

# CEMENT-SUPERPLASTICIZER COMPATIBILITY AND FLOW PROPERTIES OF BINDER PASTE AND MORTAR USING MARSH CONE AND FLOW TABLE METHOD

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## Abstract

Flow behavior of the binder paste renders a fair idea about the properties of high-performance concrete, especially, in the fresh state. Optimisation of the cement matrix phase or the paste phase in terms of fluidity is an important step in the development of high-performance concrete. It is, therefore, imperative to have a simple, effective, and reliable methodology to assess the flow behavior of the paste. Marsh cone test is often employed for this purpose, and limited review of the prior art indicates no standardization of the quantity of the paste corresponding to which the flow time should be measured and the saturation dosage of superplasticizer to be assessed. Rate of flow through the cone orifice may not remain same, and rather decreases with time. This paper investigates the flow time for different quantities of the paste with an aim to assess the optimum quantity to be used with Marsh cone test for the determination of saturation dosage of superplasticizer. The effect of mixing time upon the flow behavior of the paste is next evaluated with the help of Marsh cone test. Further, the mix design of high-performance concrete of compressive strength in the order of 100 MPa often excludes the coarse aggregates, and hence, resulting in a significant increase in the cost of concrete production. This paper also investigates the flow behavior of the mortar prepared with a low sand-to-cement ratio of 0.62, which is typically the case with ~100 MPa concrete utilizing coarse aggregates. Marsh cone test may not be feasible in such a case on account of low water-cement ratio. Conventional flow-table test is indigenously extended for this purpose to make inference on the fluidity of paste and the saturation of superplasticizer dosage. Finally, results of the paper, in principle, enable assessment of the cement-superplasticizer compatibility. Three different brands of cements are used throughout the test program with a well-known brand of superplasticizer.

**Keywords:** Cement-superplasticizer compatibility; Flow table; High performance concrete; Marsh cone; Mixing time; Saturation dosage of superplasticizer

## 1. INTRODUCTION

Unlike conventional concrete, high-performance concrete requires the use of admixtures like pozzolanic fillers, and superplasticizers in addition to cement, water, and aggregates as its ingredients. The incorporation of these admixtures enhances the flow properties in the fresh state, and the mechanical, and durability properties in the hardened state of concrete. The flow behavior of binder paste gives a fair idea about the properties of high-performance concrete especially in the fresh state<sup>[1]</sup>. In general, the rheology of concrete also depends upon the aggregate characteristics, but it is the excess paste (the paste in excess of what fills the voids in aggregates) that overcomes the intergranular friction between the aggregates, and lubricates the concrete mix to provide workability<sup>[2,3]</sup>. More the surface area of aggregates, more excess paste will be required to provide the lubrication<sup>[3]</sup>. Hence, optimisation of cement matrix phase or paste phase in terms of fluidity is an important step in the development of high-performance concrete<sup>[4]</sup>. Since the cohesion and flowability are provided by the paste phase, it will not be wrong to assume that the workability, and other rheological properties of concrete depend upon the characteristics of the binder paste. It is therefore imperative to have a simple, effective, and reliable methodology to assess the flow behavior of paste. Furthermore, it is also necessary to use the optimum dosage of admixture as low dosages may result in the loss of fluidity, and high dosages, besides being uneconomical, may cause the segregation, and set retardation<sup>[1]</sup>. Several methods are already in use for assessing the flowability of cement paste and mortar, for example, Marsh cone test, mini-slump test, and flow-table test. Marsh cone test is a simple method, used globally by the researchers to get an idea regarding the flow characteristics of paste, and the optimum dosage of superplasticizer. The fluidity of cement paste is represented in this method by time taken for a certain quantity of paste to pass through the orifice of cone<sup>[5]</sup>. The optimum or saturation dosage of superplasticizer

Table 1: practices adopted in the prior art

AUTHORS	INITIAL VOLUME (ml)	VOLUME OF FLOW CONSIDERED FOR MEASURING THE FLOW TIME (ml)
Agullo <i>et al.</i> <sup>[4]</sup> , Roncero <i>et al.</i> <sup>[11]</sup> , Giaccio, and Zerbino <sup>[30]</sup>	800	200
Jayasree and Gettu <sup>[1]</sup> , Thankaswamy and Xavier <sup>[10]</sup> , Robert <i>et al.</i> <sup>[31]</sup> , John and Gettu <sup>[32]</sup> , Manomi <i>et al.</i> <sup>[33]</sup>	1000	500
Sonebi <i>et al.</i> <sup>[34]</sup>	1000	700
Benaicha <i>et al.</i> <sup>[35]</sup> , and Hallal <i>et al.</i> <sup>[9]</sup>	1000	1000
Shrivastava and Kumar <sup>[8]</sup>	Full capacity of Marsh cone	1000
Kondraivendhan, and Bhattacharjee <sup>[36]</sup> , and Krishnamoorthy <i>et al.</i> <sup>[37]</sup>	Full capacity of Marsh cone	200
Tiwari <i>et al.</i> <sup>[38]</sup>	Full capacity of Marsh cone	Entire volume considered

is defined as that dosage beyond which no significant decrease in the flow time or increase in the fluidity takes place. Although the test is widely used, there is no consensus regarding the benchmark to be used for measuring the flow time. Flow time variations with the amount of paste flowing out of the cone is not linear throughout the test. This was identified by Roussel *et al.*<sup>[6]</sup> with a focus on measuring the fluidity in terms of plastic viscosity, and plastic yield value rather than optimisation of flow quantity for measuring the flow time. Different researchers used different quantities of paste to characterize the flow time. Table 1 summarizes some of the practices adopted in the prior art.

Rapid slump loss sometimes occurs in concrete despite using the saturation dosage which indicates the incompatibility of cement and superplasticizer. On contrary, if high fluidity is maintained for longer period (60-90 minutes), the cement and superplasticizer are said to be compatible for all practical purposes<sup>[7]</sup>. It is therefore essential to study the fluidity behavior of cement paste at different time intervals after mixing. Shrivastava, and Kumar<sup>[8]</sup> reported the fluidity of cement paste as the Marsh cone flow time at 5, 30, 60, 120, and 240 minutes. Hallal *et al.*<sup>[9]</sup>, and Thankaswamy, and Xavier<sup>[10]</sup> reported the flow time immediately after mixing and 60 minutes later. Roncero *et al.*<sup>[11]</sup> measured the flow time immediately and 90 minutes after the mixing. It is also believed that the rheological properties of concrete and cement paste depend upon the mixing regime, duration, and shear rates<sup>[12-14]</sup>. Altable and Casanova<sup>[15]</sup> observed that the sequence of mixing influences the flow properties of cement-paste and reported a better flow by delaying the addition of superplasticizers. Khalid *et al.*<sup>[12]</sup> also reported that prolonged mixing time might have variable effects on the self-compacting concrete systems depending upon the secondary raw materials used in the mix. Agullo *et al.*<sup>[4]</sup> also reported a significant variation in the Marsh cone flow time by altering the sequence of mixing various ingredients of paste. Sometimes, the fluidity of concrete was also observed to increase after mixing depending upon the nature of cement, the temperature and the mixing duration<sup>[14]</sup>. Regnaud *et al.*<sup>[14]</sup> noticed that such increase

in fluidity after mixing reduces with an increase in mixing time.

Based on the limited review of the prior art presented above, the quantity of paste for estimating the flow time and saturation dosage of superplasticizer is not yet standardised. Rate of flow through the cone orifice is expected to decrease with time. Initially, the flow will be faster and, as the material flows out and the weight of the paste inside the cone reduces, the flow will slow down. It seems interesting to study the flow time for different quantities of paste flowing out of the cone (after initially filling it to its full capacity) so as to decide the optimum quantity for estimating the flow time and saturation dosage. Although the optimum quantity may vary for the pastes of different fluidities, yet the minimum quantity that should be allowed to flow before deciding the saturation point can be conceptualized. The first goal of the present paper is to explore this issue. The duration of mixing is also envisaged to influence the flow behavior of concrete but has so far not been reported with rationale. The effect of mixing time upon the flow behavior of paste is next studied in this paper with the help of Marsh cone test. This paper also investigates the flow behavior of mortar prepared with a low sand-cement ratio (~0.62) which is typically the case with high strength concrete (~100 MPa) but using coarse aggregates. Marsh cone test may not be feasible in such a case owing to the low *w/b* ratio. Flow table test is used in that case but adopting the most suitable mixing time indicated by Marsh cone test.

Before discussing the key contributions, a brief description of the experimental setup including the material characterization is presented. The saturation dosage of superplasticizer is next discussed with an emphasis on the optimum quantity of pastes to be used for characterising the flow time. The compatibility of cement, and superplasticizer, effect of mixing time on the fluidity and variability of fluidity with three commercially available cement brands are then investigated. Finally, the flow behavior of cement paste at low *w/b* ratio ( $\leq 0.30$ ) is presented using the flow table test.

## 2. EXPERIMENTAL PROGRAMME

### 2.1 Materials used

#### 2.1.1 Cement

Three different brands of ordinary Portland cement (OPC) of grade 53; Cement-A, Cement-U, and Cement-P, all conforming to the IS: 269 (2015)<sup>[16]</sup> are used in this study. The specific surface area of Cement-A, Cement-U, and Cement-P as measured by Blaine fineness test are 322, 281, and 339 m<sup>2</sup>/kg, respectively. The chemical composition of the cement is determined by 'Inductively Coupled Plasma – Optical Emission Spectroscopy' (ICP-OES). 50 mg of cement is weighed and digested using hydrofluoric acid (HF), nitric acid (HNO<sub>3</sub>), and hydrochloric acid (HCl) as reagents. Once the digestion is complete, the samples are diluted with 2 % HNO<sub>3</sub> to make a stock volume of 50 ml. Further, 0.15 ml is taken from the stock volume and diluted to 15 ml (with 2 % HNO<sub>3</sub>) to obtain a 10 ppm concentration solution. This 10 ppm solution is subjected to ICP-OES analysis to get the elemental composition of cement. The elemental composition is converted to oxide composition and is given in Table 2. Phase composition of cement is calculated using Bogue's equations and is given in Table 2. Cement-U has the highest content of calcium aluminate present whereas Cement-P has the lowest.

#### 2.1.2 Silica fume

Silica fume (conforming to BS 13263<sup>[17]</sup>) is directly purchased from a local vendor with following manufacturer's specifications: i) Specific gravity and bulk density are 2.2 and 395 kg/m<sup>3</sup>, respectively; ii) The average particle size is in the range of 1.5-2.5 micron; and iii) SiO<sub>2</sub> content is higher than 85 %.

The particle size distribution of the silica fume is determined by laser diffraction particle size analyser and is given in Figure 1. D<sub>10</sub>, D<sub>50</sub>, and D<sub>90</sub> of the silica fume was found to be 1.09 micron, 10.57 micron and 27.05 micron, respectively. This larger particle size indicated in the distribution curve is due to the agglomeration of very fine particles, since as-produced silica fume is very difficult to handle, it is supplied in the dry densified form. An efficient superplasticizer is required to disperse, and deflocculate the agglomerated silica fume particles during mixing. Also, the abrasive action of aggregates during mixing helps in the deflocculation of silica fume particles.

#### 2.1.3 Sand

Locally available sand conforming to the grading zone III of IS: 383 (2016)<sup>[18]</sup> is used in the preparation of mortar for the flow table test. The particle size distribution curve of the sand is given in Figure 1. The specific gravity, water absorption, and fineness modulus of the sand are determined as 2.64, 0.9, and 2.74 %, respectively, through laboratory testing as per the relevant IS standards.

#### 2.1.4 Water and superplasticizer

Potable tap water available in the laboratory is used for mixing. Polycarboxylic-ether (PCE) based superplasticizer [conforming to IS: 9103 (1999)<sup>[19]</sup> manufactured by BASF with a solid content of 30 % is used throughout the testing. The superplasticizer as per the manufacturer has such a configuration which allows its delayed adsorption on the cement particles<sup>[20,21]</sup>.

### 2.2 Testing procedure

The testing programme includes an investigation of the fluidity of cement paste, and mortar prepared from the three different brands of cement. The fluidity of cement pastes is studied using the Marsh cone test, employing three different mixing times whereas that of cement mortars are investigated with the help of a flow table test (adopting the most suitable mixing time given by the Marsh cone test).

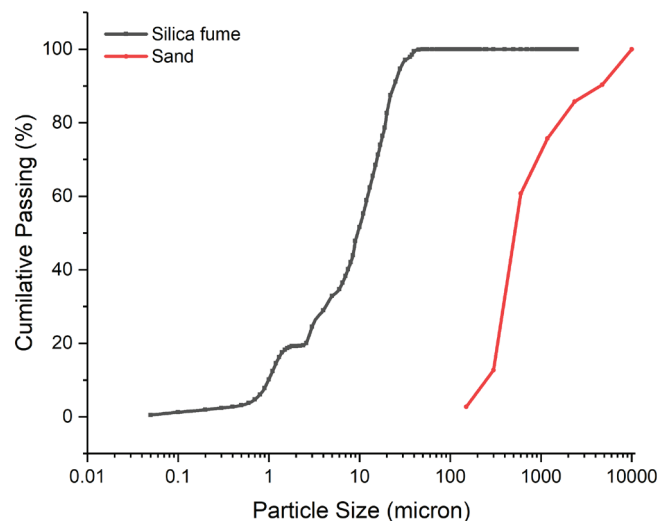


Figure 1: Particle size distribution for silica fume and sand

Table 2: Chemical composition of cement

CEMENT	PERCENT BY WEIGHT								BOGUE'S COMPOSITION			
	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	MgO	Na <sub>2</sub> O	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	C3A	C2S	C3S	C4AF
U	61.76	4.04	0.61	5.30	1.52	21.46	0.38	4.3	4.55	20.98	53.66	12.3
A	64.1	3.47	0.52	3.46	0.80	23.23	0.45	3.5	3.4	24.34	55.93	10.56
P	62.25	4.66	0.75	4.61	1.11	21.86	0.35	4.13	3.06	22.72	52.87	14.18

### 2.2.1 Marsh cone test

Marsh cone with an opening nozzle of size 8 mm is used for the test. The test is conducted at different dosages of superplasticizer over a varying range of water-binder ratios. For example, the superplasticizer dosage is varied from 0.4-1.6 % by weight of cement (in equal increment of 0.3 %) whereas the water-binder ratios from 0.28-0.34 (typically adopted for high performance concrete) in equal increment of 0.2. The superplasticizer dosage indicates here the liquid superplasticizer by weight of cement, and the associated water content is taken into account while making the paste. Silica fume is added as cement replacement at the rate of 10 % by weight of cement in every mix. Mixing is performed in a planetary mixer as given in Table 3. Total mixing time of 5, 8, and 10 minutes is employed after adding the water to cement. After mixing is complete, the Marsh cone is filled up to its full capacity and paste is allowed to flow out. Time, after every 100 g of paste (100, 200, 300 g etc.) flows out of the cone is recorded. This is done twice for each mix, once immediately after the mixing, and then 60 minutes later, to investigate any change in the fluidity with time.

### 2.2.2 Flow table test

Flow table test is performed at the superplasticizer dosages similar to that of Marsh cone test i.e., 0.4-1.6 % by weight of cement. Cement mortars are prepared with the same brands of cement as used in the Marsh cone test. Oven-dried sand is used in all the mixes to eliminate any variation in moisture conditions affecting the results and additional water to compensate for the water absorption of sand particles is included. The sand-binder ratio is fixed at 0.62, and cement is partially replaced by silica fume at the rate of 10 % by weight in all the mortar mixes. Water-binder ratios used are 0.26, 0.28, and 0.30. The most suitable mixing time (that is the mixing duration for which the fluidity is maximum and over-fluidification is also not observed in Marsh cone test) is adopted and the mixing is performed with planetary mixer in a similar way as described above. This mixing time is adopted as naturally fluidity should go down with time due to some of the water being used up in hydration reaction, and evaporation. However, during Marsh cone test it is found that at lesser mixing times some of the mixes show better fluidity as the time passes which is unexpected and is referred

Table 3: Mixing arrangement

MIXING STAGE	SPEED	MIXING TIME (MINUTES)	TOTAL MIXING-TIME AFTER ADDING WATER (MINUTES)
Dry mixing	Low	1	
Addition of 70 % water	High	3	
Addition of remaining 30 % water premixed with superplasticiser	Medium	2	5
		5	8
		7	10

to as over-fluidification<sup>[14]</sup>. Hence, Marsh cone test is repeated by increasing the mixing time to 8 minutes, and 10 minutes. This step significantly improves the fluidity. In addition, over-fluidification is not observed for a mixing time of 10 minutes. This is considered as the most suitable mixing time for flow table test carried out at lower water-binder ratios. Flow diameter for each mortar mix is measured immediately, 30 minutes, and 60 minutes after the mixing.

## 3. RESULTS AND DISCUSSION

### 3.1 Marsh cone test

#### 3.1.1 Saturation dosage

Saturation dosage is the dosage beyond which further addition of superplasticizer does not enhance the fluidity appreciably<sup>[4,22]</sup>. This point is often determined subjectively from the shape of the curve<sup>[4]</sup>. The flow time curve consists of two lines which have different directions or slopes and the saturation point is taken as the intersection of these two lines<sup>[22]</sup>. Figure 2 presents the variation of flow time against the superplasticizer dosage for the paste prepared with Cement-U at a water-binder ratio of 0.34. These tests are performed immediately after mixing for 5 minutes and flow time is measured for different quantities of paste (ranging from 200 g up to 2000 g in increments of 200 g). The curves are initially flat with no clear distinction of the saturation point, for example, if the flow time curve for 200 g~600 g is considered (when compared with 1600 g~2000 g). However, as the material flows out of the cone, the curves become steeper, and the saturation point becomes more evident. This is further clear in Figure 3, where for 200 g curve, there is no change in flow time at all when superplasticizer dosage is increased from 0.4 to 0.7 %, and further to 1, 1.3, and 1.6 %. Based on this, one can infer that saturation is already

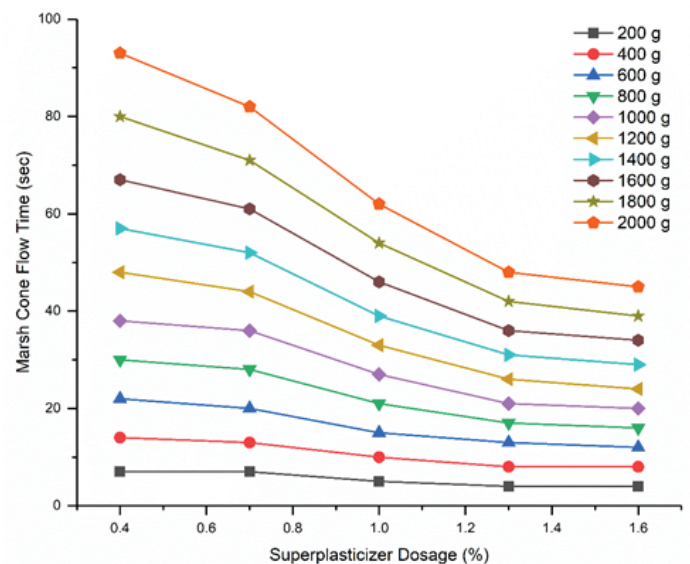


Figure 2: Variation of flow time with respect to superplasticizer dosage immediately after mixing for 5 minutes (w/b = 0.34, cement-U)

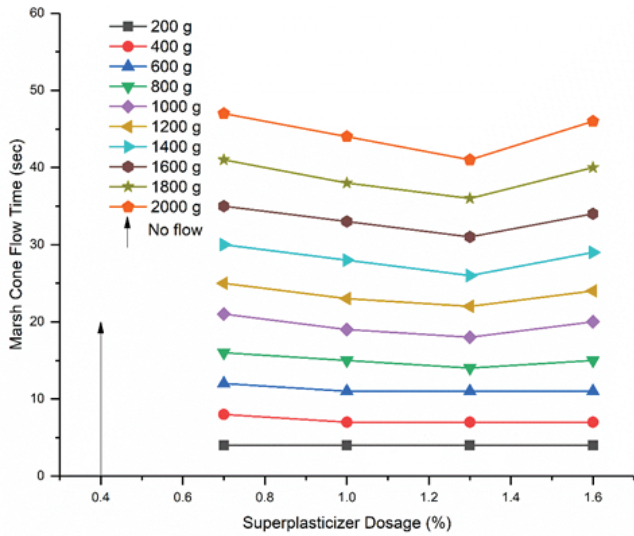


Figure 3: Variation of flow time with respect to superplasticizer dosage immediately after mixing for 10 minutes ( $w/b = 0.34$ , cement-P)

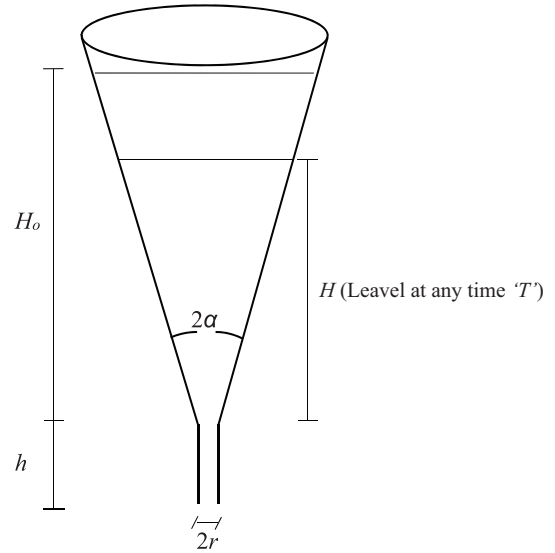


Figure 4: Marsh cone apparatus

reached at 0.4 % dosage. Up to 600 g, no change in fluidity can be seen when superplasticizer dosage increases from 1 to 1.3 %, and further to 1.6 %. However, for 2000 g curve, flow time continuously decreases up to the dosage of 1.3 %. A similar trend of results is also observed for the other brands of cement at different water-binder ratios using different mixing times. Flow velocity is expected to reduce as the material flows out of the cone and that in turn reduces the flow rate through the orifice. The flow time for a fluid of viscosity ' $\mu$ ' filled in the Marsh cone (Figure 4) can be given by a flow time equation, Equation 1 [23].

$$T = \frac{8\mu}{3\rho g r^3 \tan \alpha} \left[ \left( 1 + \frac{3h \tan \alpha}{r} \right) (\tan^2 \alpha) (H_0 - H) \left( \frac{H_0 + H}{2} + h \right) - 2 \tan \alpha (h \tan(\alpha) - r) (H_0 - H) + (h \tan(\alpha) - r)^2 \ln \left( \frac{H_0 + h}{H + h} \right) - \frac{r^3}{h \tan \alpha - r} \left( \ln \left( \frac{H_0 \tan(\alpha) + r}{H \tan(\alpha) + r} \right) - \ln \left( \frac{H_0 + h}{H + h} \right) \right) \right] \quad (1)$$

Where

$$H = \frac{1}{\tan \alpha} \left[ \left( (H_0 \tan(\alpha) + r)^3 - \frac{3V \tan \alpha}{\pi} \right)^{1/3} - r \right]$$

Here, ' $\rho$ ' is the density of paste, ' $r$ ' is the radius of orifice, ' $g$ ' is the acceleration due to gravity, ' $\alpha$ ' is the angle between the generatrix and vertical axis; ' $h$ ' is the height of the cylindrical part of Marsh cone, ' $H_0$ ' is the initial height of the filling in the Marsh cone, ' $H$ ' is the height of paste in the Marsh cone at time ' $T$ '. ' $V$ ' is the volume of the paste that has left the Marsh cone in time ' $T$ '.

From Equation 1, ' $H$ ' can be written in terms of volume fraction,  $\gamma = V/V_0$ , where ' $V_0$ ' is the total initial volume in the cone as below;

$$H = \frac{1}{\tan \alpha} \left[ \left( (H_0 \tan(\alpha) + r)^3 - \frac{3\gamma V_0 \tan \alpha}{\pi} \right)^{1/3} - r \right] \quad (2)$$

Variation of flow time against the volume fraction of flow ( $\gamma$ ) calculated from Equation 1, and 2 is shown in Figure 5. Also included in the same figure is the variation of flow time from Marsh cone test for  $w/b = 0.34$  and superplasticizer dosage as 1 %. The volume fraction in the cone can be taken as equivalent to ratio of weight of paste leaving the cone to the total initial weight of the paste in the cone, assuming, the density does not change over a short duration of test. Both the cases exhibit a stiffening nature with increasing ' $\gamma$ ', and the relative differences may be attributed to the difference in the viscosity (and its time dependency) of the paste as the actual viscosity of the cement paste is not known. This difference and the overall stiffening nature of the paste is expected to increase with the reduction of  $w/b$  ratio. Therefore, one must be careful while

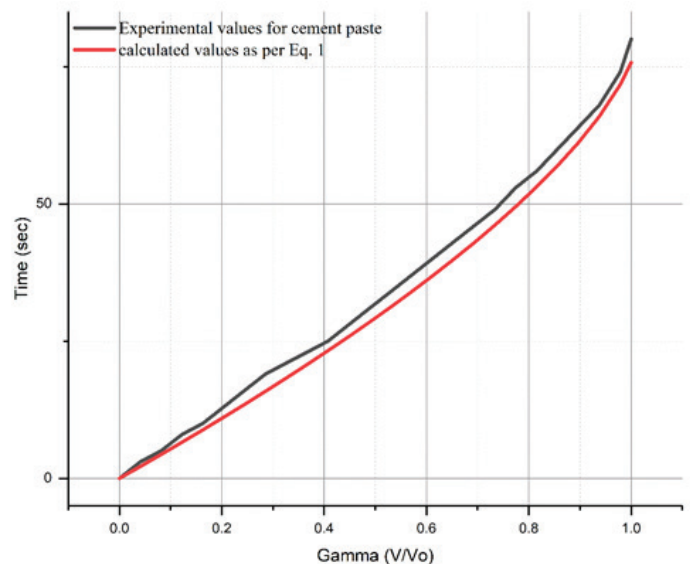


Figure 5: Variation of flow time with  $\gamma$  ( $w/b = 0.34$  and superplasticizer dosage = 1%),  $\rho = 2086 \text{ kg/m}^3$ ,  $\mu = 2 \text{ Pa-s}$ ,  $r = 0.004 \text{ m}$ ,  $H_0 = 0.245 \text{ m}$ ,  $h = 0.006 \text{ m}$ ,  $\alpha = 14.2 \text{ degree}$

selecting the saturation dosage of superplasticizer, and should allow the sufficient quantity of the paste to flow out of the cone. Otherwise, the estimated saturation point is likely to be misleading, and even in some cases, can be wrongly inferred as non-existent.

### 3.1.1.1 Calibration of flow time equation with experimental data

Flow time equation can be used to determine the viscosity ' $\mu$ ' for a given mix and superplasticizer dosage, using the test data for flow time ' $T$ '. With increase in the superplasticizer dosage, the viscosity should decrease till the saturation point is reached. The test data for flow time measured immediately after mixing (cement-U,  $w/b = 0.34$ , mixing time 10 minutes) is fitted to the flow time equation, and viscosity of the cement paste is evaluated. The variation of viscosity with the superplasticizer dosage is shown in Figure 6. It is seen, as the superplasticizer dosage increases, the viscosity goes down till the dosage of 1 %. With further increase, the viscosity does not decrease. Flow time variation with superplasticizer dosage also shows the same trend (Figure 6). Flow time reduces till the dosage of 1 % is reached, with no further reduction beyond this dosage, indicating saturation point as 1 %.

### 3.1.2 Cement and superplasticizer compatibility

**Cement-A:** Flow time curves for 2000 g paste of Cement-A corresponding to different mixing times at water-binder ratios 0.34, and 0.32 are shown in Figure 7, and 8, respectively. At  $w/b$  of 0.34, and mixing time of 5 minutes, [Figure 7(a)], it takes more than 300 sec for 2000 g of paste to flow out of the cone at a superplasticizer dosage of 0.4 % when tested immediately after the mixing. The flow does not occur at all in this mix at 60 minutes after the mixing. At higher dosages, the flow

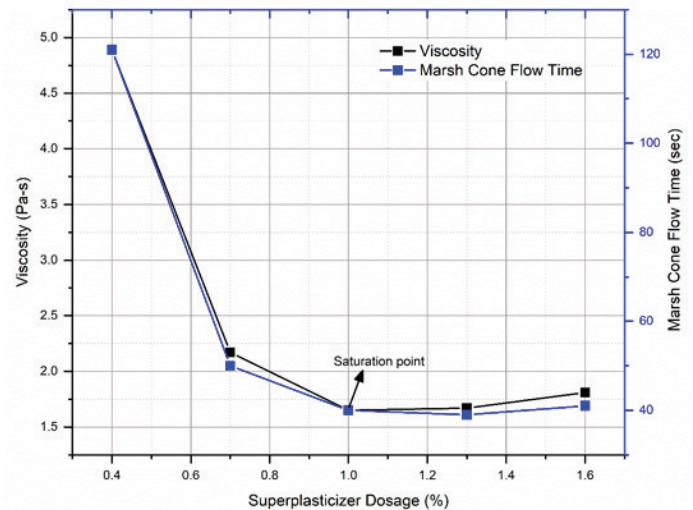


Figure 6: Calibration of flow time equation with experimental data

occurs much quickly (within 100-120 sec) and good fluidity retention is also observed at 60 minutes after the mixing. A better fluidity as compared to that observed immediately after the mixing is noticed at 60 minutes after the mixing. In other words, the fluidity increases with time. This behavior was also reported elsewhere [14,24] and often termed as over-fluidification [14,25]. However, this over-fluidification is either negligible or not exhibited when mixing time is increased to 8 minutes [Figure 7(b)] and 10 minutes [Figure 7(c)]. Further, the flow time at both the testing periods (immediately, and 60 minutes after the mixing) is drastically reduced by increasing the mixing time from 5 minutes to 8, and 10 minutes. However, the flow does not occur for the mixing time of 8, and 10 minutes at 0.4 % superplasticizer dosage which is not the case with 5 minutes mixing time. At  $w/b$  of 0.32 (Figure 8), no flow is observed with 0.4 % superplasticizer dosage for both the testing periods in any of the pastes irrespective of the mixing time.

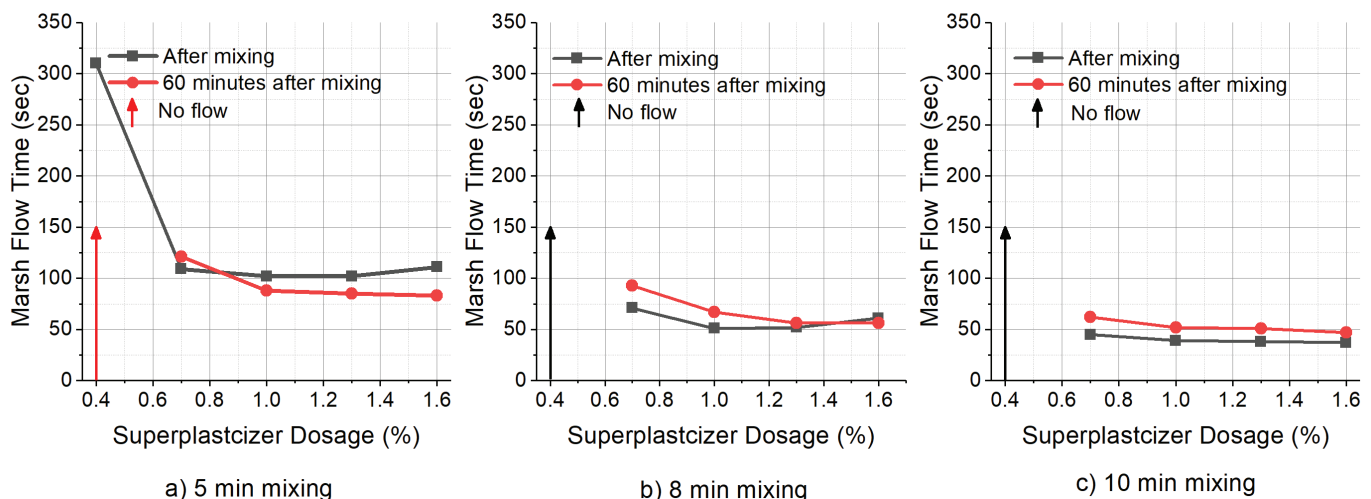


Figure 7: Marsh cone flow time for 2000 g paste made with cement-A at different mixing times for  $w/b$  0.34.

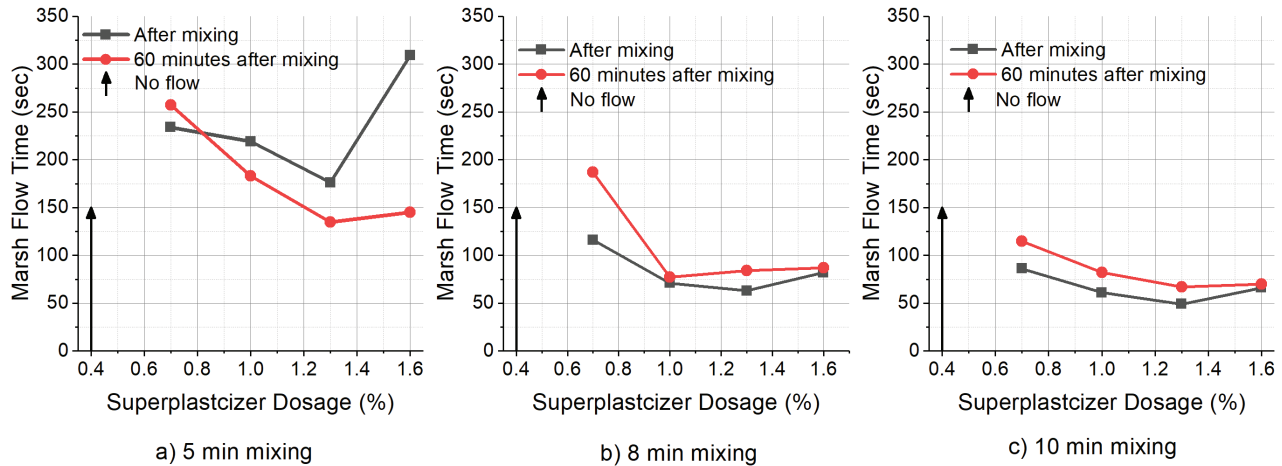


Figure 8: Marsh cone flow time for 2000 g paste made with cement-A at different mixing times for w/b 0.32

For 5 minutes of mixing time, [Figure 8(a)], the pastes at other dosages again show better fluidity at 60 minutes compared with that immediately after the mixing except the one with 0.7 % superplasticizer dosage. A slight increase in flow time is observed in that case after 60 minutes of mixing. However, this increase in fluidity or over-fluidification is again not observed with prolonged mixing time [Figure 8(b), and Figure 8(c)] indicating a better mixing and adsorption of superplasticizer. When w/b is reduced to 0.30, the flow does not occur for the pastes with superplasticizer dosages below 1 % except the one with 10 minute mixing time. In that case, the flow is observed at superplasticizer dosage of 0.7 % when tested immediately after mixing which however is not retained till 60 minutes. Similar behavior in the fluidity (as reported with w/b of 0.34 and 0.32) is observed in this case also immediately and 60 minutes after the mixing. However, the increase in fluidity after 60 minutes of mixing is noted as more predominant for 5 minutes of mixing time. With further reduction of w/b ratio to 0.28, the paste is thick enough at all dosages and flow does not occur at all through the Marsh cone. Overall, fluidity is maintained reasonably

well even 60 minutes after mixing especially if mixing time of 8, and 10 minutes is adopted indicating a good compatibility of cement and superplasticizer.

Cement-P: Flow does occur at all the superplasticizer dosages with a w/b of 0.34 and a mixing time of 5 minutes. However, significant improvement in fluidity is observed with superplasticizer dosages exceeding 0.4 %. This is true for both immediately and 60 minutes after the mixing. The flow is noted to be faster with the increase of mixing time, for example, 8 and 10 minutes, although ceases at a superplasticizer dosage of 0.4 % or lower. Fluidity is retained reasonably well in all the cases with slightly better retention observed against increasing mixing time. When w/b is reduced to 0.32 (Figure 9), the flow neither occurs immediately nor 60 minutes after the mixing with superplasticizer dosage of 0.4 %. A similar trend as that of 0.34 w/b is observed at all other dosages of superplasticizer. The pastes with a w/b of 0.3 do not flow at superplasticizer dosages below 1 % possibly owing to the increased demand. Further, none of the mixes at this w/b ratio show a flow time less than 140 sec for 2000 g of paste. The minimum flow time of 147 sec is

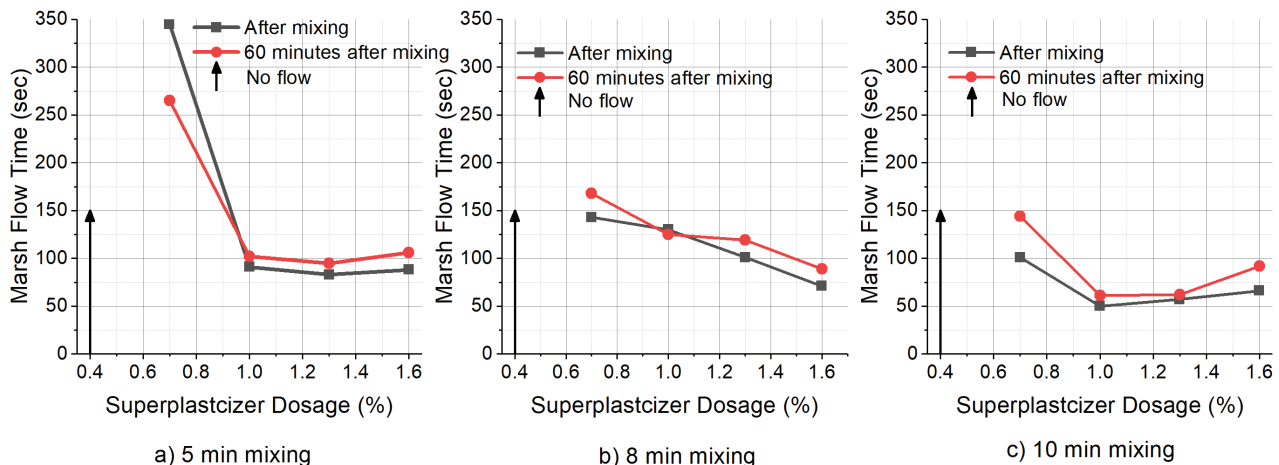


Figure 9: Marsh cone flow time for 2000 g paste made with cement-P at different mixing times for w/b 0.32

observed for 1.3 % superplasticizer dosage with mixing time of 10 minutes. Some of the mixes in this case also show better fluidity at 60 minutes after the mixing provided the mixing time is less than 10 minutes. However, this over-fluidification behavior disappears if the mixing is continued up to 10 minutes.

**Cement-U:** The marsh cone results for cement-U at  $w/b$  ratio 0.34 is shown in Figure 10. A significant loss in the fluidity is observed after 60 minutes [Figure 10(a)] for a paste with  $w/b$  ratio of 0.34 and a mixing time of 5 minutes. However, this loss in fluidity reduces with increasing mixing time, for example, 8, and 10 minutes [Figure 10(b), and (c)]. Further, the resulting saturation dosages are different when tested immediately and 60 minutes after the mixing. This behavior; however, is not observed with prolonged mixing time, for example, 8, and 10 minutes. Flow time, if mixed for 5 minutes is longer than 800 sec for 2000 g paste with  $w/b$  of 0.32 although the paste does not flow at superplasticizer dosage of 0.4 % or lower. The flow time drastically reduces to 218 sec for the same paste but with mixing time increased to 10 minutes and however the flow ceases for a mixing time of 8 minutes. Similarly, the flow time reduces significantly with an increase in the mixing time for all other dosages of superplasticizer. A similar trend of results for flow time is also observed at  $w/b$  of 0.30. Moreover, the increase in fluidity at 60 minutes after the mixing is again noticed for 5 minute mixing time which however is not the case with prolonged mixing time.

Therefore, the results indicate that the superplasticizer is compatible with all the three cement brands as fluidity is maintained reasonably well at even 60 minutes after mixing. The degree of fluidity is different though. This is further explained in section 3.1.4. The increase in fluidity with time or the over-fluidification observed in some cases may be attributed to acrylate based PCEs in which ester bonds at high pH of cementitious system (12.5-13) are cleaved/hydrolysed with time. Such PCEs show slow adsorption until the first few minutes of coming into contact with cement as is also mentioned in the

data sheet provided by the manufacturer<sup>[20,21]</sup>. Once the ester bonds are hydrolysed, the PCEs that are still free in the solution become more ionic and further adsorption takes place, which leads to a better flow of paste. This contradicts with the loss of fluidity with time and the PCEs with such polymers are good slump keepers<sup>[25]</sup>. Further explanation over this is presented in section 3.1.2.1. The significant loss of fluidity with time in Cement-U is probably due to the higher content of C3A in this cement compared to the other two as seen in Table 2. C3A during hydration intercalates the PCE superplasticizer making less amount of it available for adsorption and hence reduces its effectiveness<sup>[26]</sup>. This will also be discussed in more detail in the subsequent sections.

### 3.1.2.1 Rationale of over-fluidification

PCE comb polymers consist of an anionic backbone bearing carboxylic groups and side chains of polyethylene glycol (PEG) attached covalently to the backbone<sup>[25]</sup>. The anionic backbone enables it to adsorb onto the cement surface while PEG side chains stretch into the solution<sup>[27]</sup>. Depending upon the number of free carboxylic groups in the backbone, negative charge is developed on the cement surface<sup>[25]</sup>. Also, PEG chains induce steric repulsive forces, if the surfaces come very close to each other<sup>[25,27]</sup>. The backbone may consist of acrylic acid, methacrylic acid, and maleic acid as their anionic components and polyethylene oxide, also known as polyethylene glycol (PEG), are used as side chains in majority of the PCE polymers. These side chains are attached to the backbone via ester, amide or ether bonds. The backbone in acrylate based PCEs is formed of acrylic acid (acrylic ester or acrylic amide). Ester bonds in acrylic ester polymers in the alkaline pore solution of cement paste (pH~12-13) cleave/hydrolyse with time while methacrylic ester bonds are more stable in the cementitious system. Thus, PCEs where PEG chains are connected to acrylic units by ester bonds, due to ester bond cleavage, increase the number of carboxylic groups. Hence, the ionic charge in the backbone increases with time, which in turn, leads to further adsorption

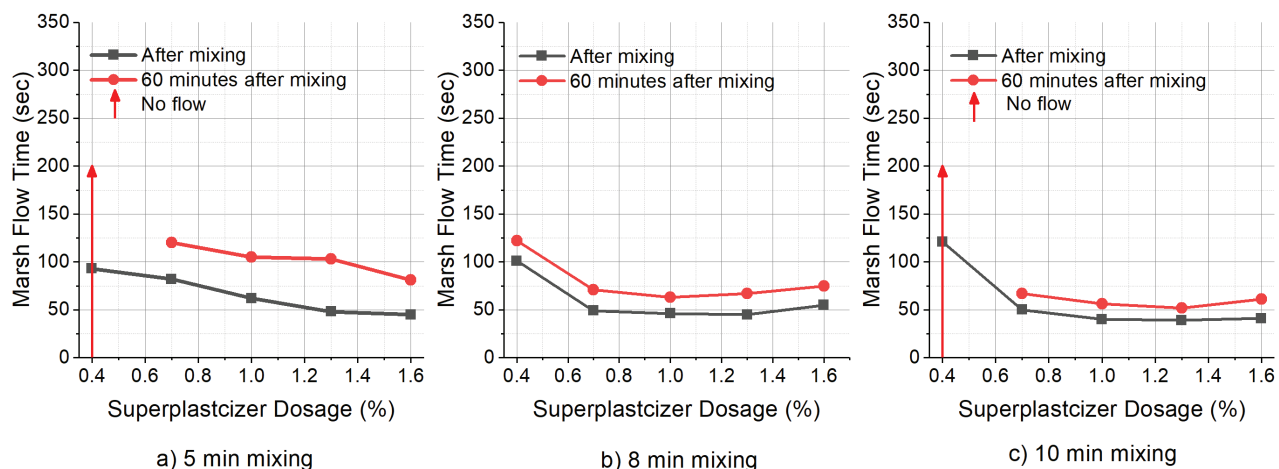


Figure 10: Marsh cone flow time for 2000 g paste made with cement-U at different mixing times for  $w/b$  0.34



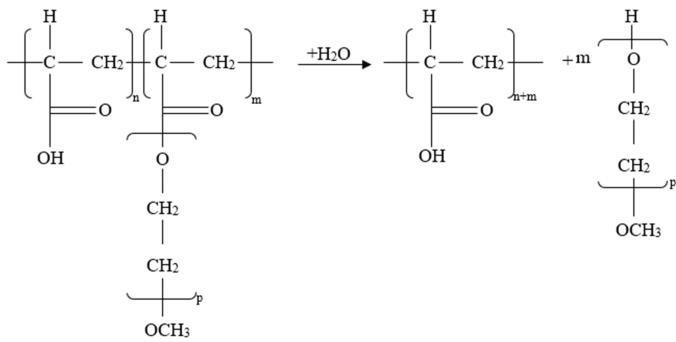


Figure 11: Ester hydrolysis (adapted from Flatt, and Schober [25])

with better flow of paste. This kind of ester hydrolysis is shown in Figure 11. However, if the side chains are connected via amide or ether bonds, these bonds are more stable in the alkaline pore solution and hence, will not be cleaved with time. Different strategies are adopted to incorporate such flexible ester groups in the PCEs. For example, all side chains can be linked to the backbone via acrylic ester bonds. It will lead to the formation of polymers with no or reduced degree of grafting against the release of PEG chains with time. Among other options include the use of acrylic as well as methacrylic ester bonds. In this case, methacrylic ester bond will either not hydrolyse in the pore solution, or hydrolyse only to a small extent. This will result in the formation of a more ionic PCE while also maintaining its comb shape [25].

### 3.1.3 Effect of mixing time on fluidity of pastes

In some mixes, especially where higher superplasticizer dosages or lower water-binder ratios are used, the fluidity is better at 60 minutes after the mixing as compared to that observed immediately after the mixing. This behavior is explained above and can be seen in Figure 7(a), 7(b), 8(a), and 9(b). Therefore, if mixing is continued for a longer duration, one may anticipate a better degree of fluidity, especially, immediately after the mixing. In other words, expectation is loss of fluidity over

time with prolonged mixing time. Hence, the test is repeated adopting the mixing time of 8, and 10 minutes. The variation of flow time with superplasticizer dosage corresponding to different mixing time for Cement-A is shown in Figure 12. Other cements also follow the similar trend. A very significant reduction in flow time is observed in the pastes made of Cement-A, and -U for prolonged mixing time of 8, and 10 minutes when compared with the previous case of 5 minutes at all  $w/b$  and both the testing periods. Although the least flow time is shown by the pastes mixed for 10 minutes, the reduction when compared to the pastes mixed for 8 minutes is relatively insignificant. No significant improvement in the fluidity is observed in the case of Cement-P when the mixing time is increased to 8 minutes. However, with a further increase in the mixing time until 10 minutes, flow time is reduced significantly in all the pastes at both the testing times. Further, as already explained in section 2.2, the over-fluidification is also not observed for a mixing time of 10 minutes indicating the incomplete mixing and/or poor adsorption in the former cases. Regnaud *et al.* [14] also observed the reduction in the over-fluidification when mixing time was increased. A better fluidity due to increased mixing time may be attributed to better dispersion of cement particles. The shear forces generated during mixing may also remove the early hydration products from the surface, creating a larger surface area for adsorption of superplasticizer [25]. Prolonged mixing time also allows more ester bonds to hydrolyse by offering more time (as ester bonds hydrolyse with time) and adsorbing more on the surface of cement particles as explained in section 3.1.2.1. This may also be considered as a contributing factor.

### 3.1.4 Variability of fluidity with cement brand

The variation of fluidity with the superplasticizer dosage for Cement-A, Cement-U and Cement-P immediately and 60 minutes after the mixing is shown in Figure 13 and Figure 14 for  $w/b$  ratio of 0.34 and 0.32, respectively. All three brands of cement at both  $w/b$  ratios, show by-and-large the same degree

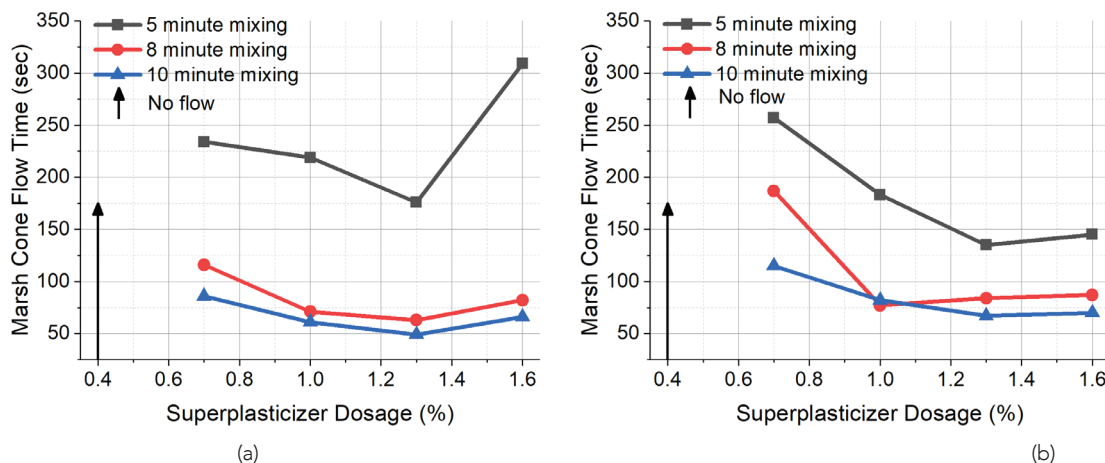


Figure 12: Variation of flow time with dosage for cement-A ( $w/b = 0.32$ ) at different mixing times (a) after mixing, (b) 60 minutes after mixing

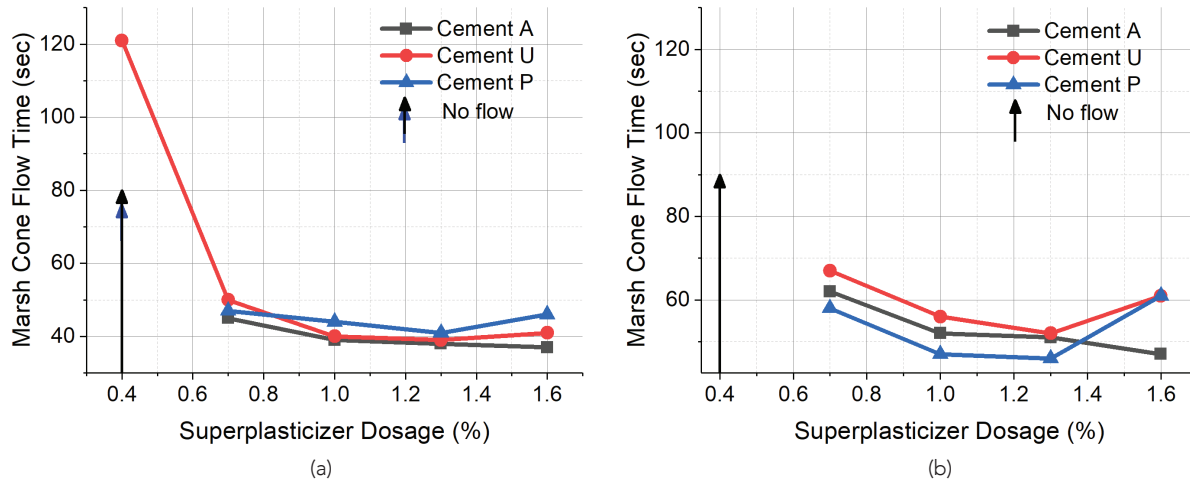


Figure 13: Flow time for cement-A, -U and -P (a) after mixing (b) 60 minutes after mixing for  $w/b$  0.34

of fluidity as well as the same superplasticizer demand when tested immediately after the mixing. However, a significant difference in fluidity is observed at 60 minutes after the mixing. Saturation dosages for all three cements are noted as about 1 percent for  $w/b$  0.34 (Figure 13b). Cement-P shows the least flow time which is followed by Cement-A with Cement-U as the maximum. This trend is in the order of their C3A content (Table 2). Further, the superplasticizer demand at  $w/b$  ratio of 0.32 (Figure 14) is the least for Cement-P with a saturation dosage of 1 percent; whereas, that associated with Cement-A and -U is about 1.3 percent. Similar results were reported by Nkinamubanzi and Aitcin<sup>[7]</sup> based on the testing of 10 cements in order of their C3A contents with an influence of increasing superplasticizer demand (as the C3A content increases). C3A during hydration initially forms calcium aluminium layered double hydroxides (Ca-Al-LDHs) which are metastable compounds with hydroxide as an interlayer anion<sup>[28]</sup>. Number of anions in between the cationic layers of these LDH compounds can be intercalated by replacing the hydroxide ions. Linear polyelectrolytes such as polyacrylate, polystyrene sulfonate, and others can also intercalate between these cationic layers<sup>[29]</sup>.

Superplasticizers also belong to the category of polyelectrolyte admixture and hence can intercalate into the hydrating C3A resulting in the formation of organo-mineral compound<sup>[25,28,29]</sup>. This sequestered material may become unavailable for adsorption and reduce the effectiveness of superplasticizer in increasing the fluidity. Although, the hydration of C4AF may also lead to the formation of LDHs, it seems intercalation of superplasticizer is more governed by the presence of C3A. Thus, interaction with the superplasticizer is expected to increase with C3A content of cement. Finally, OPC with low C3A content is preferred for use in high-performance concrete<sup>[29]</sup>.

### 3.2 Flow table test

*Cement-A:* The flow table results for Cement-A at  $w/b$  0.28 are shown in Figure 15. The results are similar at other  $w/b$  ratios as well. However, the mortar is stiff at  $w/b$  ratio of 0.26, and does not show any significant spread in the diameter until 1% dosage of superplasticizer. Significant improvement in the flow is also noted beyond this dosage. At the dosage of 1.3%, the flow diameter is measured as 141 mm, which further increases

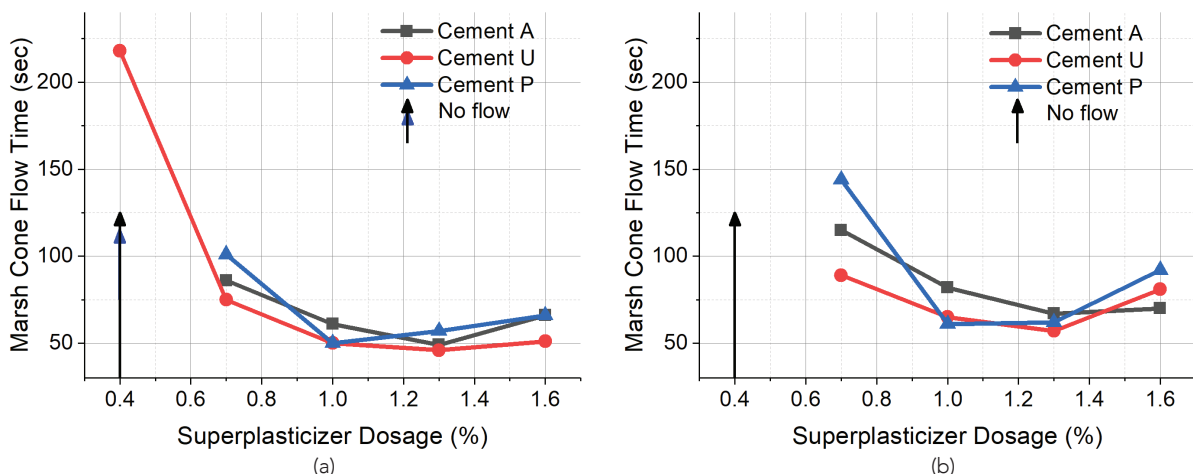


Figure 14: Flow time for cement-A, -U and -P (a) after mixing, (b) 60 minutes after mixing for  $w/b$  0.32

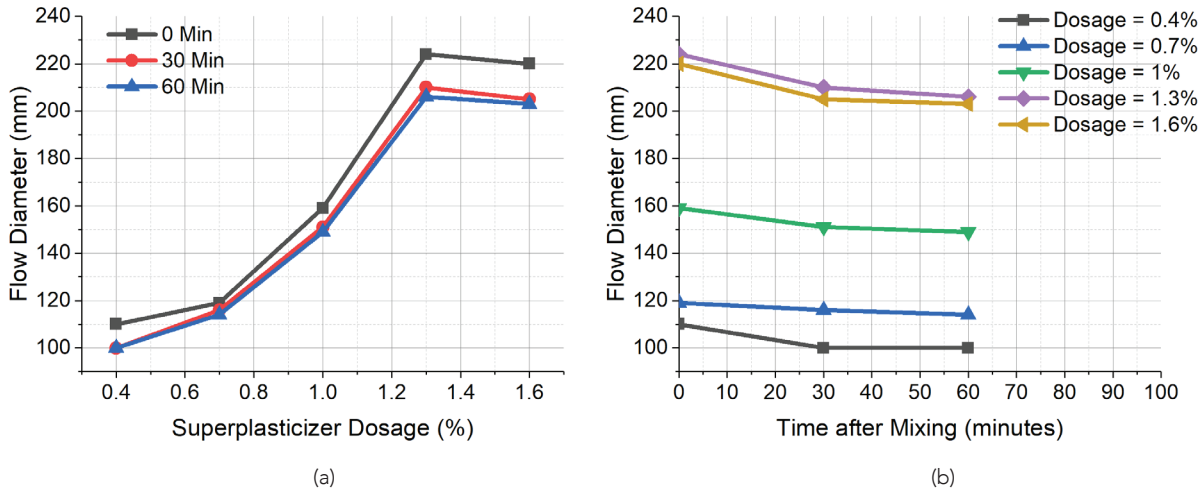


Figure 15: Variation of flow diameter with (a) superplasticizer dosage, (b) time for cement-A at w/c 0.28

to 166 mm at the dosage of 1.6 % when tested immediately after the mixing. No significant reduction in the flow diameter is observed at 30 minutes, and 60 minutes after mixing indicating good compatibility of cement and superplasticizer. Significant improvement in the flow is observed at w/b ratio of 0.28 (Figure 15) but beyond the superplasticizer dosage of 0.7 %. Maximum benefit in the flow is observed at the dosage in the range of 1 to 1.3 %. A slight reduction in the flow diameter beyond this range indicates 1.3 % as the saturation dosage. Overall, no significant reduction is observed in the flow of the mortar with time once again indicating a good compatibility. However, some initial reduction in the diameter is observed from 0 to 30 minutes after mixing which is later stabilised with no further reduction between 30 to 60 minutes. This may probably be attributed to the initial absorption of water by dry sand particles. Superplasticizer demand, as expected, further reduces when the w/b ratio increases to 0.30. Flow table test seems not possible beyond the superplasticizer dosage of 1 % as the diameter of spread exceeds that of flow table. In this case also, some initial reduction in the flow diameter is observed from 0 to 30 minutes after the mixing which later stabilises with no such reduction in spread beyond 30 minutes.

**Cement-U:** Slightly better fluidity as compared to Cement-A is evident. No significant spread in the diameter is observed at a w/b ratio of 0.26 till the superplasticizer dosage increases to 0.7 %. A continuous increase in the flow diameter is observed beyond this dosage. Significant increment in the spread of the mortar immediately after mixing is noticed when superplasticizer dosage changes to 1.6 % from 1.3 %. However, it fails to retain its fluidity with no considerable difference in spread diameter at 30 and 60 minutes after mixing. No significant loss in fluidity is observed at all other dosages. A similar trend of results with improved fluidity is observed at w/b ratio of 0.28 with a saturation point around 1.3 %. The test was possible until the dosage of

0.7 % at w/b ratio of 0.30. Beyond this dosage, spread diameter exceeded the diameter of the table.

**Cement-P:** No significant improvement in the fluidity is observed at w/b ratio of 0.26 till the superplasticizer dosage of 1.3 %. Only a marginal increase in mortar flow is observed beyond this dosage. The flow diameter increases continuously at w/b ratio of 0.28 until the superplasticizer dosage of 1.3 %. There is no considerable improvement in the flow beyond this dosage, indicating 1.3 % as a saturation dosage. Reduction in the fluidity of mortar is also not noticed with time. The mortar shows better fluidity with reduced superplasticizer demand at w/b ratio of 0.30. The flow table test is also possible at 0.30 w/c at higher superplasticizer dosages in this cement. This cement shows lesser fluidity when compared with other two, consistent with the Marsh cone test results at this w/b performed earlier.

It is observed that at lower w/b ( $\leq 0.30$ ), Cement-P, despite having the least C3A content, does neither show the least flow time nor the largest flow diameter, which, however, is the case when w/b ratio is higher ( $> 0.30$ ). The fineness or specific surface area of Cement-P is the largest ( $339 \text{ m}^2/\text{kg}$ ), followed by Cement-A ( $322 \text{ m}^2/\text{kg}$ ), and Cement-U ( $281 \text{ m}^2/\text{kg}$ ). Larger surface area means more water is required to cover the surface. Also, the superplasticizer required to adsorb on the surface of the cement particles will be more. Thus, fineness of the cement increases the water and superplasticizer demand. In other words, less fluidity will be achieved at a given w/b ratio and a superplasticizer dosage. It seems that the fineness of Cement plays a more dominating part at lower w/b ratio than C3A content to influence the fluidity and superplasticizer demand. The early hydration might not be so fast due to lesser water availability. Hence, the fineness of the cement, increasing the surface area of hydration may come into the picture and show a dominating influence on the fluidity of the paste. This might cause Cement-U with least fineness to flow better than Cement-A, and Cement-P when w/b ratio is lower than 0.30.

## 4. CONCLUSIONS

1. Flow time curves are by-and-large flat at the initial stage and become steeper as the material flows out of the cone due to a drop in the flow velocity. Consequently, the saturation point of the superplasticizer becomes more evident on the flow time curve. Hence, one should decide the saturation dosage of the superplasticizer only after allowing a sufficient quantity of the paste to flow out of the cone. In the absence of a well-defined optimum, it is recommended to consider the time to empty the apparatus. Arbitrary selection of the reference quantity of flow is likely to infer either the non-existence of a well-defined saturation point or the existence of an incorrect saturation point.
2. Increasing the mixing time results in a significant improvement in the fluidity and its retention. Further, the over-fluidification behavior due to slow initial adsorption of superplasticizer does not occur with the prolonged mixing time. Hence, while deciding the compatibility of cement, and superplasticizer, one must ensure that the mixing is complete. It is recommended to adopt a mixing time of 10 minutes based on the limited experiments carried out in this paper.
3. Superplasticizer demand of the cement paste is influenced by C3A content and the fineness of cement. At higher  $w/b$  ratio ( $> 0.30$ ), the cement with the least C3A content shows better fluidity and the least superplasticizer demand. However, the fineness of cement has a more dominating influence on the superplasticizer demand or the fluidity at lower  $w/b$  ratio ( $\leq 0.30$ ) and the cement with least fineness shows the highest degree of fluidity.
4. Marsh cone test is not suitable for determining the flow behavior of the paste at  $w/b$  ratio below 0.3 due to an increase in its viscosity. However, for low sand to cement ratio ( $\sim 0.62$ ), as is generally the case for  $\sim 100$  MPa concrete with coarse aggregates, the flow behavior can be effectively studied with the help of a flow table when  $w/b$  ratio is lower than 0.30. Inferences based on the results of flow table test are consistent with that from marsh cone test at the  $w/b$  of 0.3.

## REFERENCES

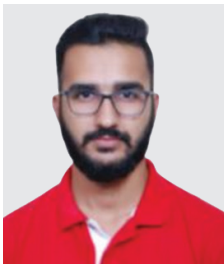
- [1] Jayasree, C., Gettu, R. (2008). "Experimental study of the flow behaviour of superplasticized cement paste". *Materials and Structures/Materiaux et Constructions*. Vol. 41, No. 9 pp. 1581-1593. doi:10.1617/s11527-008-9350-5
- [2] Li, L. G., and Kwan, A.K.H. (2013). "Concrete mix design based on water film thickness and paste film thickness". *Cement and Concrete Composites*. Vol. 39, pp. 33-42. doi:10.1016/j.cemconcomp.2013.03.021
- [3] Kennidyyt, C.T. (1940). "The design of concrete mixes." *Proceedings of the American Concrete Institute*. Vol. 36, No. 2, pp. 373-400.
- [4] Agulló, L., Toralles-Carbonari, B., Gettu, R., and Aguado, A. (1999). "Fluidity of cement pastes with mineral admixtures and superplasticizer - A study based on the Marsh cone test". *Materials and Structures/Materiaux et Constructions*. Vol. 32, No. 7, pp. 479-485. doi:10.1007/bf02481631
- [5] BS EN 445:2007 (2007) "Grout for prestressing tendons - Test methods" *British Standards Institution*.
- [6] Roussel, N., and Roy, R. L (2005). "The Marsh cone: A test or a rheological apparatus?" *Cement and Concrete Research*. Vol. 35, No. 5, pp 823-830. doi:10.1016/j.cemconres.2004.08.019
- [7] Nkinamubanzi, P. C., and Aitcin, P. C. (2004). "Cement and superplasticizer combinations: Compatibility and robustness". *Cement, Concrete and Aggregates*. Vol. 26, No. 2, pp. 102-109. doi:10.1520/cca12329
- [8] Shrivastava, A. K., and Kumar, M. (2016). "Compatibility issues of cement with water reducing admixture in concrete". *Perspectives in Science*. Vol. 8, pp. 290-292. doi:10.1016/j.pisc.2016.04.055
- [9] Hallal, A., Kadri, E. H., Ezziane, K., Kadri, A., and Khelafi, H. (2010). "Combined effect of mineral admixtures with superplasticizers on the fluidity of the blended cement paste". *Construction and Building Materials*. Vol. 24, No. 8, pp. 1418-1423. doi:10.1016/j.conbuildmat.2010.01.015
- [10] Thankaswamy, A., and Xavier, C. S. B. (2021). "Investigation on the effect of Colocasia esculenta extract on the fresh properties of cement paste". *Materials Today Proceedings*. Vol. 45, No. 6 pp. 4712-4718. doi:10.1016/j.matpr.2021.01.142
- [11] Roncero, J., Gettu, R., Gomes, P. C. C., and Agull, L. (2000) "Study of Flow Behavior of Superplasticized Cement Paste Systems and its Influence on Properties of Fresh Concrete". *Symposium Paper*. pp. 273-294.
- [12] Khalid, A. R., Rizwan, S. A., Hanif, U., and Hameed, M. H. (2016). "Effect of Mixing Time on Flowability and Slump Retention of Self-Compacting Paste System Incorporating Various Secondary Raw Materials". *Arabian Journal for Science and Engineering*. Vol. 41, No.4, pp. 1283-1290. doi:10.1007/s13369-015-1885-5

- [13] Nkinamubanzi, P. C., Mantellato, S., and Flatt, R. J. (2016). "Superplasticizers in practice". *Science and Technology of Concrete Admixtures*, Woodhead Publishing 2016, pp. 353-377, ISBN 9780081006931, <https://doi.org/10.1016/B978-0-08-100693-1.00016-3>.
- [14] Regnaud, L., Nonat, A., Pourche, S., and Pellerin, B. (2006). "Changes in cement paste and mortar fluidity after mixing induced by PCP: A parametric study". *Proceedings of the 8th CANMET/ACI International Conference on Superplasticizers and other chemical admixtures in concrete*. pp. 389-408.
- [15] Fernández-Altable, V., and Casanova, I. (2006). "Influence of mixing sequence and superplasticiser dosage on the rheological response of cement pastes at different temperatures". *Cement and Concrete Research*. Vol. 36, No. 7, pp. 1222-1230. doi:10.1016/j.cemconres.2006.02.016
- [16] IS: 269 (2015). "Ordinary portland cement specification", Bureau of Indian Standards, New Delhi, India
- [17] BS: 13263 (2005). "Silica fume for concrete (Part 1): Definitions, requirements and conformity criteria". *British Standards Institution*.
- [18] IS: 383 (2016). "Coarse and fine aggregate for concrete-specification (Third Revision)". Bureau of Indian Standards, New Delhi, India
- [19] IS: 9103 (1999): "Specification for concrete admixtures". Bureau of Indian Standards, New Delhi, India
- [20] "<http://www.master-builders-solutions.com/en-in>" [www.master-builders-solutions.com/en-in](http://www.master-builders-solutions.com/en-in). PCE based superplasticiser for high quality ready-mix concrete using Total Performance Control™. Accessed September 14, 2022.
- [21] <https://www.master-builders-solutions.com/en-in/products/masterglenium/masterglenium-sky-8784>. MasterGlenium SKY 8784. Accessed September 14, 2022.
- [22] Aïtcin, P. C. (1998). "High\_Performance\_Concrete". CRC Press.
- [23] Roy, R. L., and Roussel, N. (2005). "The Marsh cone as a viscometer: Theoretical analysis and practical limits". *Materials and Structures/Materiaux et Constructions*. Vol. 38, No. 1, pp. 25-30. doi:10.1617/14115
- [24] Schober, I., and Mader, U. (2003). "Compatibility of polycarboxylate superplasticizers with cements and cementitious blends". *American Concrete Institute, ACI Special Publication*. Vol. 217, pp. 453-468.
- [25] Flatt, R., and Schober, I. (2012). "Superplasticizers and the Rheology of Concrete". *Woodhead Publishing Series in Civil and Structural Engineering, Understanding the Rheology of Concrete* Woodhead Publishing Limited pp. 144-208. doi:10.1533/9780857095282.2.144
- [26] Ng, S., Metwalli, E., Müller-buschbaum, P., and Plank, J. (2013). "Occurrence of intercalation of PCE superplasticizers in calcium aluminate cement under actual application conditions, as evidenced by SAXS analysis". *Cement and Concrete Research*. Vol. 54 pp. 191-198. doi:10.1016/j.cemconres.2013.09.002
- [27] Hirata, T., Ye, J., Branicio, P., Zheng, J., Lange, A., Plank, J., and Sullivan, M. (2017). "Adsorbed Conformations of PCE Superplasticizers in Cement Pore Solution Unraveled by Molecular Dynamics Simulations". *Scientific Reports*. Vol. 7, No. 1, pp 1-10. doi:10.1038/s41598-017-16048-3
- [28] Plank, J., Zhimin, D., Keller, H., Hössle, F., and Seidl, W. (2010). "Cement and concrete research fundamental mechanisms for polycarboxylate intercalation into C3A hydrate phases and the role of sulfate present in cement". *Cement and Concrete Research*. Vol. 40, No. 1, pp 45-57. doi:10.1016/j.cemconres.2009.08.013
- [29] Plank, J., Keller, H., Andres, P. R., and Dai, Z. (2006). "Novel organo-mineral phases obtained by intercalation of maleic anhydride – allyl ether copolymers into layered calcium aluminum hydrates". *Inorganica Chimica Acta*. Vol. 359, No. 15, pp. 4901-4908. doi:10.1016/j.ica.2006.08.038
- [30] Giaccio, G., and Zerbino, R. (2002). "Optimum superplasticiser dosage for systems with different cementitious materials". *Indian Concrete Journal*. Vol. 76, No. 9 special, pp. 553-557.
- [31] Robert, C. R, Sathyan, D., and Anand, K. B. (2018). "Effect of superplasticizers on the rheological properties of fly ash incorporated cement paste". *Materials Today Proceeding*. Vol. 5, No. 11, pp. 23955-23963. doi:10.1016/j.matpr.2018.10.188
- [32] John, E., and Gettu, R. (2014). "Effect of temperature on flow properties of superplasticized cement paste". *ACI Materials Journal*. Vol. 111, No. 1, pp 67-76. doi:10.14359/51686447
- [33] Manomi, N., Sathyan, D., and Anand, K. B. (2018). "Coupled effect of superplasticizer dosage and fly ash content on strength and durability of concrete". *Materials Today Proceedings*. Vol. 5, No. 11, pp. 24033-24042. doi:10.1016/j.matpr.2018.10.196

- [34] Sonebi, M., Kwasny, J., and Jumahat, M. A. H. (2012). "Effect of diutan gums and superplasticizers on the rheology of cement-based grouts". *American Concrete Institute, ACI Special Publication*. Vol. 288 SP pp. 119-130. doi:10.14359/51684224
- [35] Benaicha, M., Jalbaud, O., Alaoui, A. H., and Burtschell, Y. (2015). "Marsh cone coupled to a plexiglas horizontal channel: Rheological characterization of cement grout". *Flow Measurement and Instrumentation*. Vol. 45, pp. 126-134. doi:10.1016/j.flowmeasinst.2015.06.004
- [36] Kondraivendhan, B., and Bhattacharjee, B. (2015). "Flow behavior and strength for fly ash blended cement paste and mortar". *International Journal of Sustainable Built Environment*. Vol. 4, No. 2, pp. 270-277. doi:10.1016/j.ijbsbe.2015.09.001
- [37] Krishnamoorthy, T. S., Gopalakrishnan, S., Balasubramanian, K., Bharatkumar, B. H., and Rao, P. R. M. (2002). "Investigations on the cementitious grouts containing supplementary cementitious materials". *Cement and Concrete Research*. Vol. 32, No. 9, pp. 1395-1405. doi:10.1016/S0008-8846(02)00799-8
- [38] Tiwari, A. K., Panseriya, M. M, Mathur, P. C., and Chowdhury, S. (2015). "Effect of supplementary cementitious materials on the rheology of blended cements". *American Concrete Institute, ACI Special Publication*. Vol. 303 Special., pp. 205-216.



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