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Grout rheological properties for preplaced aggregate concrete production

A. I. Ganaw[1], D. C. Hughes[2] and A. F. Ashour[3]

Abstract

This paper investigates the effect of cement based grout rheology on the injection process through coarse aggregate for producing preplaced aggregate concrete (PAC). Four different sands were used in the grout production at different water-cement ratios and cement-sand ratios. Superplasticiers (SP) and pulverised fuel ash (Pfa) were also employed in the grout production. Coarse aggregate of known weight was compacted into 150mm cubic forms, and then the grout was injected through a plastic pipe under self weight into the stone skeleton. It has been found that there are threshold values of the rheological parameters beyond which full injection is not possible. In particular, all grout mixes with and without additives and admixtures exhibited the same yield stress threshold value for full injection, whereas the threshold values for other rheological properties including the grout plastic viscosity, flow time and speed were different according to the materials added to the mix.

Keywords: Concrete technology & manufacture, Grouting, Rheology, Workability, Bleeding, Admixture, preplaced aggregate concrete.

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Notations and abbreviations

g	=	Yield stress of grout
h	=	Plastic viscosity of grout
N	=	Speed of Viskomat
T	=	Torque of Viskomat
v_1	=	First grout level for bleeding test
v_w	=	Final grout level for bleeding test
W_b	=	Water bleed of grout
G/C	=	Weight ratio between injected grout to concrete produced
w/c	=	Water-cement ratio
c/s	=	Cement-sand ratio
PAC	=	Preplaced aggregate concrete
Pfa	=	Pulverised fuel ash
SP	=	Superplasticier

Introduction

Preplaced aggregate concrete (PAC) is produced by two-stages technique. In the first stage, coarse aggregate is placed into the forms to be concreted then, grouting the aggregate voids by high fluidity grout in the second stage (Neville, 1995; and Abdelgader, 1996). Consequently, it is the grout fluidity that underpins the quality of PAC.

Yahia and Khayat (2001) reported that the existence of yield stress can significantly influence the flow rate and filling-ability of non-Newtonian cement based grouts especially for mixtures placed without vibration. They added that the yield stress can also be used as an index of quality control of self levelling grouts. On the other hand, Swaddiwudhipong et al. (2002) reported that the ability of cement grout to penetrate voids of aggregate media, during the injection process of PAC production, is strongly dependent on its viscosity. They also showed that grout flowability can be judged by grout consistency measured by the flow cone test or flow table test but there is no relationship between grout consistency and viscosity.

According to Nowek et al. (2007) and Abdelgader and Elgalhud (2008), grout of high flow can be produced by mixing the main paste ingredients in a high shear mixer or normal mixer by adding mineral and chemical admixtures to improve grout properties. The use of mineral additives is to minimize bleed water and reduce the heat of hydration evolved. On the other hand, admixtures can serve various functions; for example, superplasticizers is to increase the grout flow-ability and expanding agents are used to achieve the required expansion before setting occurs (Neville, 1995; and ACI 304.1R, 1997). Because of the ability of current technology to produce a high strength stable grout of high durability, there is no need to use expansive agents in grouts for PAC as reported by Warner (2004).

Grout consistency for PAC can be measured as the discharge time of a given mix quantity from the flow cone (ASTM-C939-02, 2003; and Warner, 2004). However, if the grout is not fluid enough, the pressure gradient created by grout weight in the funnel of the flow cone is not sufficient to overcome the yield stress in the nozzle (Roussel and Roy, 2005). Similarly, Swaddiwudhipong et al., (2002) noticed that the efflux of cement grout in the flow cone test was not completed after 1 min and the flow stopped. However, the ACI 304.1R, (1997) recommends the use of the flow cone test to measure the grout consistency for PAC but only for grout flow time of 35 seconds or less. On the other hand, Tattersall and Banfill (1983) reported that the mortar consistency should be identified by two point tests in which the rheological properties can be measured, namely yield stress and plastic viscosity. Viskomat NT is capable of producing the flow curves of mortar with high accuracy and, from these curves, the rheological parameters can be predicted (Banfill, 1994 and 1995).

The purpose of this paper is to identify the rheology of grout with and without additives and admixtures that can fully penetrate among the stone skeleton to produce PAC. The flow cone test according to ASTM-C 939-02 (2003), induced bleeding test according to ASTM-C 940-89 (2003), and the Viskomat NT were used for testing the fresh grout properties. Grout penetration through compacted coarse aggregate for PAC production was investigated using all mixes.

Experimental Program

Materials

Portland cement (CEM1), grade 42.5 N was used in the production of cement grout. Drax pulverised fuel ash (Pfa) with loss of ignition of less than 7% was used as a cement replacement at 20%, producing composite cement classified as CEM II/A-V. Glenium C315 superplasticizer (SP) was added to the grout at 1% and 2%, that is a third generation SP based on modified poly-carboxylic ether, complies with EN934 part 2 and compatible with all types of cement (BASF, 2010). Four different types of natural sand (S1, S2, S3 and S4) with maximum aggregate size of 2mm are used as fine aggregate and their gradation curves of sands are shown in Figure 1. S2 is the finest and S1 is the coarsest, whereas S4 is single size aggregate used as a reference as presented in Figure 1.

PAC production is achieved by injecting the grout through coarse aggregate. Since coarse aggregate is in contact before and after grout injection, its selection is of great importance. Either crushed stone or natural gravel can be used in the production of PAC (Abdelgader, 1996; and ACI 304.1R, 1997). Moreover it should be durable and chemically stable aggregate; flaky and elongated stones are not preferred as they may create narrow channels, that defects the grout flow (Littlejohn, 1984). In addition, the maximum aggregate size of coarse aggregate should not exceed the third of the smallest dimension of concrete members to be casted. On the other hand, the smallest particle size of coarse aggregate is controlled by the maximum particle size of sand used in the grout production because the minimum coarse aggregate particle determines the channels through which grout passes (ACI 304.1R, 1997).

In the current investigation, rounded natural gravel of maximum aggregate size of 37.5mm was used as coarse aggregate. It is hard, clean from any impurities with water absorption of 0.017. Coarse aggregate gradation is in the range suggested by ACI 304.1R (1997) for PAC production as presented in Figure 2.

Mix proportions and grout testing procedure

Mix proportion

Grouts were first produced without any mineral and chemical admixtures at different water-cement (w/c) ratios by weight and at cement-sand (c/s) ratios of 1/0.9 and 1/0.6 by volume using S1, S2, S3 and S4. In the second phase of the testing, SP was added at 1% and 2% to all mixes and the effect of grout consistency on the injection threshold through the coarse aggregate voids was investigated. Finally, SP of 1% was employed and 20% of cement was replaced by Pfa. S4 was excluded from the lab work when SP employed because of the high segregation resulted. Although c/s ratios were chosen by volume to compare different sands, the quantity of sand required for mixing is converted to weight according to sand aerated density (Hu, 2005). Mix proportions for all grouts considered are presented in Table 1. The wide range of w/c ratio was employed to ensure suitable workability achieved without any mineral or chemical admixtures. Three c/s ratios of 1/0.6, 1/0.9 and 1/1.2 were initially tested, however, higher c/s ratio of 1/1.2 was eventually abandoned because of its stiff consistency and unsuitability for PAC.

Grout testing procedure

Grout was produced by mixing the constituents by Hobart mixer as follows. Water was put into the mixer bowl and the stop watch was operated. The cement was added into the bowl and the mixer was operated at low speed for 30 sec. After that, the sand was added gradually for about 30 sec during low speed mixing. The mixer was stopped after two minutes of mixing and any grout collected on the sides of the bowl was scrapped into the middle of the bowel. Finally, the mixer was operated at medium speed for three minutes.

Grout rheology

Viskomat NT was used to measure the rheological parameters of grouts**.** Flow curves can be plotted from the readings in the form of speed, N, against torque, T, and it is confirmed that grout flow obeys Bingham model as follow:

$$T = g + hN \tag{1}$$

where g and h are two material characteristics that are related to the yield stress and plastic viscosity, respectively (Tattersal and Banfill, 1983; Banfill, 1994; Banfill, 1995). g is the intercept of the flow curves with the torque axis, in Nmm; and h is the slope of flow curves, in Nmms, and will be used throughout the paper to reflect the rheological properties of mortars.

Bleeding test

The amount of excess water in grouts can adversely affect the concrete strength, and, therefore, it is important to measure the amount of bleed water at the grout surface. The grout is poured in quantities of about 800±10 ml into 1000ml graduated cylinder. The first grout level, v_1, is measured and the final reading, v_w, is taken after 3 hours (ASTM C 940-89, 2003). The water bleed, W_b, is calculated from:

$$W_b\% = \frac{v_w}{v_1} \times 100 \tag{2}$$

Flow cone test

Grout fluidity is defined by the required time in seconds to discharge 1725ml of grout from a standard funnel (ASTM-C 939-02, 2003).

Grout speed

Flow of a known volume of grout through a horizontal channel is one of the methods by which grout fluidity can be defined. In the flow meter test (ACI 304.1R, 1969), a quantity of 1.13 litres of grout is released to flow through an open scaled channel and the flow is defined by the distance of the grout transmission in cm.

Since the grout used in PAC production has to be highly flowable, colcrete flow channel of 700 mm length as recommended by ACI 304.1R (1969) is not sufficient to measure the grout fluidity. Consequently, to overcome the limitation of the channel length, the time required for the grout to reach a certain distance through the channel was recorded. For each grout the speed was then calculated by dividing the grout distance flow by the recorded time. This modification allows the measurement of fluidity of both high flow grouts and relatively stiff grouts that did not penetrate through the flow cone.

PAC specimen preparation

Coarse aggregate used was soaked in water for 24 hours to achieve full saturation. Then, it was washed with water to remove any dust and impurities which may decrease the injection rate or bond between aggregate and grout. After that, a solid plastic pipe of 20mm diameter and 2m height was inserted at the middle of the 150mm cubic mould. Following that, coarse aggregate was weighed and put into the mould around the pipe without any mechanical compaction or vibration (Warner 2004; Abdelgader 1999). Fresh grout was then poured through a funnel fixed at the upper end of the 2m plastic pipe and injected under gravity action into the stone skeleton as shown in Figure 3, similar to the method used by Abdelgader (1996 and 1999); Nowek et al. (2007); and Abdelgader and Elgalhud (2008). The head of grout in the pipe was kept constant throughout the process until full penetration. When grout flow through coarse aggregate stopped and grout covered all coarse aggregate, the pipe was gradually withdrawn. The volume occupied by the pipe was automatically filled with the grout released from inside the pipe during the withdrawal process. Finally, the surface was finished and concrete was left in moulds for 24 hours and weighed.

It was observed that the amount of grout penetration through coarse aggregate voids changes according to its consistency or rheology. High flow grouts easily penetrated through coarse aggregate. On the other hand, very low flow grouts did not even penetrate through the funnel and the pipe. Medium consistency grouts varied in the penetration rate where some grouts did not penetrate through the whole coarse aggregate mass. As the quantity of coarse aggregate in the mould was known, it was possible to calculate the quantity of grout injected after 24 hours of casting from the difference in weight of PAC and coarse aggregate. Grout inject-ability through coarse aggregate expressed as the weight ratio between the injected grout to the concrete produced (G/C).

Results and discussions

Effect of w/c ratio on grout injection

As grout flow increases with the increase in water content, it is worth studying the change in w/c on grout inject-ability through coarse aggregate as given below.

Effect of w/c ratio on injection process for non-admixture grouts

Effect of w/c ratio on grout injection for non-admixture grouts at c/s ratios of 1/0.9 and 1/0.6 is presented in Figures 4(a) and (b), respectively. G/C ratio increases with the increase in w/c ratio for both c/s ratios owing to the increase of grout fluidity and ability to pass through coarse aggregate. For the current experimental parameters including the void content of coarse aggregate and its degree of compaction, G/C ratio did not increase above 0.4 irrespective of the fluidity of the grout used, signifying the full injection point. The highest injection ratio was resulted from grouts produced from S4 sands and the lowest injection from grouts produced from S2 sand for the same w/c ratio, whereas grouts produced from S1 and S3 sands show close results.

Figure 4(a) shows that grouts of high sand content, c/s of 1/0.9, and medium water content result in partial injection and only high water content grouts at w/c of 0.6 show full injection. Figure 4(b) illustrates that grouts produced from S1, S3 and S4 sands at low sand content of c/s of 1/0.6 have full injection at w/c of 0.55 and 0.6 due to the high cement paste in grouts allowing easier movement because of the lower internal friction of sand particles. The grouts produced from the finest sand (S2) show full injection only at a high water content, w/c of 0.6 and low sand content of c/s ratio of 1/0.6 owing to the need of higher paste volume to cover its large surface area and to separate its particles. On the other hand, grouts produced from the coarsest sand (S4) show the highest inject-ability for both c/s ratios because of its lowest surface area, accompanied with higher particle separation and less internal friction which, of course, resulted in the lowest yield stress agreeing with previous investigations, for example Hu, (2005) and Ganaw et al. (2010).

Effect of w/c ratio on the injection process for 1% SP grouts

Because of the incomplete injection process for non admixture grouts, SP was employed at 1% dosage in order to improve grout workability especially at high sand and low water contents. Single size S4 was excluded from the lab work when SP employed because of the high grout segregation observed in this case.

Figures 4(c) and (d) show the relations between G/C and w/c ratio at c/s of 1/0.9 and 1/0.6, respectively. Higher injection was resulted from grouts produced from S1 and S3 sands where the lowest injection resulted from grouts produced from S2 sand in both cases of c/s ratios. Figure 4(c) indicates that full injection of grouts produced from S1 and S3 sands occurred at w/c ≥ 0.45, where full injection of grouts produced from S2 sand was achieved at w/c ≥ 0.55. Grouts of low sand content, c/s of 1/0.6, achieved full injection for all sands when w/c ≥ 0.4 as presented in Figure 4(d).

Effect of w/c ratio on injection process for 2% SP grouts

Grouts produced from S2 sand at c/s of 1/0.9 were not fluid enough to be injected at w/c of 0.5 as presented in the previous section; it is of interest investigating the effect of increasing SP dosage to 2% on the grout injection, as this is the maximum dosage recommended by the SP manufacturer (BASF, 2010). Relations between G/C and w/c ratio for grouts with 2% SP are illustrated in Figures 4(e) for c/s of 1/0.9 and (f) for c/s of 1/0.6. Figure 4(e) shows that full injection of grouts produced from S1 and S3 sands occurred at w/c ≥ 0.45, but grouts produced from S2 sand achieved full injection at w/c ≥ 0.5. Comparing results in Figure 4(c) and 4(e) indicate that the increase in SP from 1% to 2% achieved little injectability improvement for grouts produced from S2 sand. Figure 4(f) shows that grouts produced from S2 and S3 sands at c/s of 1/0.6 were fully injected at w/c ≥ 0.4, similar to 1% SP grouts. Grouts produced from S1 sand at c/s of 1/0.6 and w/c of 0.4 resulted in low injection due to the effect of high SP percentage at low sand content. In addition, S1 contains many large particles which may settle quickly owing to the segregation and, consequently, blocking the grout flow through coarse aggregate.

Effect of w/c ratio on injection process for 1% SP and 20% Pfa grouts

Little improvement in the grout injection has been achieved by using 2% SP at c/s of 1/0.9, for example grouts produced from S2 sand, and was also accompanied by aggregate segregation especially for grouts produced from S1 sand at c/s of 1/0.6. Similarly, Jefferis and Sarandilly (1988) reported that superplasticisers in self leveling systems may result in particle segregation and this problem may be avoided by the addition of fines, which improves cohesion. Consequently, it was beneficial to investigate the effect of another material such as Pfa on grout workability and its injectability through the coarse aggregate mass. Pfa was also employed in the production of PAC grouts in previous investigations (Abdelgader, 1996; Littlejohn, 1984; Neville 1995). Khayat et al. (2008) reported that a proper replacement of cement by additives can lead to higher packing density of fine powder, reducing the inter-particle friction. They also concluded that a partial replacement of cement by 20 to 30% fly ash in presence of SP can increase the plastic viscosity from 48 to 135 % compared with the reference grout. Moreover, fly ash of 20% of cement weight was employed in self consolidated mortars by Sonebi (2001), and Rizwan and Bier (2009 and 2012). Therefore, SP of 1% with Pfa at 20% of the cement weight replacement was employed in the current investigation.

Relations between G/C and w/c ratio at c/s of 1/0.9 and 1/0.6 are shown in Figures 4(g) and (h), respectively. Injection percentage increases with the increase in w/c ratio in both cases of c/s ratio. Figure 4(g) shows that the threshold injection ratio of grouts produced from S1 and S3 sands occurred at w/c ≥ 0.40, but that for grouts produced from S2 sand started from w/c=0.5, showing slight improvement compared with 1% SP grouts without Pfa presented in Figure 4(c). Figure 4(h) shows that full injection for grouts produced from S1 and S3 sands at c/s of 1/0.6 occurred at w/c of 0.35 and grouts produced from S2 sand at w/c of 0.4, lower than those presented in

Figure 4(d). Consequently, cement replacement of 20% with Pfa can improve grout injection for both cases of sand contents as grout fully injected at lower w/c ratios.

Effect of grout rheology on the injection process

Effect of yield stress on the injection process

The relation between G/C ratio and grout yield stress, g, for all grouts is shown in Figure 5. A yield stress threshold in the range of about (6-7) Nmm in the injection process can be identified for all grouts. Moreover, grouts having g values larger than 7 Nmm are no longer injected through the whole mass of coarse aggregate. It is of interest to observe that the grout yield stress, g, showed the same threshold for full injection despite the difference of materials used. As a result, yield stress property can be relied on in the grout injection process in the production of PAC agreeing with Yahia and Khayat (2001) as presented previously in the literature.

Effect of grout plastic viscosity on the injection process

The relations between G/C ratio and grout viscosity, h, for all grouts are presented in Figure 6. Mixes without any chemical and mineral admixtures showed different full injection threshold at around 2 Nmms whereas other mixes exhibited higher injection threshold between 5 and 6 Nmms for SP grouts only and 6.5 Nmms when Pfa employed at 20% with 1% SP.

The high h threshold value at which full injection occurred in the presence of SP can be attributed to the ability of grouts to fill up aggregate voids because of the higher grout cohesion. In other words, the self levelling behaviour of grout at higher viscosity has the ability to fill the voids. Grouts contain Pfa show slightly higher threshold than others due to the higher cohesion resulted. The higher cohesion is attributed to the addition of Pfa in the presence of SP as reported by Jefferis and Sarandilly (1988) which can be certified also to the ability of getting the required flow at low water content. It can be concluded that h threshold required for full injection differs according to whether chemical and mineral admixtures employed in the mix or not. This result is different from the yield stress where all mixes exhibited the same g threshold for full injection in spite of the difference in material added as presented in Figure 5.

Effect of grout flow time on the injection process

Relation between G/C ratio and flow time for all grouts is illustrated in Figure 7. Full injection threshold slightly changes with the variation of grout materials used. The lowest value of the flow time threshold occurred by grouts without SP at around 65 seconds. On the other hand, the highest threshold of around 90 seconds is resulted from 1% SP and 20% Pfa grouts, and grouts with only SP showed injection threshold at around 75 seconds. Although ACI 304.1R (1997) and Swaddiwudhipong (2002) suggested that the flow time for PAC should be less than 35 seconds, the results from this investigation show that it is possible to inject grouts for PAC with flow time up to 90 seconds depending on the admixture used in the mix. This difference may be attributed to the cut off measuring time of grout flow from flow cone orifice as this moment for SP grouts was not sharp. However, grouts without SP presented a threshold of around 65 sec, still far from the 35 sec suggested by the ACI 304.1R. Consequently, the sensitivity of the flow cone test is heavily relying on the grout viscosity and individual judgement.

It can be concluded that the effect of flow time of grout injection changes according to the materials added. Consequently, the identification of grout workability by only the flow time test is not enough for PAC production.

Effect of grout speed on the injection process

The effect of grout speed on G/C ratio is shown in Figure 8. As the speed of grout increases, the injection percentage increases to reach a certain threshold (around 10 m/sec) larger than which all grouts achieved full injection. The lowest threshold was achieved by grouts with 1% and Pfa where the highest one was achieved by grouts with 2% SP. Therefore, grout speed threshold differs according to the material type and dosage employed in the mix. As a result, grout injection threshold using different mixes cannot be defined only by grout speed test.

Relation between G/C ratio and water bleeding in grout

Water bleeding in grout is an important factor because of its effect on the resulting concrete properties. Excess water in grouts may be trapped underneath coarse aggregate and, consequently, weakens the bond in the tranzition zone between the hardened grout and coarse aggregate and that, of course, adversly affects concrete properties (Mehta, 1986).

The relation between grout water bleed and G/C ratio is investigated for all mixes as presented in Figure 9. Bearing in mind that the bleeding measurments were taken after 3 hrs from mixing (as explained earlier) and the injection was done immediately after mixing, however, it is possible to produce PAC with grouts of less than 5% bleeding as presented in Figure 9. Grouts with only 1% SP and grouts with 1% SP and 20% Pfa exhibited full injection at very low bleeding ratios of less than 1%. On the other hand, grouts with 2% SP were injected at high water bleeding and that will adversley affect on the resulting concrete properties.

Importance of grout yield stress for PAC production

It has been shown that the yield stress is the only grout property that can be used to define the threshold of full grout injection. It has the same threshold for all grouts regardless of all other factors such as material type or quantity used in the mix. Grout of yield stress of 7 Nmm and less was found to be fully inject-able through the voids of rounded coarse aggregate mass under gravity action from 2m head to cast 150 mm PAC cubes. It is of interest to the grout specifier or designer to know how to produce grout of yield stress of 7 Nmm or less from the grout mix proportion. Hu (2005) and Ganaw et al (2010) reported that grout yield stress is a function of cement paste yield stress and excess paste thickness. Consequently, by knowing the paste yield stress and excess paste thickness from different factors such as w/c ratio, c/s ratio, sand voidage and sand surface area, then it is possible to design the required grout yield stress which of course has to be less than a certain value (7 Nmm in the current investigation) to achieve full injection.

The effect of high pressure by the help of pumps on grout injection is suggested to be further investigated using grouts of different rheological properties. Consequently, the relation between pressure and rheological properties of grout and G/C ratio can be clarified for large scale concreting of PAC.

Conclusions

The effect of fresh grout rheology on the threshold injection through coarse aggregate in the production of PAC was investigated for four types of sands. Different water and sand contents in the mix were used with and without chemical and mineral admixtures. The degree of grout workability required for full injection was identified by measuring grout rheological properties such as, yield stress, plastic viscosity, flow time and speed. However, many other factors affecting the experimental outcomes such as shape and compaction of coarse aggregates are not covered in the current investigation. The main conclusions drawn from the above investigation are summarised below:

- Water increase in grout improved its inject-ability through coarse aggregate and that also noticed by employing SP and Pfa.
- Increasing sand quantity from c/s ratio of 1/0.6 to 1/0.9 adversely affected grout inject-ability, especially for mixes with no SP at the same w/c ratio.
- The finest sand grouts resulted in lower injection at the same water content because of the need for more cement paste to cover the larger surface area of sand and overcome the higher yield stress of grout.
- Grouts with 1% SP and 20% Pfa were fully injected at very low bleeding rates, following that grouts containing only 1% SP and finally grouts with 2% SP injected at high bleed rates. Therefore, PAC is better produced by injecting grouts with 1% SP and 20% Pfa because of low water bleeding, consequently ensuring lower volume of voids between grout and coarse aggregate.
- Grout yield stress results showed the same threshold to achieve full injection through the coarse aggregate for all mixes, in spite of the difference in ingredients and materials used. However, the value of grout viscosity required for full injection differs according to whether chemical and mineral admixtures employed in the mix or not. As a result, yield stress parameter can be considered as a main indicator for grout injectability in the design of PAC.

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List of Table Captions

List of Figure Captions

Table 1 Mix proportion for all grouts considered.

	S1 sand		S2 sand		S3 sand		S4 sand		Additives & Admixtures
	c/s= 1/0.9	c/s= 1/0.6	c/s= 1/0.9	c/s= 1/0.6	c/s= 1/0.9	c/s= 1/0.6	c/s= 1/0.9	c/s= 1/0.6	
w/c	0.60, 0.55	0.60, 0.55, 0.50, 0.49, 0.48, 0.47	0.60	0.60, 0.56, 0.55, 0.54, 0.52, 0.50	0.60, 0.55	0.60, 0.55, 0.50, 0.47	0.60, 0.55, 0.50	0.60, 0.55, 0.50, 0.45, 0.40	None
w/c	0.60, 0.55, 0.50, 0.49, 0.47, 0.45, 0.40	0.40, 0.37, 0.35	0.60, 0.55, 0.50	0.45, 0.42, 0.40, 0.37, 0.35	0.50, 0.45, 0.42, 0.40	0.40, 0.37, 0.35	N/A	N/A	1% SP
w/c	0.60, 0.55, 0.50, 0.45, 0.40, 0.35	0.50, 0.45, 0.40, 0.35, 0.30	0.60, 0.55, 0.50, 0.45, 0.40	0.50, 0.45, 0.40, 0.35	0.60, 0.55, 0.50, 0.45, 0.40, 0.35	0.50, 0.45, 0.40, 0.35, 0.30	N/A	N/A	2% SP
w/c	0.50, 0.45, 0.40, 0.35	0.45, 0.40, 0.35, 0.30	0.60, 0.55, 0.50, 0.45	0.50, 0.45, 0.40, 0.35	0.50, 0.45, 0.40, 0.35	0.45, 0.40, 0.35, 0.30	N/A	N/A	1% SP + 20% Pfa

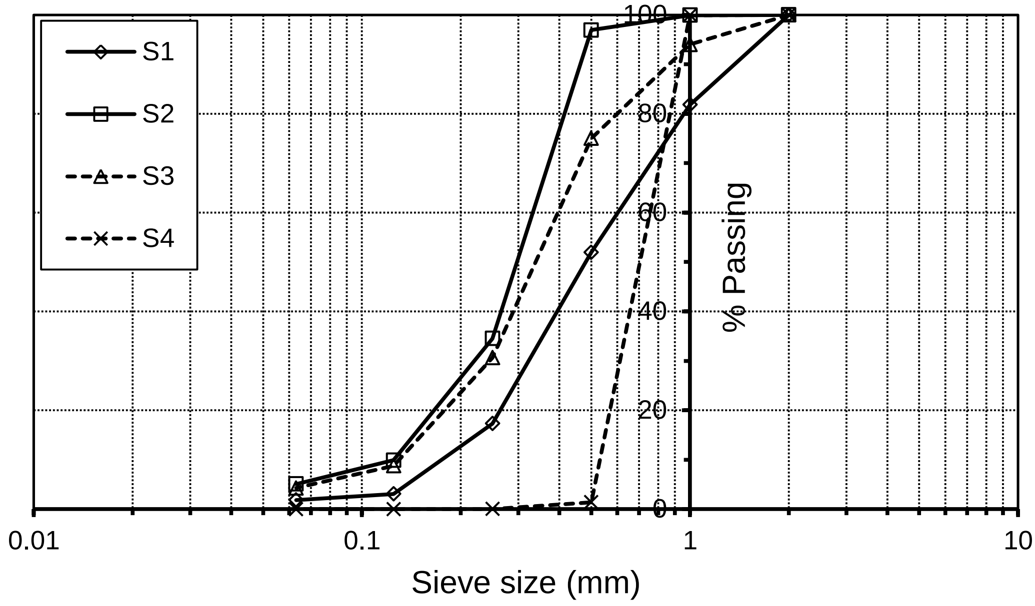


Figure 1 Sand gradation.

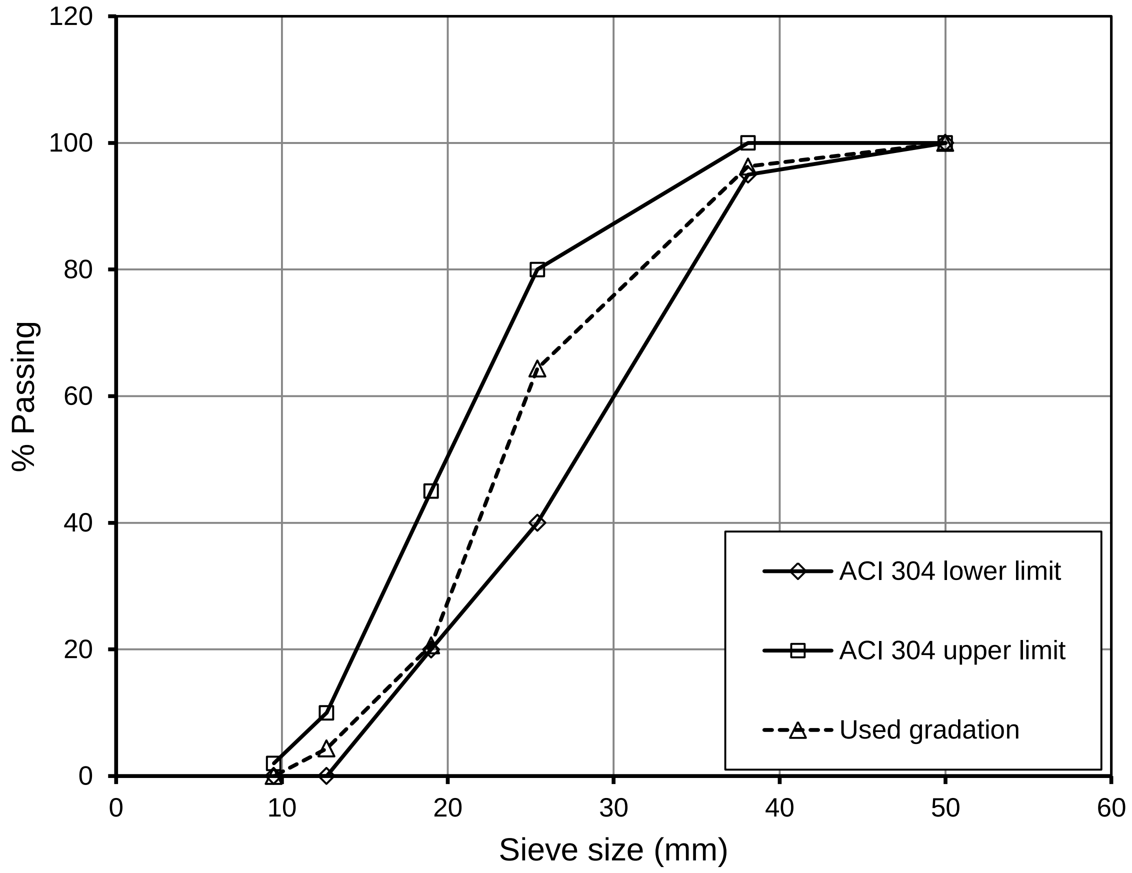


Figure 2 Coarse aggregate gradations and ACI 304 gradation limitations.

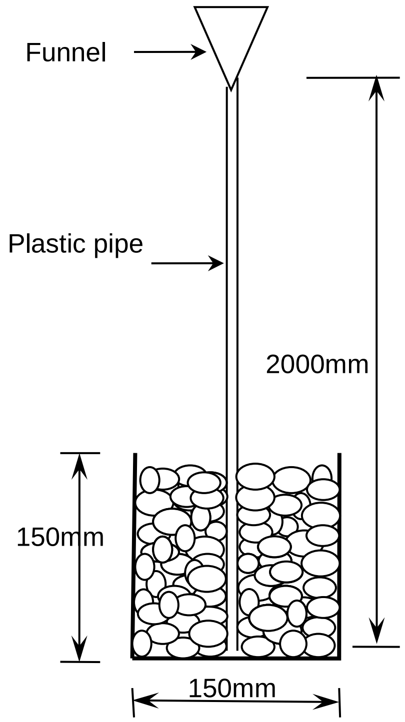
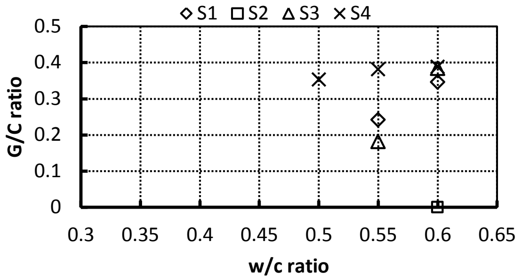
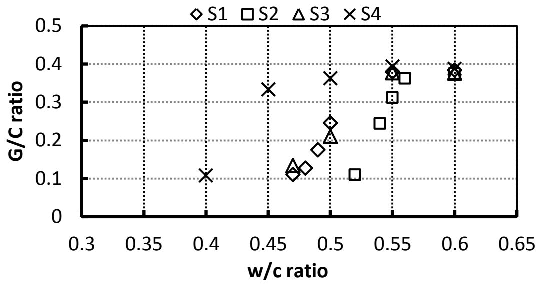


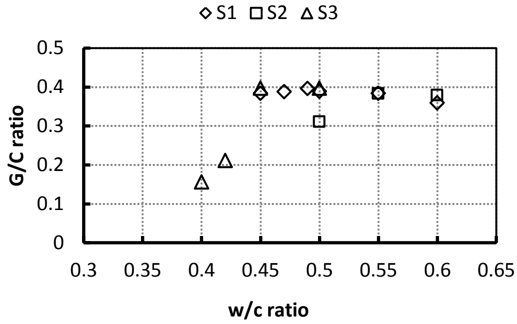
Figure 3 Compacted coarse aggregate in the form ready for grouting.



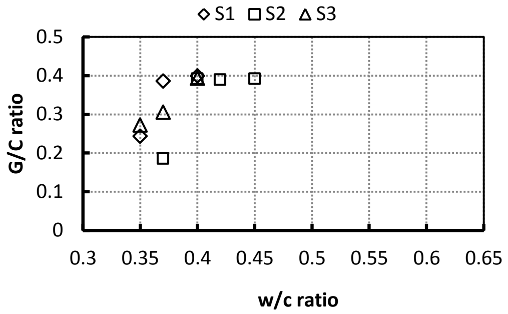
(a) c/s of 1/0.9 for non admixture grouts



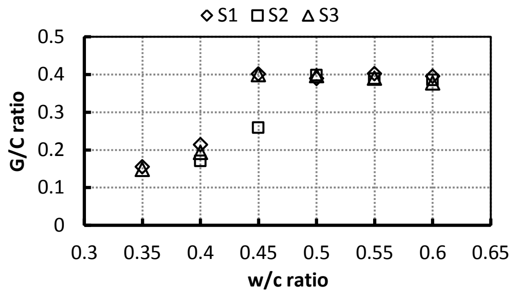
(b) c/s of 1/0.6 for non admixture grouts



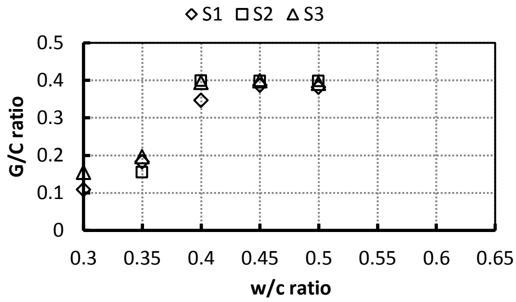
(c) c/s of 1/0.9 for 1% SP grouts



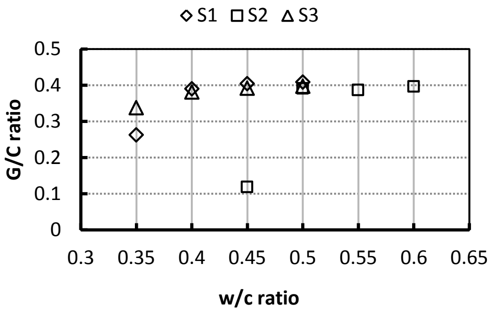
(d) c/s of 1/0.6 for 1% SP grouts



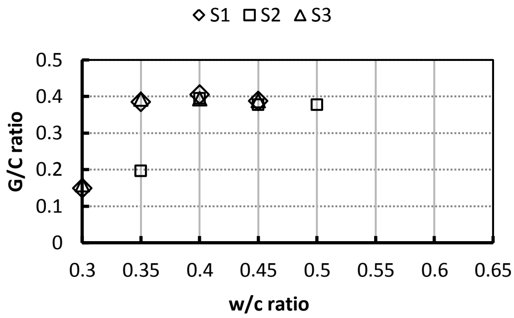
(e) c/s of 1/0.9 for 2% SP grouts



(f) c/s of 1/0.6 for 2% SP grouts



(g) c/s of 1/0.9 for 1 % SP and 20% Pfa grouts



(h) c/s of 1/0.6 for 1 % SP and 20% Pfa grouts

Figure 4 G/C ratio vs. w/c for all grouts.

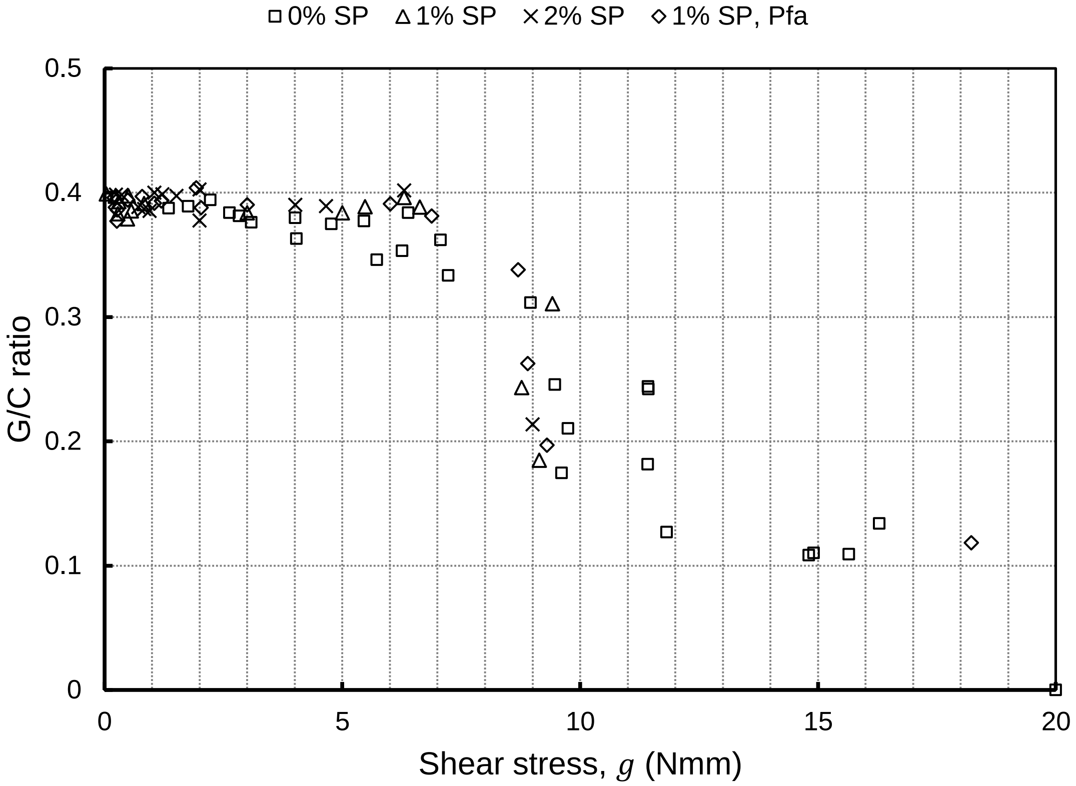


Figure 5 G/C ratio vs. yield stress for all grouts.

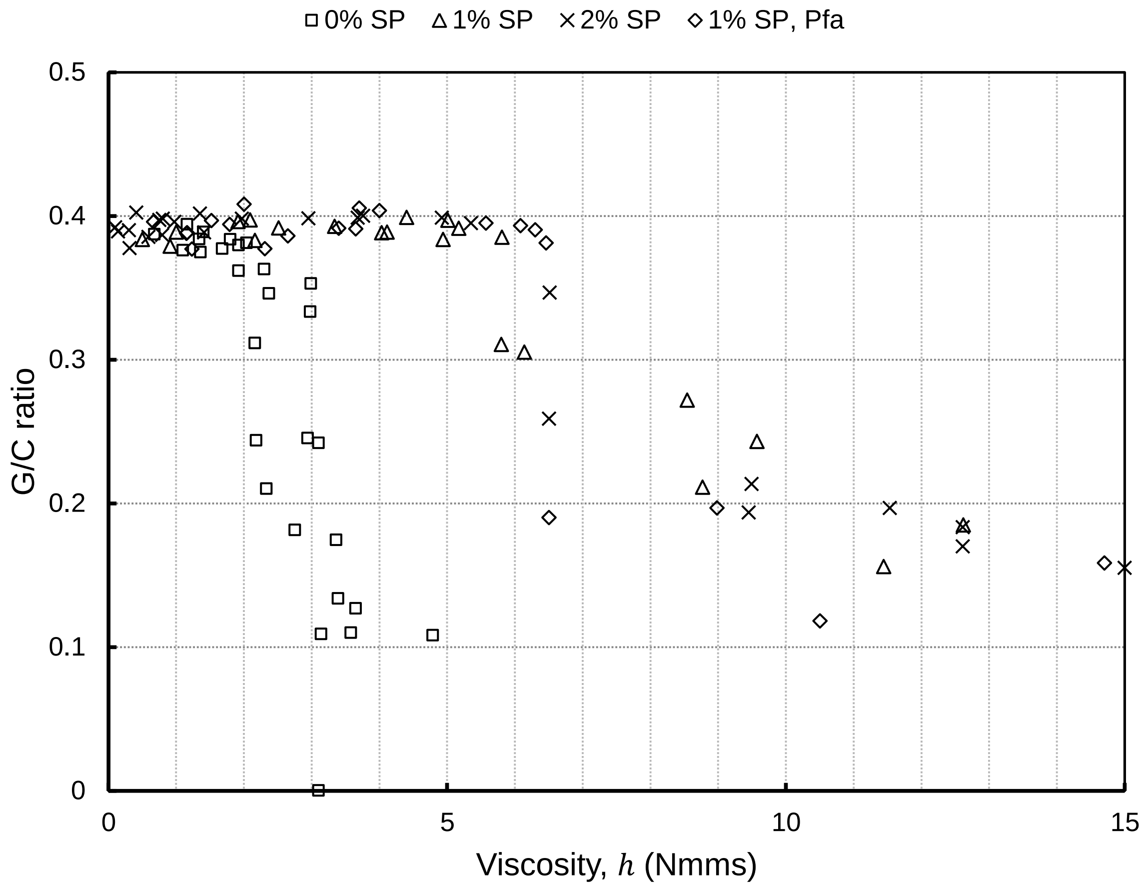


Figure 6 G/C ratio vs. plastic viscosity for all mixes.

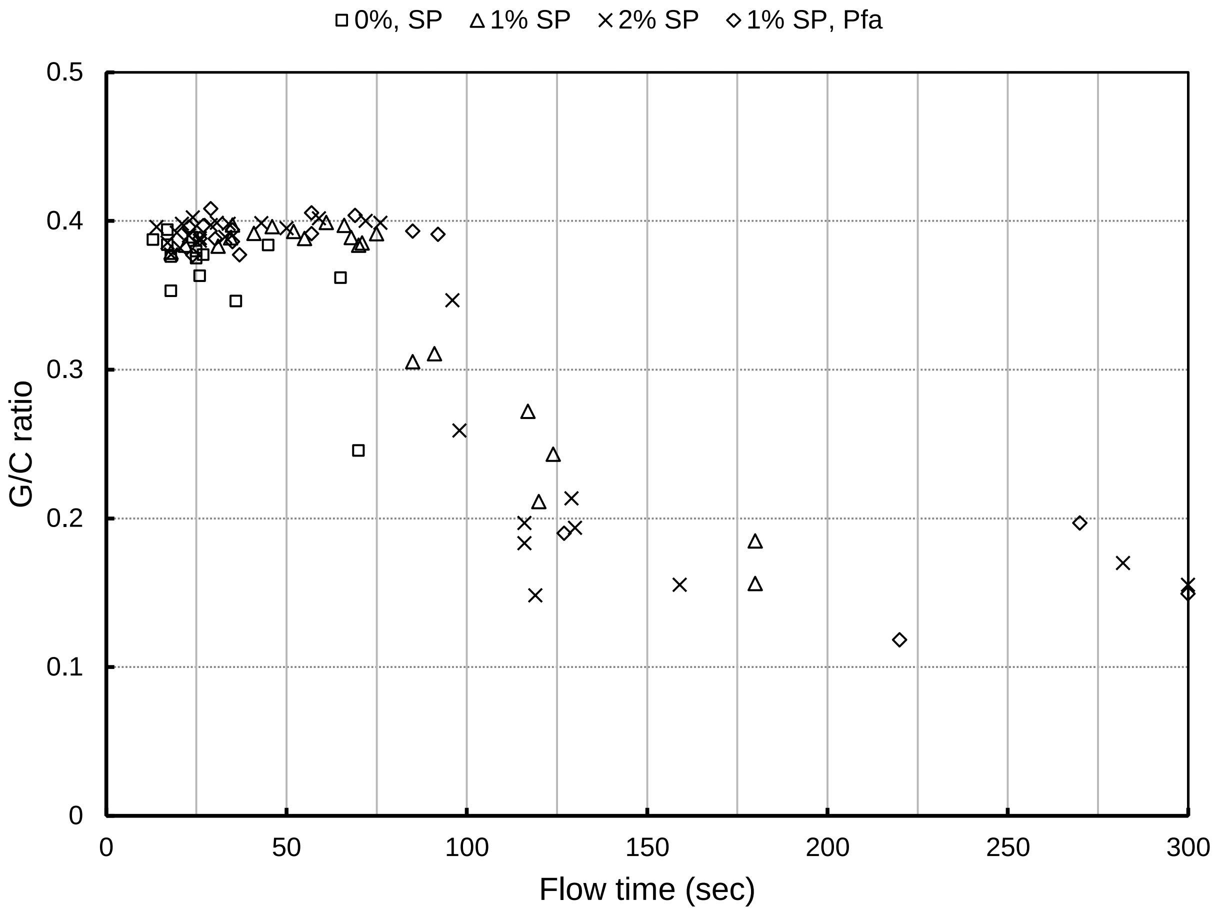


Figure 7 G/C vs. flow time for all grouts.

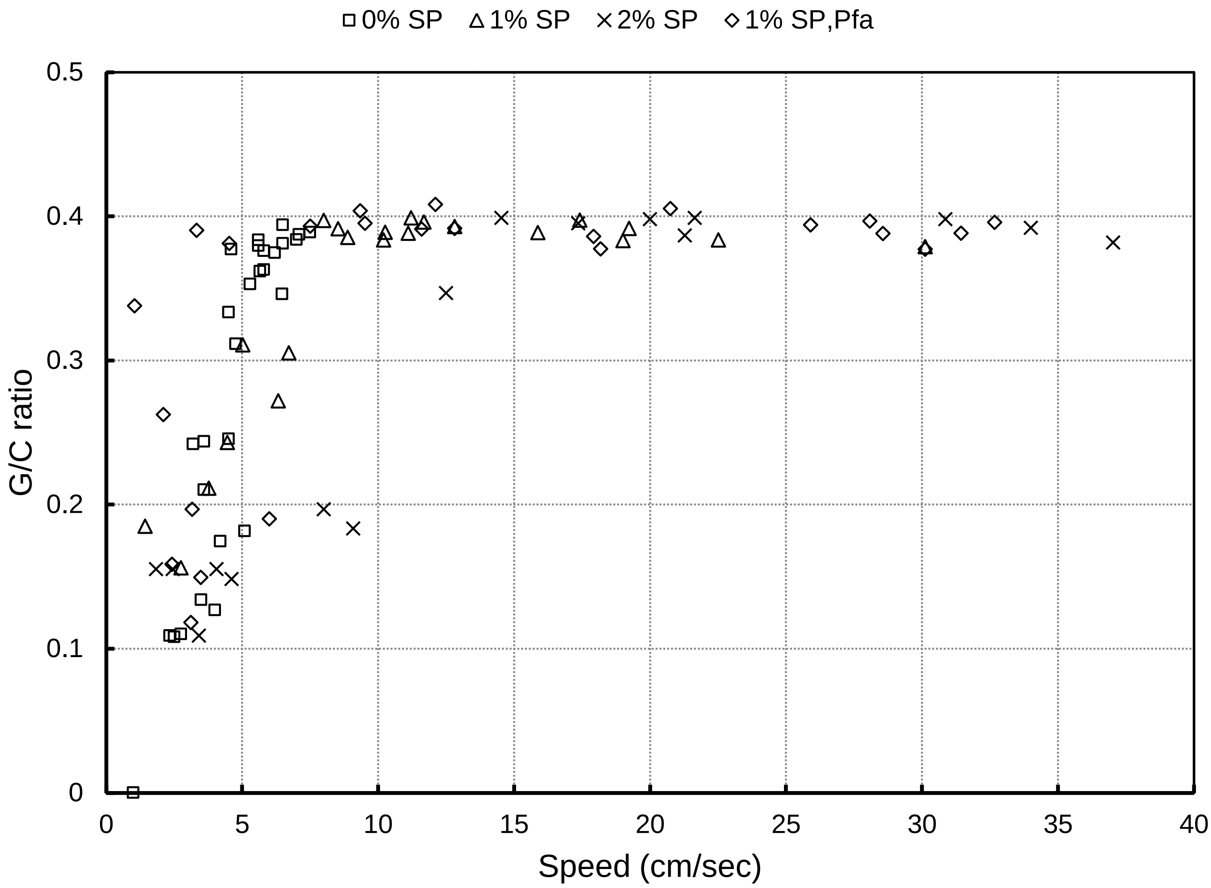


Figure 8 G/C vs. speed for all grouts.

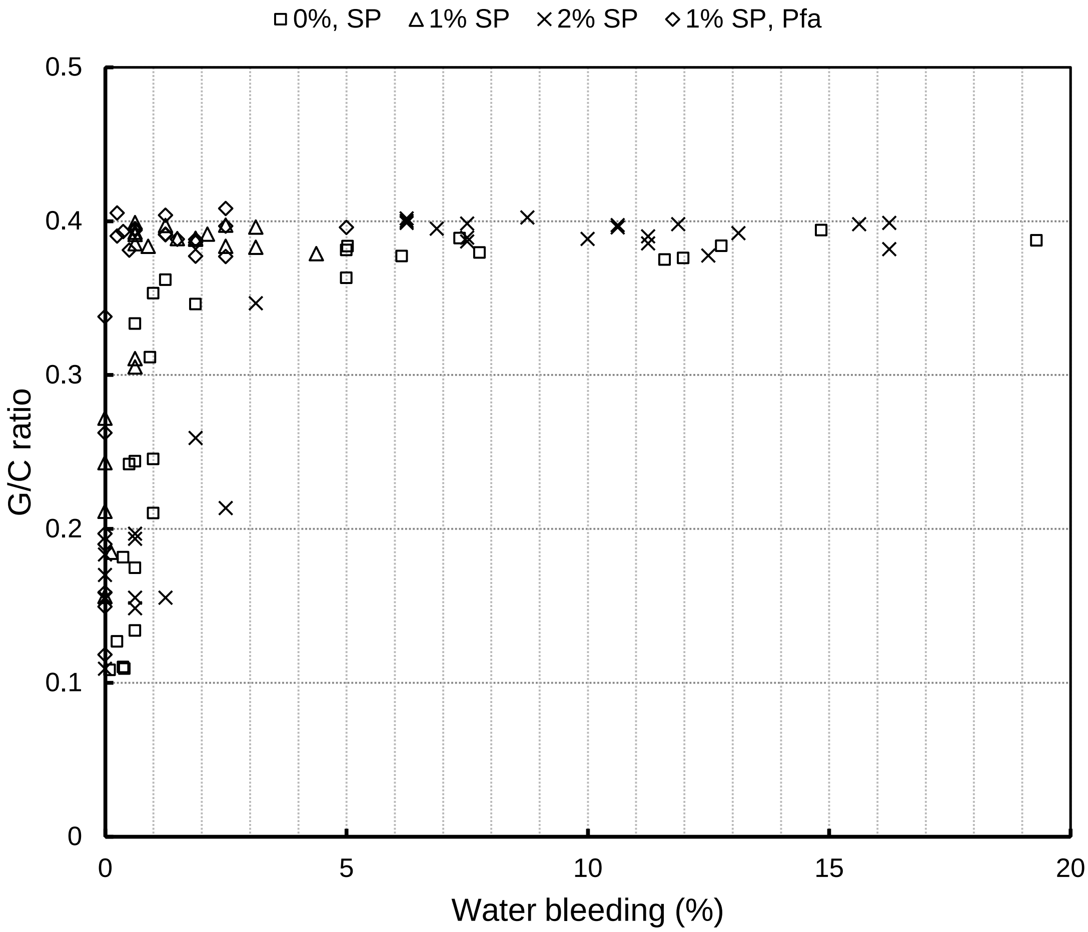


Figure 9 G/C ratio vs. water bleeding percentage for all mixes.