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Rheological properties of mortars prepared with different sands

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Biography:

Abdelhamed Ganaw is a lecturer at Alkhums University, Alkhums, Libya. He received his BSc and MSc in civil Engineering from Tripoli University, Libya and his PhD from University of Bradford, UK. His research interest includes high workability mortars using super-plasticisers and fly ash and their effect on the production of preplaced aggregate concrete, and concreting in hot environment.

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Abstract

The principal aim of this paper is to investigate the effect of sand grading, surface morphology and content on the rheological properties, i.e., yield stress and plastic viscosity of fresh mortar. Mortars were produced from four different types of sand, at two volumetric cement-sand ratios of 1/0.9 and 1/0.6. Each blend was prepared with five water-cement ratios of 0.60, 0.55, 0.50, 0.45 and 0.40. The rheometer, Viskomat NT, was used to determine yield

stress and plastic viscosity parameters of each cement paste and mortar. Test results show that the relative yield stress and plastic viscosity of mortar to cement paste is inversely proportional to the excess paste thickness up to low values below which the surface texture of sand particles becomes significant.

Introduction

High flowability of fresh concrete is needed in modern concrete technology, such as in self-compacting concrete where no compaction is employed upon cast works and in pre-placed aggregate concrete where mortar must develop high flowability filling the voids between the coarse aggregate compacted mass without any vibration (Warner, 2004; Abdelgader, 1999). Erdogan et al. (2008) reported that, although the flow characteristics of fresh concrete are usually identified by its workability properties, it still lacks an accurate quantitative basis. Hence, rheology, that is the science of the deformation and flow of matter in the form of relationships between stresses, strains and time, has been recently introduced to tackle this problem. Tattersall (1991) reported that, for full understanding of material flowability characteristics, both yield stress and viscosity are important parameters to be identified as some materials may have the same yield stress but different viscosity or vice versa.

Few investigations were conducted so far under the study of the effects of physical properties of sand on mortar rheology (Banfill, 1994; Westerholm et al., 2008; Donza et al., 2002; Hu, 2005; Cortes et al., 2008). Banfill (1994) and Westerholm et al. (2008) concluded that an increase of sand fineness increases both yield stress and plastic viscosity of mortar because of both the high inter-particle friction and particle shape of crushed sand. Sand gradation has also an effect on mortar flow; well graded sand mortars exhibited better flowability than others because of the lower un-compacted sand volume of voids (Hu, 2005). Moreover, the negative effect of poorly graded and shaped sands on mortar workability can be reduced or eliminated by increasing the paste volume (Westerholm et al., 2008). Similarly, Cortes et al. (2008) reported that a larger volume of paste is needed to achieve the required flow when angular crushed fine aggregates are used. The excess paste theory was employed for both fresh concrete and mortar (Kennedy, 1940; Nishibayashi al. 1996; and Oh et al., 1999) in which the cement paste in excess of the amount needed to fill up the voids between aggregate particles provides a thin film of paste which lubricates each aggregate particle and gives fresh mortar or concrete workability. Despite of the significant research conducted on the effect of sand properties on fresh mortar, the effect of sand surface texture on the rheological properties of mortar is still not clear and further research is needed in this area.

In the current investigation, the effect of grading, surface texture and sand content on mortar-paste relative rheological properties is investigated. A total of 40 mortar mixes were cast with four different types of sand, at two cement-sand ratios (in volume) and five water-cement (w/c) ratios. The rheometer (Viskomat NT) was used to determine yield stress and plastic viscosity parameters of cement paste and mortar. The relationships between the excess paste thickness and the relative rheological properties of mortar to cement paste were then assessed.

Research Significance

High flowability of fresh concrete is needed in modern concrete technology, such as in self-compacting concrete and pre-placed aggregate concrete. This paper investigates the effect of grading, surface morphology and content of sand as well as water/cement ratio on rheological properties of fresh mortar. The main finding of the investigation is that the relative yield stress and plastic viscosity of mortar to cement paste is inversely proportional to the excess paste thickness up to low values below which the surface texture of sand particles becomes significant.

Materials Used

Cement

Portland cement (CEM1), grade 42.5 N was used in the production of the cement pastes and mortar. Cement density was determined using the Hosakawa powder densometer. Three aerated cement samples of 100 cm^3 (6.1 in^3) volumes were weighed and the average cement density obtained was 870 kg/m^3 (54.31 lb/ft^3).

Sand

Four different types of natural rounded sand available in the UK market were used with maximum aggregate size of 2mm (0.079in) as fine aggregate; these were identified as S1, S2, S3 and S4. The Hosakawa powder densometer was also used to obtain the sand densities. Sand properties including un-compacted densities, specific gravity and absorption were all determined as explained below.

Sand gradation

Gradation curves of sands are shown in Figure 1. As shown in the figure, S2 is the finest and S1 is the coarsest, whereas S4 is single size aggregate used as a reference.

Sand absorption

Sand absorption was measured as an average of the results for three samples by the frying pan method (Neville, 1995). In this experiment, a fully saturated sand sample of about 150gm (0.33*lb*) was partially heated in a pan and stirred with spatula until the water evaporated from the surface; as soon as no sand adhered to the sides of the spatula, the sand surface was deemed to be dry and its inside still saturated. After that, the sample was weighed and left in an oven at 105^{o}c. After 24 hrs, sand was weighed again. The absorption is determined thus:

$$Absorption = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100 \quad (1)$$

where W_{SSD} is the weight of saturated sand with surface dry and W_{OD} is the weight of oven dry sand. Results obtained from Eq. (1) for the four sands are presented in Table 1, indicating that the highest water absorption sand is S2, whereas S4 exhibits the lowest absorption.

Sand specific gravity

Specific gravity of aggregate shown in Table 1 was measured by using the pycnometer; the pycnometer is one litre jar with a water tight metal conical screw top with a small hole at the apex which can be precisely filled with water having the same volume every time (Neville, 1995). 800 gm (1.6 *lb*) of oven dried sand was first prepared, then the pycnometer is filled with water and weighed as w_1. The pycnpmeter is then filled with the 800 gm (1.6 *lb*) of sand and topped with water and weighted as w_2. Specific gravity of sand can be calculated according to the following equation:

$$SG = \frac{800}{w_1 - w_2 + 800} \times 100 \quad (2)$$

As shown in Table 1, S4 has a slightly higher specific gravity than S1 and S3, whereas S2 shows the lowest specific gravity.

Void ratio of sand

Void ratio V of each sand was measured from its density and specific gravity according to the following equation:

$$V = \left(1 - \frac{\gamma}{SG}\right) \times 100 \quad (3)$$

where γ is the aerated sand density in (g/cm^3) and SG is the specific gravity of sand.

As presented in Table 1, S2 has the highest void ratio as it has the lowest aerated density and is the finest sand. On the other hand, S4 has the lowest void ratio owing to its highest aerated density.

Sand surface area

Sand surface area was calculated by summing up the surface area of each set of known size after sieving them. Sand particles were assumed as equivalent spheres having a diameter of the average of each two successive-sieves sizes and the surface area of one particle was then calculated. The number of sand particles in each set was calculated according to the weight retained on a certain sieve and the corresponding sand specific gravity. The surface area of each set is the number of particles multiplied by the surface area of one particle (Hu, 2005; Oh et al., 1999).

Table 1 indicates that S2 presented the highest surface area followed by S3, S1 and S4, respectively, showing good agreement with the results of sand gradation presented in Figure 1.

Mix proportions and mixing procedure

In this study, the effect of w/c ratio on the rheology of mortar and cement paste, and the effect of cement/sand (c/s) ratio on the rheology of mortar were examined. Forty mixes having w/c of 0.6, 0.55, 0.50, 0.45, and 0.40, and c/s of 1/0.9 and 1/0.6 for the four types of sand (S1, S2, S3 and S4) were studied. A wide range of w/c ratios was selected to ensure the achievement of suitable workability. Three c/s ratios of 1/0.6, 1/0.9 and 1/1.2 were initially tested, however, the higher c/s ratio of 1/1.2 was eventually abandoned because of its stiff consistency. Although c/s ratios were chosen by volume, the quantity of sand required for mixing was converted to weight according to their aerated density (Cortes et. al., 2008; Hu, 2005; Hu and Wang, 2007). All sands used were oven dried at 105°C for 24 hrs in order to get an oven dry sample (BS 812-109, 1990) for mortar mixing. The amount of water required for absorption was added to the water required for hydration.

Mixing of cement paste and mortar was carried out by Hobart mixer for five minutes. Mortar was mixed by adding water and cement into the mixer bowl and mixed at low speed for 30 sec. Afterwards, sand was gradually added in about 30 sec during low speed mixing. The mixer was stopped after two minutes of mixing. Finally, the mixer was operated at high speed for another three minutes.

Cement paste rheology test results

The rheometer, Viskomat NT, was used to measure the rheological parameters of cement paste and mortar. The instrument is a stress controlled device operated by computer software. Yield stress and plastic viscosity parameters of the paste and mortar with maximum particle size of 2 mm can be calculated by measuring the recorded torque at different rotating speeds (Scheibinger Gerate Viskomat NT, 2007; Banfill, 1994).

Cement pastes were produced with w/c ratios of 0.6, 0.55, 0.50, 0.45 and 0.40, and their rheological parameters were calculated from the relations torque vs. rotting speed as presented in Figure 2. The applied torque for the cement paste was significantly affected by the change of water content; as the w/c ratio increases from 0.4 to 0.6, the applied torque decreases at the same rotating speed as depicted in Figure 2, indicating that the rheometer blades are less resisted by the cement paste. This is consistent with the flowability concept in which an increase of water content increases the flow of both cement paste and mortar. In addition, the water increase creates softer paste as higher water content causes greater dispersion of cement particles. Similarly, Popovics (1982) and Hu (2005) reported that the liberation of cement particles increases by an increase in water content, leading to less yield stress and viscosity.

From the curves of the applied torque T against the rotating speed N presented in Figure 2, the paste conforms to the following equation:

$$T = g + hN \tag{4}$$

where g and h are two material characteristics that are related to the yield stress and plastic viscosity (Tattersall and Banfill, 1983; Banfill, 1990; Banfill, 1995). g is the intercept with the torque axis in (Nmm) and h is the slope of curves in (Nmms). Table 2 shows these two rheological constants of cement paste at different w/c ratios.

Effect of w/c ratio on paste rheological parameters

Regression analysis was employed to obtain the yield stress parameter (g) and plastic viscosity parameter (h) equations of cement paste as presented in Figures 3 and 4, respectively. As shown, the increasing w/c ratio reduces both g and h exponentially for all pastes, agreeing with other studies (Banfill, 1994; Tattersall, 1991; Wallevik and Wallevik, 1998; Hu, 2005). The reduction of g and h with the increase of water content is attributed to the liberation of cement particles and the consequent ease of cement particles movement.

Mortar rheology test results

For a better understanding of the effect of water contents and sand on mortar rheology, the effect of w/c and c/s ratios on mortar rheology was investigated and presented below.

Relation between mortar rheological parameters and w/c ratio

Figures 5, 6, 7 and 8 show the relations between mortar rheological constants and w/c ratio. It is clear that in both cases of c/s ratios, as the w/c ratio increases, *g* and *h* decrease for all mortars using different sands, which demonstrates good agreement with other investigations (Banfill, 1994; Hu, 2005). The reduction in mortar *g* and *h* is a reflection of the reduction in *g* and *h* of the cement paste as presented earlier. The highest rheological values were achieved by S2 mortars and the lowest values were observed for S4 at the same w/c ratio. The high rheological values of S2 mortars can be attributed to its largest void content which consumed more cement paste to fill up the space between sand particles as reported by Hu (2005). Banfill (1994) and Westerholm et al. (2007) found that an increase of sand fineness increases both yield stress and plastic viscosity as also observed in S2 sand in the current investigation which has the highest surface area as presented in Table 1. On the other hand, S4 shows the lowest rheological values because of its low surface area and void content. S1 and S3 mortars presented closer values in both cases of c/s ratios. Some mortars were too stiff, disallowing rheological properties to be measured by the rheometer as indicated in Table 3, for example S2 mortars at w/c of 0.45 and 0.40 through Figure 7 and Table 3.

The effect of sand content on mortar rheological properties can be seen in the comparison between c/s of 1/0.9 and c/s of 1/0.6 presented in Table 3. It is clear that the resulted *g* and *h* at high sand contents (i.e. 1/0.9 c/s) are larger than those of low sand content mixes (1/0.6 c/s) for the same sand type and w/c ratio. As higher amount of sand employed in mortar, internal particle friction and interlock increase, and consequently *g* and *h* increase as also reported by Hu (2005).

Relative mortar-paste rheology and excess paste thickness

From the relations between w/c ratio and mortar rheological parameters presented above, it was observed that, at a certain w/c ratio, g and h are different for different sand mortars. Therefore, there was a need to investigate another factor which causes this change.

Nishibayashi et al. (1996) reported that, in order to study the rheology of mortar, it is advantageous to consider the mortar as highly concentrated suspension where the suspended particles are the sand particles and the matrix is the cement paste. This phenomenon is consistent with the excess paste theory presented by Kennedy (1940) and Oh et. al. (1999). According to the excess paste theory, the consistency of mortar depends on the excess paste thickness and the paste property which is the rheology in this case. The need to find another factor than w/c ratio affecting mortar rheology using different sands led to the need to present the excess paste theory and apply it in this study as explained below.

Excess paste thickness

Cement paste in mortar can be divided into two parts; the first is used to fill up the sand voids whereas the second part (excess part) coats the sand surface and separates aggregate particles. The excess paste volume is responsible for mortar workability where a small thickness film of paste surrounds aggregate particles due to the excess paste. This film separates sand particles and is known as the excess paste thickness (Nishibayashi et.al., 1996; Oh et. al., 1999; Hu, 2005). In addition, as the paste thickness changes, the mortar rheological properties vary. Excess paste thickness can be calculated from the following equation (Nishibayashi et. al., 1996; Oh et. al., 1999):

$$t_p = \left(1 - 100\frac{V_s}{C_s}\right)\frac{10}{S_s V_s} \qquad (5)$$

where t_p is the thickness of excess paste in mm, C_s is the sand solid volume divided by its bulk volume (%), S_s is the specific surface area of aggregate (cm^2/cm^3) and V_s is the ratio of aggregate to mortar volumes.

<u>The sand packing has an effect on the rheological properties of mortar as the sand gradings are different as presented in Figure 1. If the packing density of sand is increased, the amount of paste needed to fill up the voids is reduced and consequently, there will be more excess paste to improve the rheological properties.</u> Therefore, in order to calculate the excess paste thickness in Eq. (5), there is a need to measure the volume of mortar as described below. A total of 40 mortar mixes similar to these considered above were prepared in small quantities; they were mixed by hand in polypropylene bags and care was taken not to lose any material. After 24 hours, mortar was taken from the bags and the volume of hardened mortar was then calculated from the difference between its weight in air and weight in water. As the sand weight was known, sand solid volume was calculated according to its specific gravity and, then, aggregate to mortar volume ratio V_s was calculated. Solid volume percentage C_s was calculated as $(1 - V)$, where V is the aerated sand void ratio, and specific surface area of sands is known as given in Table 1. Finally, excess paste thickness is calculated according to Eq. 5.

Effect of excess paste thickness on the relative rheological properties

The relation between excess paste thickness and rheological properties was performed for the 33 mixes as shown in Figures 9 and 10; the other 7 mixes were too stiff to be handled by the rheometer as given in Table 3. The relative rheological parameters, g and h, were calculated by dividing g and h of mortar by the corresponding values of paste (Nishibayashi et al., 1996; Oh et. al., 1999). Both relative rheological parameters decrease exponentially with the increase in cement paste thickness, consistent with Oh et al. (1999) and Nishibayashi et al.

(1996). Based on the presented graphs, regression analysis of data yields the following equations:

$$\text{Relative yield stress } G/g = 0.22t_p^{-1.17} \quad (6)$$

$$\text{Relative plastic viscosity } H/h = 0.68t_p^{-0.5} \quad (7)$$

where G and g are the yield stresses of mortar and paste, respectively, H and h are the plastic viscosities of mortar and paste, respectively and t_p is the excess paste thickness in (*mm*).

Although the trend in Figures 9 and 10 show that both relative yield stress and plastic viscosity decrease with the increase in excess paste thickness, it seems that, for a given sand type and c/s ratio, the relative yield stress slightly decreases with the decrease in t_p. Similarly, the relative plastic viscosity at c/s of 1/0.9 decreases with the decrease in t_p. Therefore, it was decided to further investigate a better relation between the rheological parameters for mortar, paste and the excess paste thickness.

Non-linear statistical regression analysis was performed to develop more conclusive relationships between the rheological properties of mortar and paste. The inputs are the paste rheological values and excess paste thickness and the output is the mortar rheological values. Non-linear relations between mortar and paste rheological parameters and excess paste thickness were obtained and presented below:

$$G = 0.27g^{0.63}t_p^{-1.17} \quad (8)$$

$$H = 0.68h^{0.78}t_p^{-0.5} \quad (9)$$

The relationships are statistically significant with correlation coeffiecients (R^2) of 0.93 and 0.90 for yield stress and plastic viscosity equations, respectively.

Figures 11 and 12 present Eqs. (8) and (9) with the experimental results of relative yield stress and viscosity, respectively. Note that the mortar yield stress and viscosity have been normalised with the corresponding cement paste parameter raised to powers of 0.63 and 0.78, respectively. Figures 11 and 12 show that the relative rheological parameters decrease with the increase in excess paste thickness, indicating better trends than presented in Figures 9 and 10. The trends show that the relations are applicable for all sands at different c/s ratios. Although the improvement presented in the yield stress trend for each sand mortar is clear, a slight discrepancy in plastic viscosity is observed.

Figure 13 compares Eq. (7) for the relative viscosity resulted from this study against the equation developed by Nishibayashi et al. (1996) below:

$$\log\ H/h = -23.8\, t_p + 1.06 \tag{10}$$

Figure 13 shows that Eq. (7) resulted from the present study predicts higher relative viscosities than does the curve of Eq. (10). Although, Nishibayashi et al. (1996) have underestimated the relative viscosity at high excess paste thickness to the level of nearly zero which may limit the range of the applicability of this relation, the same trend between their data and the present investigation is observed. Moreover, the lower values of Nishibayashi et al. (1996) of relative viscosity at the same excess paste thickness could be attributed to the effect of the high range water reducing admixture used. Owing to the lack of equations available on the relative yield shear, it is not possible to have any comparisons for Eq. (6) or (8).

The most significant finding from Figures 11 and 12 is that S2 mortars at c/s of 1/0.9 show the highest relative rheological properties at very low paste thickness for two mixes of w/c of 0.60 and 0.55. The higher relative rheological performance of S2 than S3 mortars at the same excess paste thickness indicates that it is not only attributed to the high sand surface area of S2. This forwards the approach suggested by Ferraris and Gaidis (1992). They concluded that sand size below 0.1mm in mortars would lubricate with the same size of cement and becomes grit in the lubricant phase which increased the rheological performance of mortar. But this approach does not seem enough to justify the above observation as S2 and S3 contain similar amounts of small size sand as their percentages passing sieve size of 0.063mm are 5.08% and 4.27 %, respectively. Consequently, there would be a need to investigate whether the sand texture is responsible for this difference on mortar rheology. Therefore, sand surface morphology was investigated by the scanning electron microscope (SEM) as depicted in Figure 14.

In the scanning test, S1, S2 and S3 were sieved and particles passed through 0.25mm and retained on 0.125mm were collected and scanned. Since S4 is a single size sand, only particles retained on sieve 0.5mm were scanned. As shown in Figure 14(b), S2 differs from others as its surface is very rough and contains many edges. Consequently, the surface texture of S2 would increase the interlocking and friction between particles, decreasing mortar workability at low cement paste content. Other sands show smooth surfaces and some even show pitting.

Conclusions

The effect of different types of fine aggregate and water/cement ratio on mortar rheological properties was experimentally investigated. The following conclusions may be drawn:

- As the sand surface area of the aggregates increases more paste is needed to cover their surface to attain certain rheology. In other words, when the paste volume is kept constant, the resulted rheological parameters are controlled by the surface area of sand.
- Mortar rheology is controlled by two main factors, namely the rheology of cement paste and excess paste thickness.

- Relative mortar-paste rheological properties increase with the decrease in cement paste thickness up to low values below which the sand surface roughness becomes very important due to the high friction of sand particles.
- The trend predicted for the relative viscosity from the equation developed in the current investigation compared reasonably well with that obtained from the existing formulae in the literature.

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TABLES AND FIGURES

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Table 1–Sand physical properties.

Sand type	S1	S2	S3	S4
Specific gravity	2.62	2.57	2.61	2.65
Void ratio (%)	39.58	49.84	41.84	38.11
Aerated density(kg/m^3)	1583	1289	1518	1640
Absorption (%)	0.83	1.10	0.13	0.07
Specific Surface area (cm^2/cm^3)	175.02	313.14	268.45	81.02

1 **kg/m**^{3} = 0.0624 lb/ft^3; 1 cm = 0.394 in.

Table 2–Rheological constants of cement paste.

Mix	w/c ratio	g (Nmm)	h (Nmms)
1	0.60	0.64	0.42
2	0.55	1.19	0.74
3	0.50	2.80	1.24
4	0.45	5.42	2.09
5	0.40	11.68	4.20

1 N = 0.225 lb; 1 mm = 0.039 in.

Table 3–Mortar rheological parameters at different w/c and c/s ratios.

Sand type	Mix	w/c ratio	*g* (Nmm)		*h* (Nmms)	
			c/s=1/0.9	c/s=1/0.6	c/s=1/0.9	c/s=1/0.6
S1	1	0.60	6.04	2.89	2.28	1.11
	2	0.55	11.44	5.89	3.1	1.75
	3	0.50	23.17	9.38	4.8	3
	4	0.45	53.75	17.17	6.34	5.09
	5	0.40	N/A	35.20	N/A	8.66
S2	1	0.60	21.46	4.97	3.09	1.60
	2	0.55	39.57	11.68	4.23	2.49
	3	0.50	N/A	24.23	N/A	4.53
	4	0.45	N/A	N/A	N/A	N/A
	5	0.40	N/A	N/A	N/A	N/A
S3	1	0.60	8.16	3.27	1.99	1.11
	2	0.55	14.41	5.14	2.76	1.79
	3	0.50	25.61	10.88	4.00	2.32
	4	0.45	58.04	22.35	5.79	4.02
	5	0.40	N/A	38.84	N/A	7.58
S4	1	0.60	1.76	1.66	1.40	0.75
	2	0.55	2.83	2.48	2.04	1.11
	3	0.50	6.26	3.87	2.99	1.79
	4	0.45	12.80	8.54	4.00	3.07
	5	0.40	25.73	14.81	7.01	4.79

1 N = 0.225 lb; 1 mm = 0.039 in.

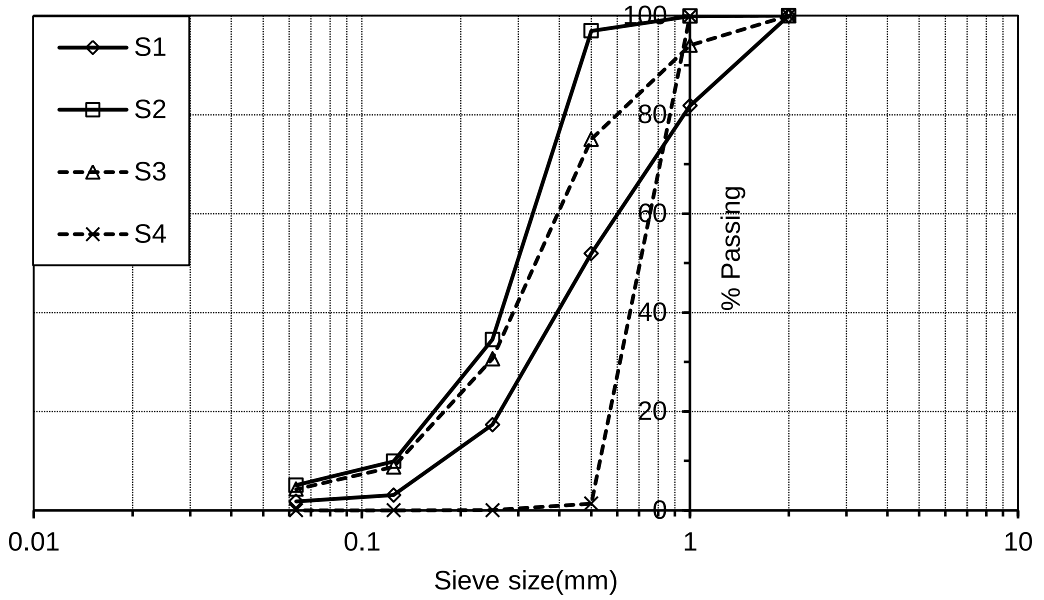


Figure 1–Sand gradation. (1 mm = 0.039 in.)

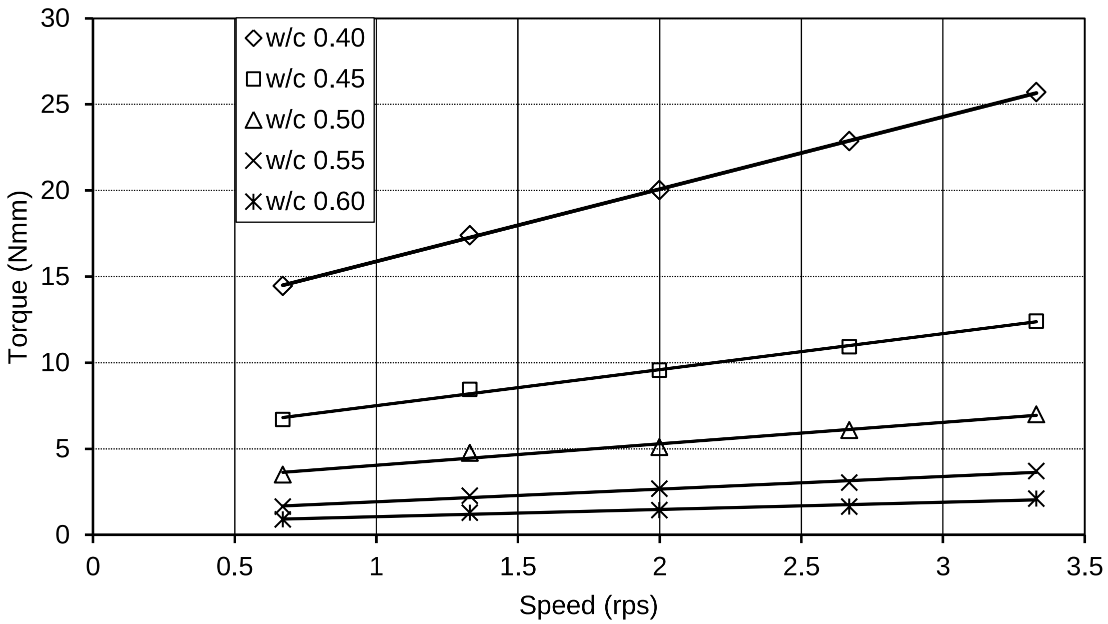


Figure 2–Torque vs. rotating speed for cement paste at different w/c ratios.

(1 N = 0.225 lb; 1 mm = 0.039 in).

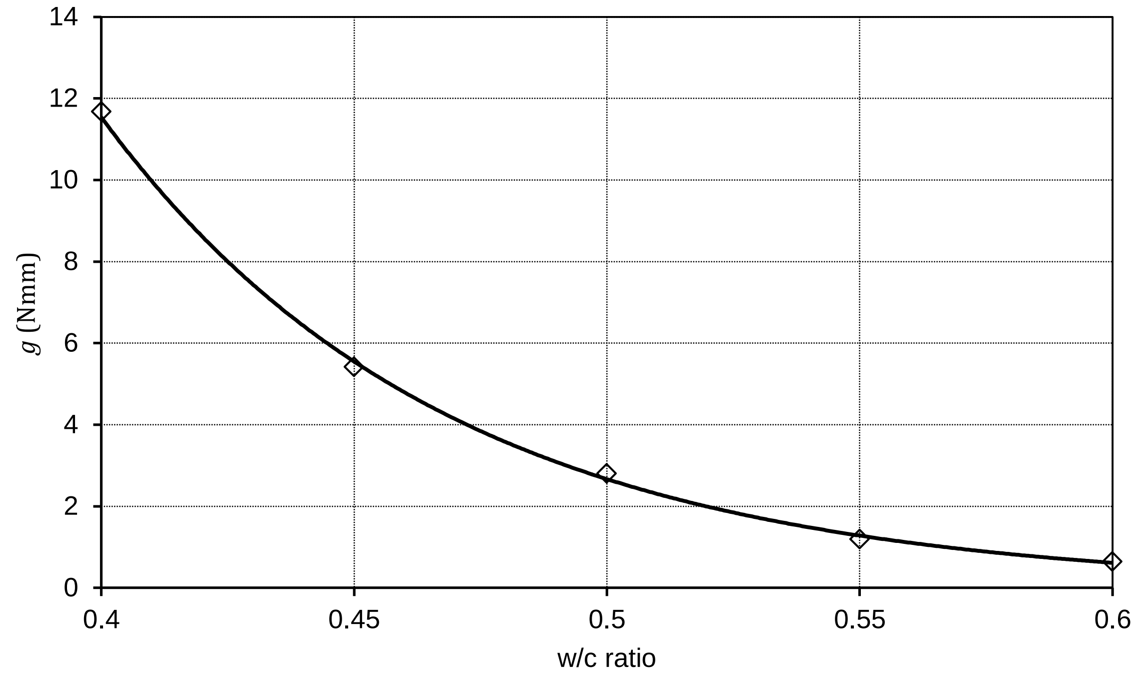


Figure 3–Yield stress vs. w/c ratio of cement paste.

(1 N = 0.225 lb; 1 mm = 0.039 in).

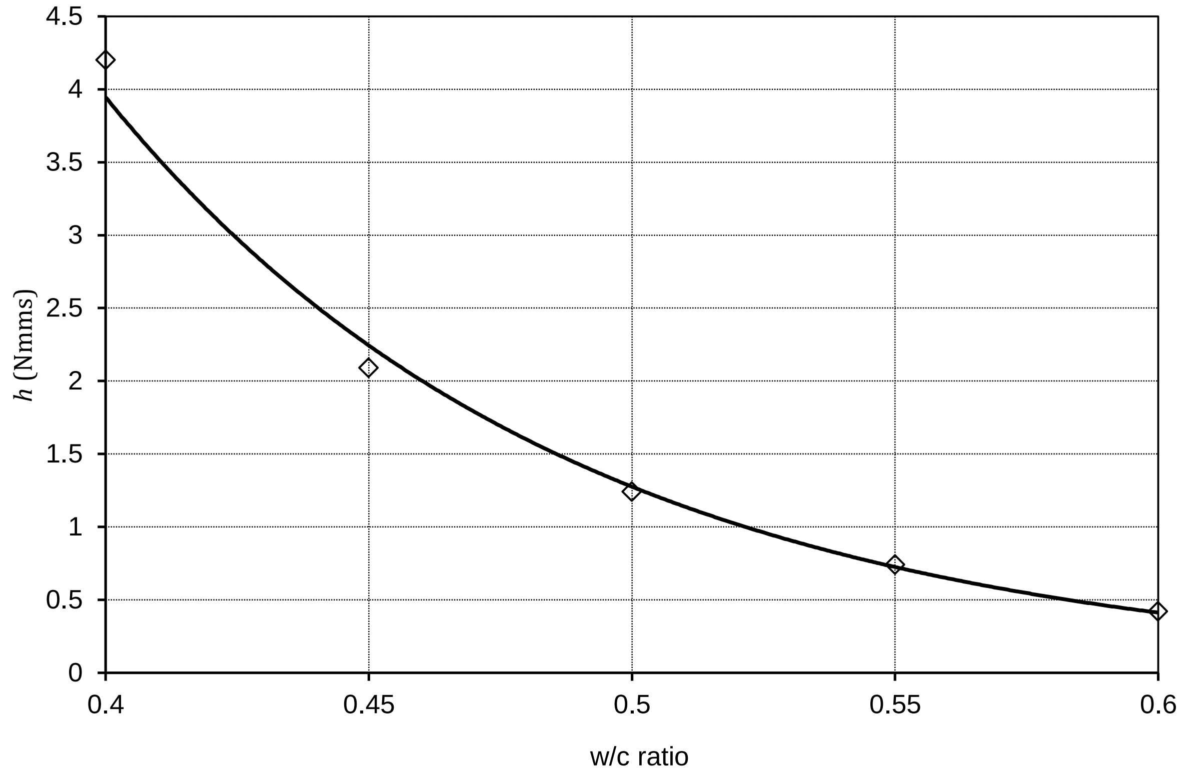


Figure 4–Plastic viscosity vs. w/c ratio of cement paste.

(1 N = 0.225 lb; 1 mm = 0.039 in).

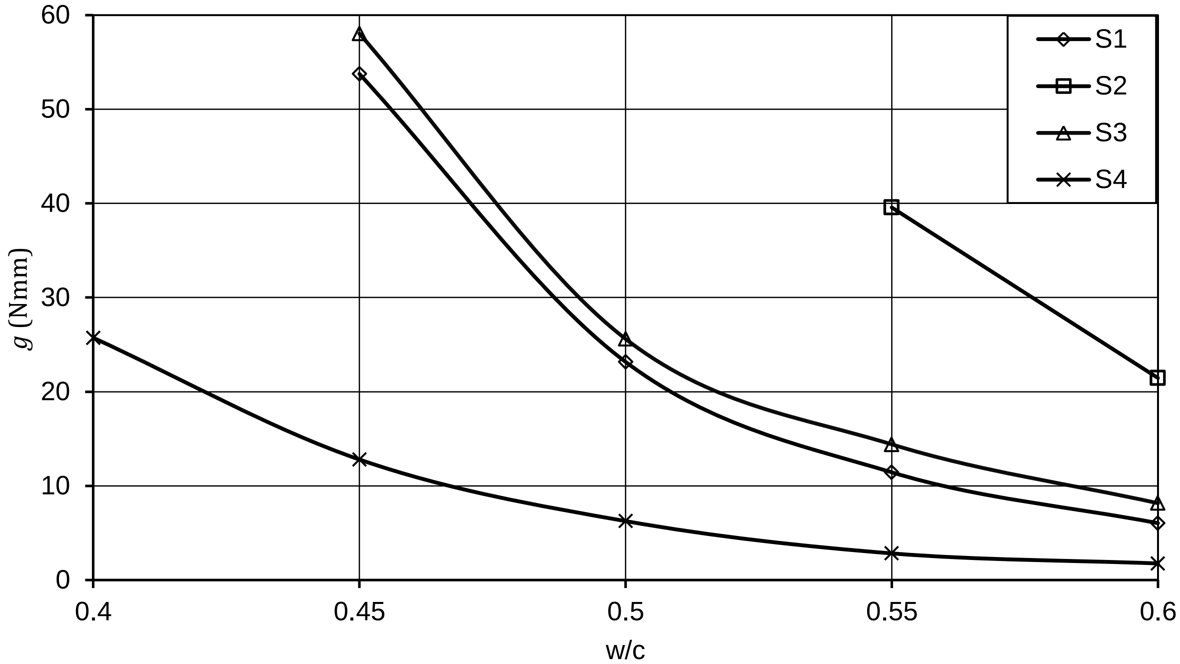


Figure 5–Yield stress vs. w/c ratio of mortars with different sands at c/s of 1/0.9.

(1 N = 0.225 lb; 1 mm = 0.039 in).

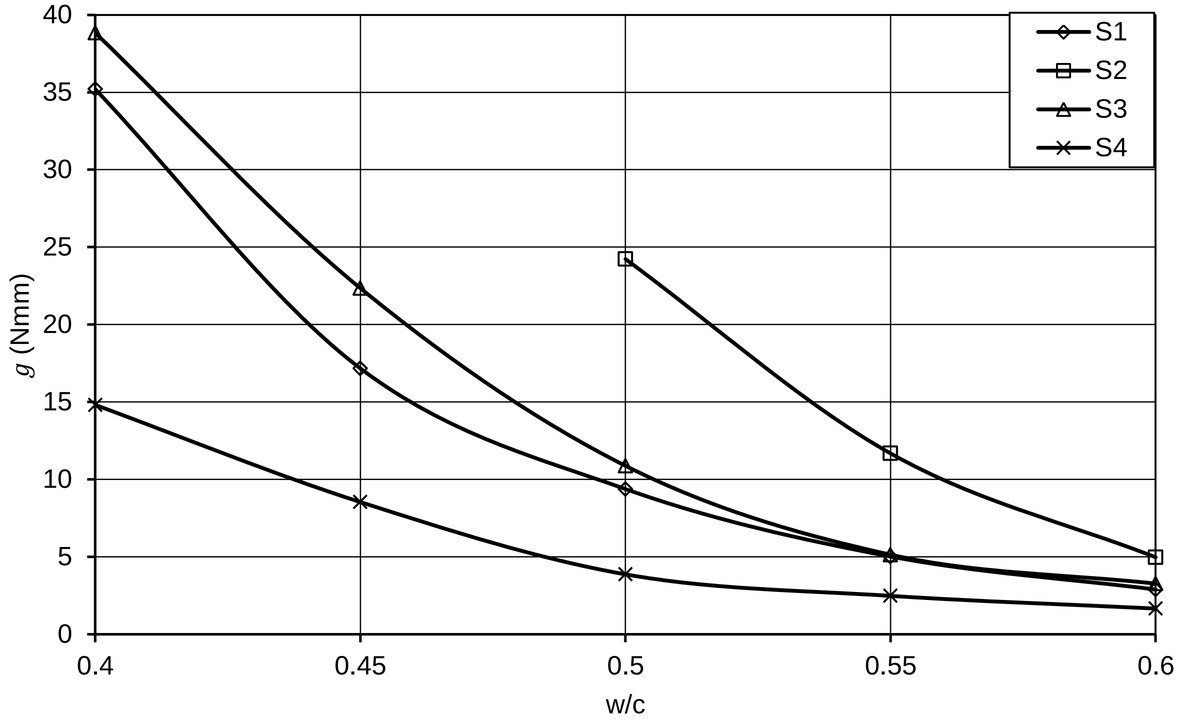


Figure 6–Yield stress vs. w/c ratio of mortars with different sands at c/s of 1/0.6.

(1 N = 0.225 lb; 1 mm = 0.039 in).

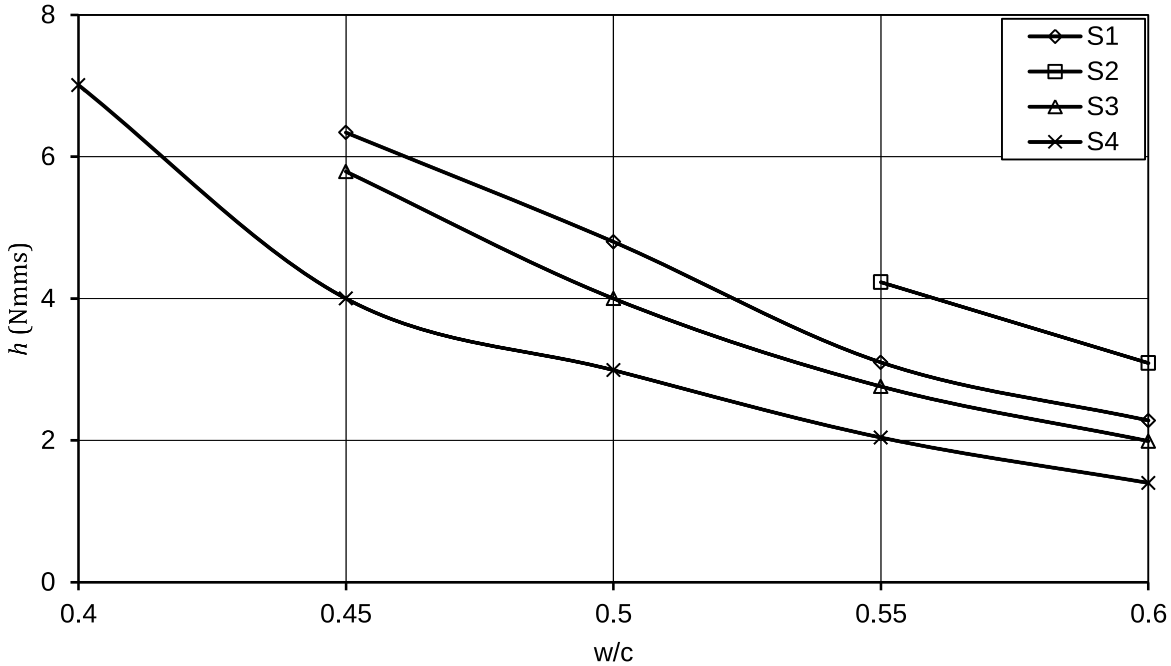


Figure 7–Plastic viscosity vs. w/c ratio of mortars with different sands at c/s of 1/0.9.

(1 N = 0.225 lb; 1 mm = 0.039 in).

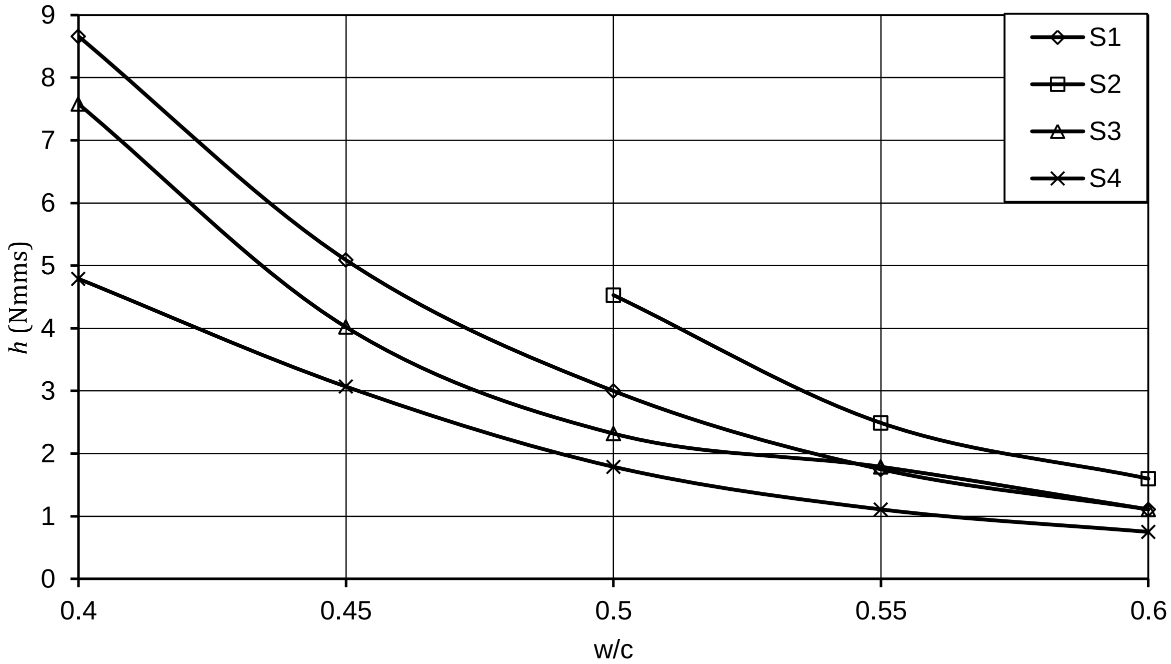


Figure 8–Plastic viscosity vs. w/c ratio of mortars with different sands at c/s of 1/0.6.

(1 N = 0.225 lb; 1 mm = 0.039 in).

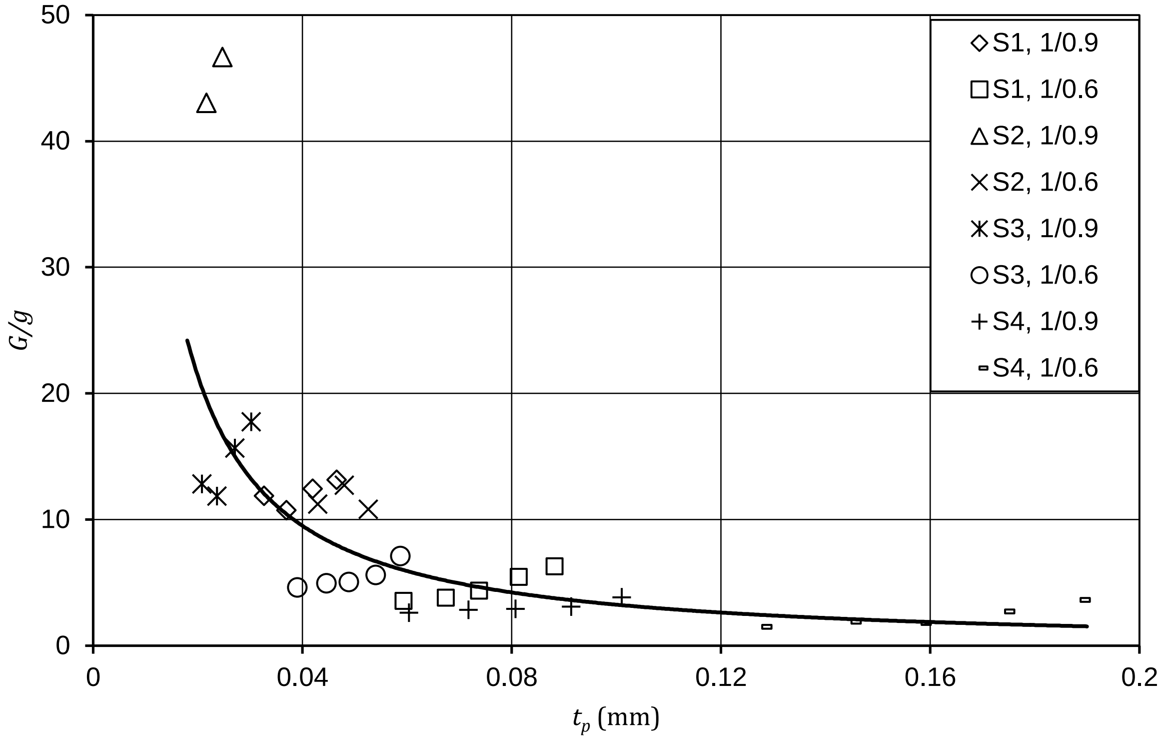


Figure 9–Relative yield stress vs excess paste thickness for all mixes. (1 mm = 0.039 in).

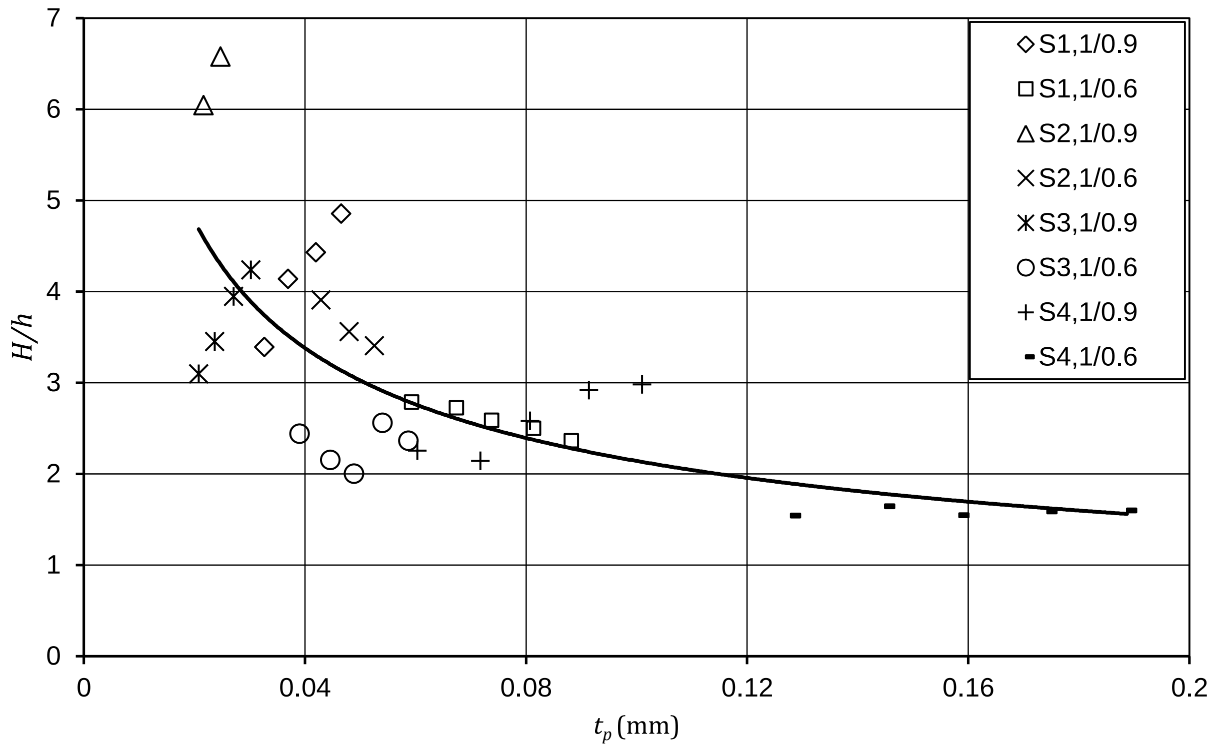


Figure 10–Relative plastic viscosity vs excess paste thickness for all mixes. (1 mm = 0.039 in).

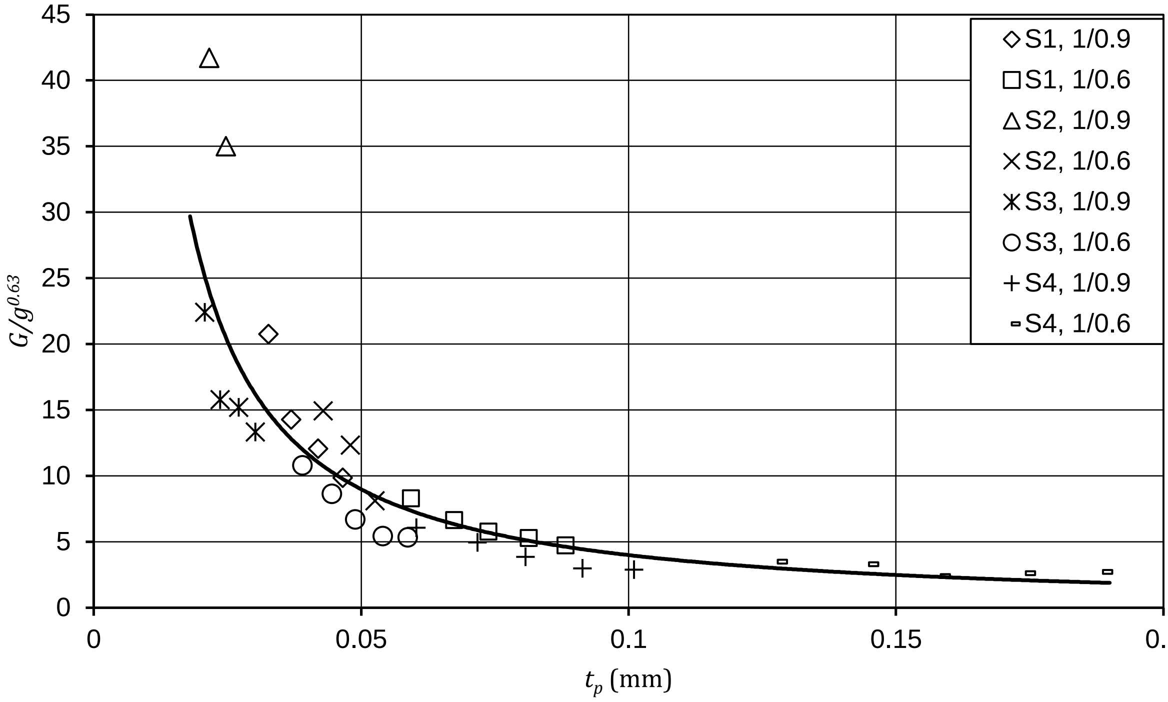


Figure 11–$G/g^{0.63}$ vs excess paste thickness for all mixes. (1 mm = 0.039 in).

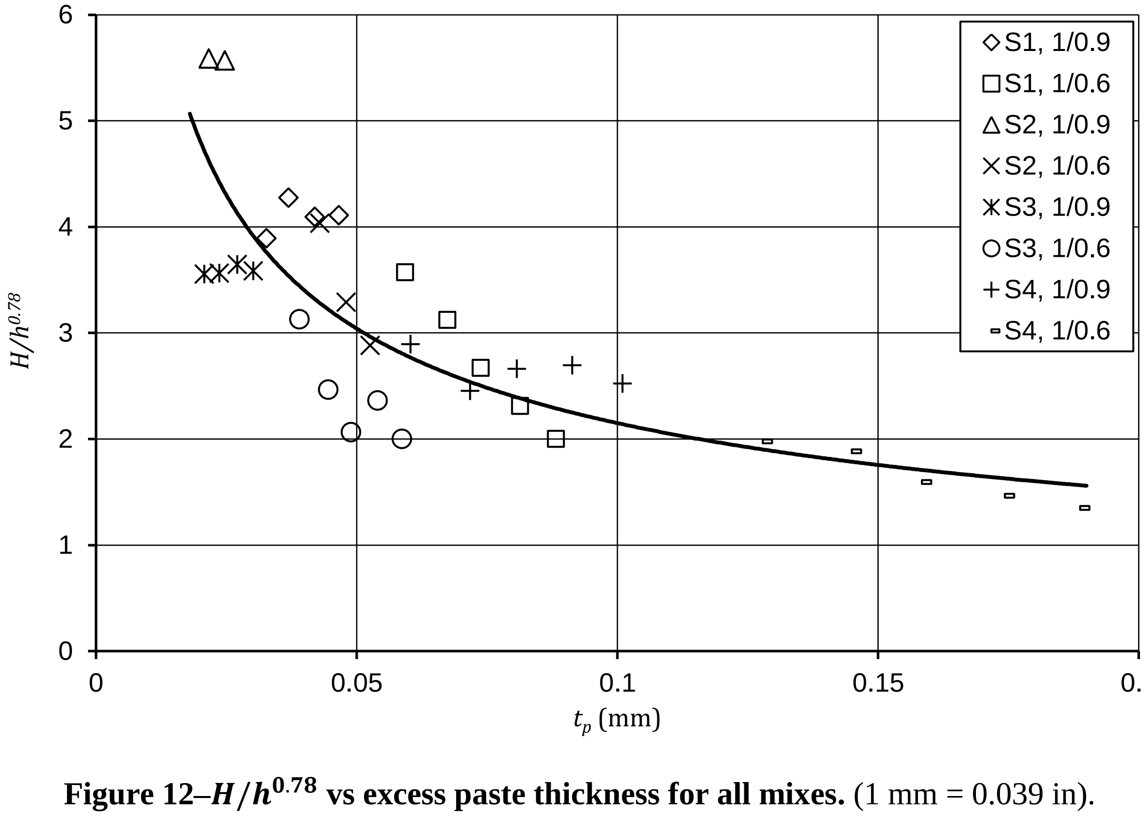


Figure 12–$H/h^{0.78}$ vs excess paste thickness for all mixes. (1 mm = 0.039 in).

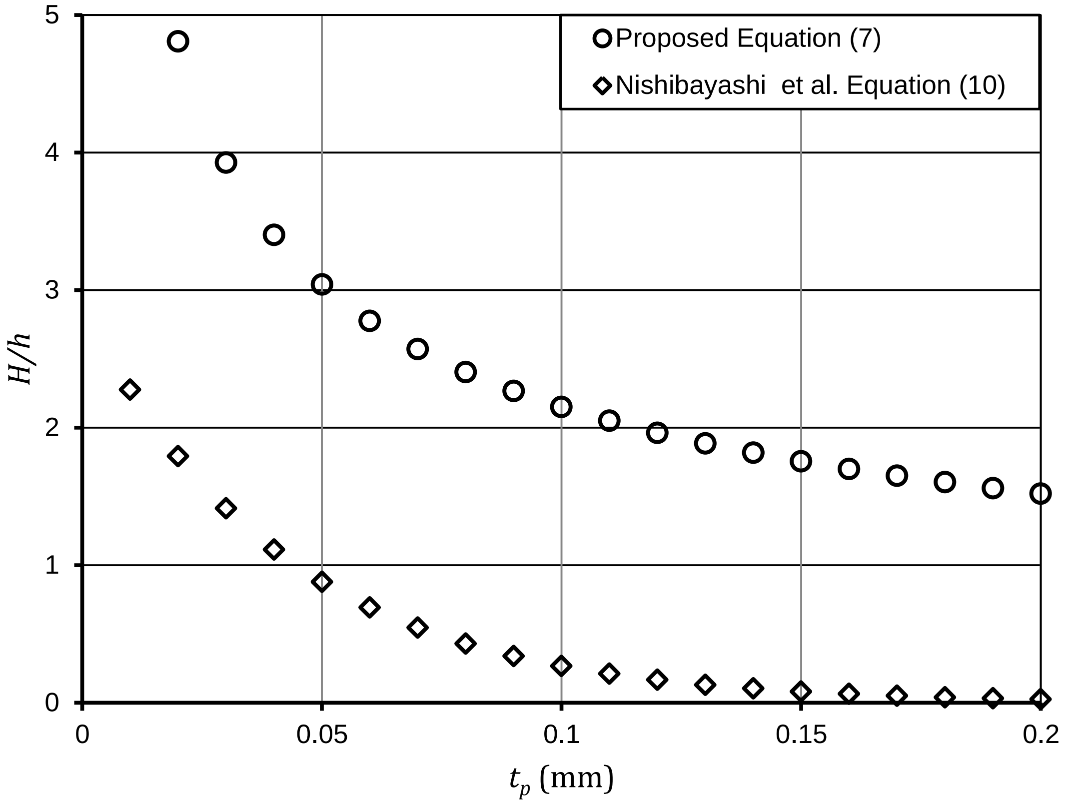
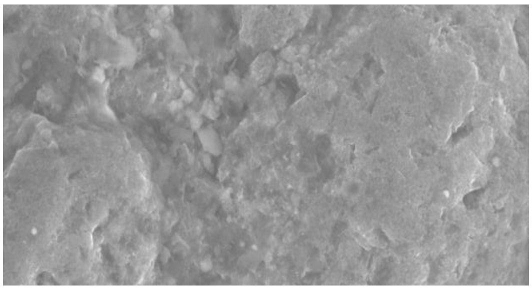
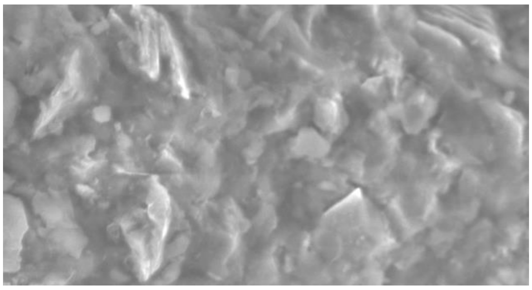


Figure 13–Comparisons between the developed relative viscosity equation with others.

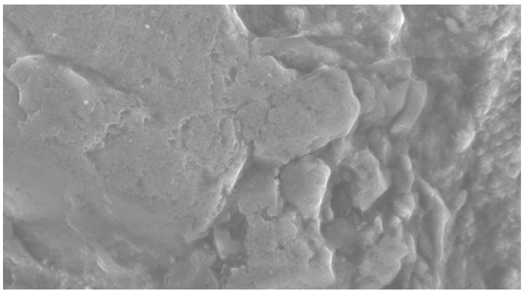
(1 mm = 0.039 in).



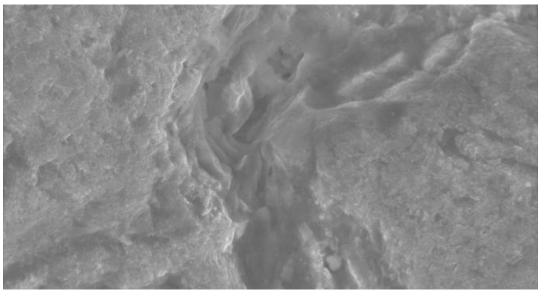
(a) S1, sand size of 0.125 mm



(b) S2, sand size of 0.125 mm



(c) S3, sand size of 0.125 mm



(d) S4, sand size of 0.50 mm

Figure 14–Sand surface magnifications of 1000 times. (1 mm = 0.039 in).