particle size (9.8 μm vs. 16.4 μm for cement), and lower hydration rate compared to cement. Therefore, GGBS particles led to fill into the spaces between larger particles of cement grains and reducing the room available for water. Consequently the water demand and also the friction forces between cement particles [Ferraris et al., 2001, Zhang & Han, 2000]. The combination of cement-GGBS system had lower hydration activity as it contained less cement and thus reducing the intercalation of SP, and resulted in higher workability of grout. The results from Figures 6, 7, 8 and 9 show that the incorporation of GGBS led to a reduction in the plastic viscosity compared to similar grout mixes made with 100% C for any given combination of VEA-SP.

For all mixes incorporating GGBS, the results showed that the diutan gum mixes exhibited high yield stress and plastic viscosity than those of the welan gum mixes for any combination of VEA-SP. This is confirms the previous conclusions regarding the mixes made only with OPC. For a fixed dosage of SP, adding diutan gum in the mixes containing 40% GGBS can increase the yield stress up 4.2 times in comparison to mixes made with similar dosage of welan gum. It was observed also that the increase of the yield stress for mixes containing diutan gum was more important for high incorporation of GGBS. For the range of VEAs between 0.02% to 0.06%, the yield stress of diutan gum mixes were 2.9 to 4.2 times for 40%GGBS mixes, 2.6 to 2.8 times for 30% GGBS mixes, and 1.5 to 3.5 times for 20% GGBS mixes, respectively, compared to similar mixes made with welan gum. For example, for a dosage of SP of 1.3% of 40% GGBS mixes, the introduction of 0.06% of diutan gum exhibited a plastic viscosity of 0.64 Pa.s compared to 0.60 Pa.s for similar mix made with welan gum.

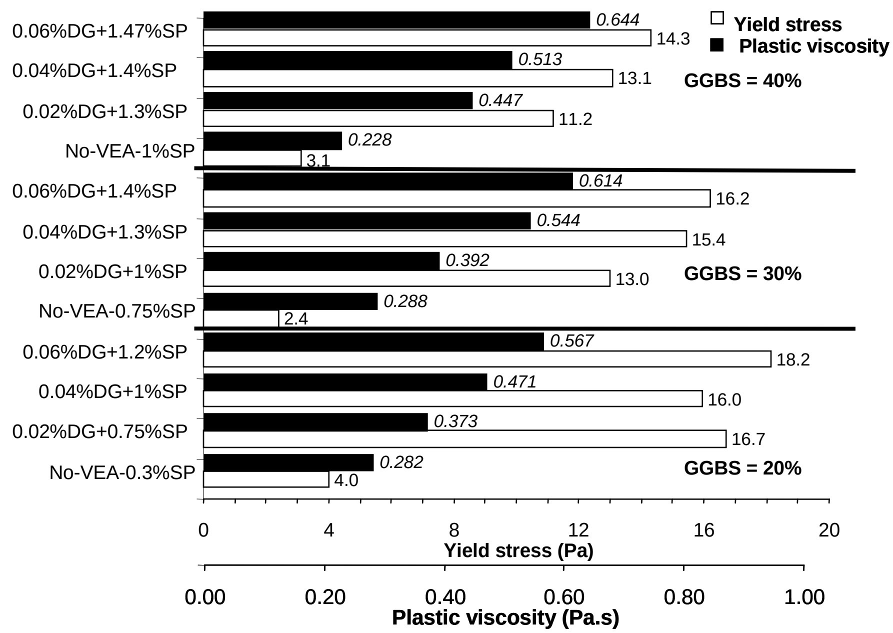

Fig. 8. Variation of Yield Stress and Plastic Viscosity with % of GGBS, and Dosages of Diutan Gum and SP (DG= Diutan gum)

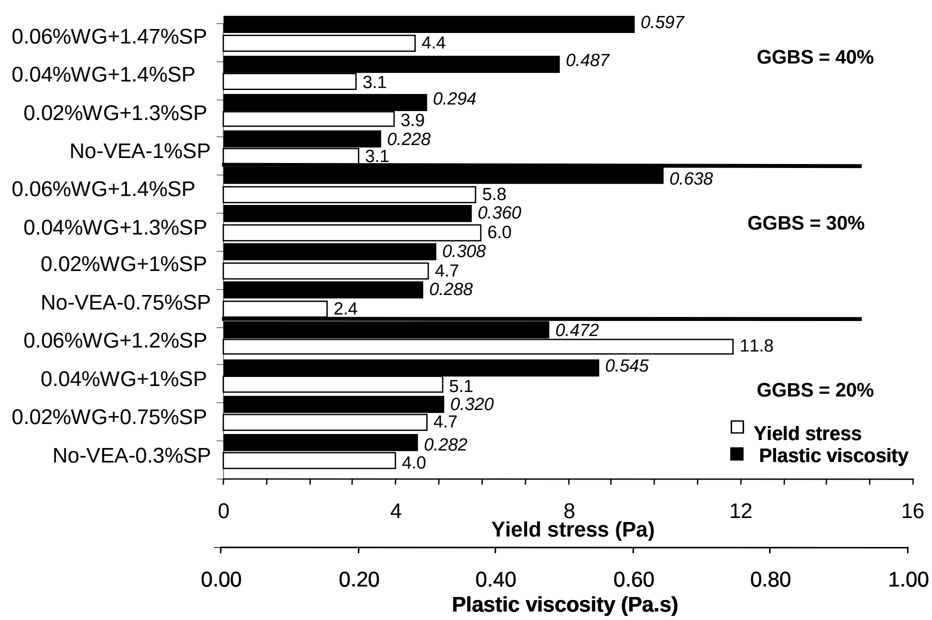

Fig. 9. Variations of Yield Stress and Plastic Viscosity with % of GGBS, and Dosages of Welan Gum and SP (WG= welan gum)

CONCLUSIONS

The following conclusions can be made on the rheological parameters and the fluidity of mixes made with diutan gum compared to similar ones made with welan gum and the effect of the replacement of cement by sustainable material by-product such as GGBS.

- Adding either diutan gum or welan gum led to an increase in the pseudoplastic behaviour and the increase in their dosage caused an increase in the shear thinning behaviour compared to similar mixes without VEAs;
- For any given dosage of VEAs, an increase in the dosage of SP resulted in an improvement of mini-slump by limiting or suppressing agglomeration of cement particles. On the contrary, for a fixed dosage of SP, an increase in the dosage of VEAs led to a significant reduction in fluidity by adsorbing and fixing part of mix water; and VEA polymers intertwining and entangling particularly at low shear rate.
- Greater viscosity at low shear rate and more pseudoplastic behaviour were observed for mixes made with diutan gum than those containing welan gum. At low shear, and especially at high concentrations, the polymer chains can intertwine and entangle, resulting in an increase in the apparent viscosity.
- For any given dosage of SP, the increase of the dosages of diutan gum or welan gum resulted in a significant increase in yield stress and plastic viscosity. Diutan gum mixes exhibited the highest yield stress and plastic viscosity. Therefore, similar rheological parameters can be secured with lower dosage of SP when diutan gum is used instead of welan gum. It is believed that the highest diutan's molecular weight led to a greater viscosity and greater water retention.
- The replacement of cement by 20%, 30% and 40% GGBS led to a reduction of yield stress for any given dosages of VEA and SP, which was more important for mixes containing welan gum. The GGBS mixes showed also a reduction of the plastic viscosity. This reduction can be attributed to lower hydration rate of GGBS to react and filling effect of GGBS which had lower average particles size than cement, thus resulting in a reduction of the friction forces between cement particles and less absorption of superplasticizer in the system (cement and GGBS). Adding diutan gum in GGBS mixes can increase the yield stress up to 4 times that of welan gum mixes, which was observed particularly with high replacement of GGBS (40%).

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