International Journal of Sustainable Built Environment (2016) xxx, xxx-xxx



Original Article/Research

Setting time and standard consistency of quaternary binders: The influence of cementitious material addition and mixing

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Received 24 August 2016; accepted 25 October 2016

Abstract

This paper presents three pozzolanic materials that were used to make quaternary binders, Granulated blast furnace slag, fly ash (PFA), metakaolin, and silica fume as partial replacement in quaternary binders with Ordinary Portland Cement (OPC) to investigate the effect of standard consistency, initial and final setting times of quaternary paste. Experiments demonstrate that SF has greater influence on the standard consistency of the OPC–FA–SF–GGBS paste, as compare to FA and GGBs. Water requirement in the paste escalates, with increase in SF percentage level within the paste, owing to the high surface area. In case of GGBS, around 3–5% of reduction in water/binder ratio was recorded, whereas for SF, it was 10–12%. In quaternary OPC–FA–SF–GGBS pastes, increases in initial and final setting times at 5%, 7.5%, 10%, and 15% replacement of SF and GGBS were observed, whereas OPC–FA–SF–MK paste setting time shows an increase at 5% replacement of SF and MK with 20% and 70% replacement of FA and OPC, however, it starts decreasing between 7.5% and 15% replacement of SF and MK. The consistency of the quaternary binders increases with an increase in percentage of SF and MK. In general the effect of FA, SF, GGBS and MK reflects in the behavior of quaternary binders even though the performance of all three pozzolans behaves completely independent of each other.

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Keywords: Ordinary Portland Cement; Pozzolans; Fly ash; Metakaolin; Silica fume; Ggbs; Consistency; Initial and final setting times

1. Introduction

Setting properties of concrete is the most important part in the field of concrete construction (Brooks et al., 2000). It helps in the development of different kinds of concreting operations such as transporting, placing, compacting and

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finishing of concrete. Placement of concrete in formwork depends on the setting time of concrete, which makes the concrete rigid (Clear and Harrison, 1985). Nowadays production of new generation concrete like geopolymer concrete, self-compacting concrete, high strength concrete, and high performance concrete has been increasing throughout the world. For their better performance and to achieve better engineering properties, mineral admixtures such as fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK) and rice husk ash (RHA) are normally added as partial replacement of cement for the better performance of advanced concrete.

http://dx.doi.org/10.1016/j.ijsbe.2016.10.004

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Peer review under responsibility of The Gulf Organisation for Research and Development.

Since the different mineral admixtures possess different chemical and mineralogical compositions as well as different particle characteristics, they could have different effects on the properties of concrete inclusive of the setting characteristics. Knowledge of the setting characteristics is important in the field of concrete construction. This will help in scheduling the various stages involved in concrete construction operation such as transporting, placing, compacting and finishing of concrete. Such information is necessary when deciding whether or not to use a retarding admixture or accelerator.

The hydration product formation starts immediately once the water is mixed within the cement. The initial and final setting time of concrete can be determined by the rigid behavior of the matrix. The initial setting time of the concrete refers to the beginning of hardening of the mixture and the final setting time refers to the sufficient hardness of the concrete mixture (Naik et al., 2001). Studies have reported that with increase in fly ash content within the binder, setting time also increases (Brooks et al., 2000; Carette and Malhotra, 1984). A study shows (Mailvaganam et al., 1983) that setting time of ternary blended concrete made of FA and GGBs shows delayed initial setting time in the range of 60–120 min.

Silica fume is the byproduct of silicon industry and it is a pozzolanic material, which is used to improve the fresh and hardened properties of concrete (Federation internationale de la Precontrainte, 1988; Yazici, 2007). Utilization of silica fume with fly ash gives an interesting substitute. Much research has been conducted on ternary binder using a combination with FA and SF (Demirboga, 2007; Yazici et al., 2008). A study also (Snelson, 2011) investigated the utilization of fly ash/or ground granulated blast furnace slag (GGBs) with silica fume. Using the Ground granulated blast furnace slag in binder, the setting time can be slightly extended. The effect of GGBS is more pronounced at high level replacement in binders. An extended setting time is an advantage, as it makes concrete remain workable for a longer period of time, therefore resulting in fewer joints and it is extremely useful in warm weather.

MK and SF have a very high surface area, due to very high fineness of MK and SF, the effects on setting time is different as compared to FA and GGBS. Although there is an increase in both initial and final setting times at low replacement levels of SF and MK, binary effects of other mineral admixtures investigated with silica fume (SF), fly ash (FA) and ground granulated blast furnace slag (GGBS), show an increase in setting times with an increase in replacement level.

The present study findings revealed that the combined quaternary effect of FA, SF and MK/GGBS with the replacement of OPC was unusual. With an increase in percentage levels of SF, and GGBS the initial and final setting time also increases, whereas, with an increase in percentage level of MK in quaternary binders, there is a decrease in initial and final setting time. A study (Mehta and Monteiro, 1993) reported that initial setting time that estimated the time limit to handle the concrete and final setting time designates the onset improvement of strength. It was also, examined that setting time of concrete depends on water/binder ratio, initial and curing temperature, dosage, type of mineral admixtures and composition of cement (Kruml, 1990; Eren et al., 1995; Naik and Singh, 1997; Naik and Ramme, 1990; Hogan and Meusel, 1981; Sivasundaram et al., 1989; Tazawa et al., 1989; Khedr and Abou-Zeid, 1994; Alshamsi et al., 1997, 1993; Pistilli et al., 1984; De Almeida and Goncalves, 1990; Malhotra and Mehta, 1996; Ramachandran and Malhotra, 1995). Some researchers have found that with the increasing percentage level of FA and GGBS, the setting time of concrete decreases (Eren et al., 1995; Naik and Singh, 1997; Naik Ramme, 1990; Hogan and Meusel, and 1981: Sivasundaram et al., 1989; Tazawa et al., 1989; Verma and Misra, 2015; Dave et al., 2016). Reverse effect has been investigated in case of silica fume. It was investigated that SF increases the setting time with the replacement level (Alshamsi et al., 1997; Alshamsi et al., 1993; Pistilli et al., 1984). The objective of this study is to investigate the combined effects of mineral admixtures in quaternary binders, to our knowledge no other author has identify the setting time effects in quaternary binders with the utilization of mineral admixtures.

2. Experimental studies

2.1. Materials

Ordinary Portland Cement, fly ash, GGBs, silica fume and metakaolin are used in the production of quaternary binders. The physical and chemical properties OPC, FA, SF, GGBS and MK are represented in Table 1. The combinations of the binder series has been divided into three groups: Group 1 (100% OPC), Group 2 (OPC + SF + FA + GGBS), Group 3 (OPC + SF + FA + MK). The details of three groups are represented in table 2.

2.2. Preparation of specimens

Vicat apparatus was used to determine standard consistency, initial and final setting time of the quaternary binders and placed in a mold as per IS 4031 part 4 and 5 (IS 4031 (4), 1988; IS 4031 (5), 1988). The mix proportion for consistency and setting times of the quaternary binders with and without supplementary cementitious materials (at 30% and 50% replacement by weight of OPC) are given in table 2. The standard consistency of the paste is determined by adding water at different percentage levels till the paste has a given resistance to penetration.

Vicat apparatus mold has been used to determine the standard consistency of different pastes. Consistency was recorded when the plunger of the Vicat apparatus pene-trated into the paste 5 mm to 7 mm above the bottom of the mold. Consistency was determined by taking an aver-

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Table 1	
Physical and Chemical properties of the OPC, FA, GGBS and SF.	

	OPC	Fly Ash	GGBS	SF	MK	Water
Physical properties						
Specific gravity	3.15	2.34	3.10	2.25	2.72	1.00
Blaine's fineness, cm ² /gm 2287		3728	3350	16028	8738	
Chemical properties						
Calcium oxide, Cao %	66.71	1.32	35.91	1.45	1.47	
Aluminum oxide, Al ₂ O ₃ %	9.83	25.98	17.1	0.8	46.89	
Silicon dioxide, SiO ₂ %	17.53	62.21	40.69	87.29	50.67	
Manganese oxide, MnO %	0.02	0.03	0.035	0.00	0.00	
Ferric oxide, Fe ₂ O ₃ %	2.18	3.29	0.69	1.51	0.39	
Magnesium oxide, MgO %	1.25	2.62	3.77	0.14	0.10	
Sodium oxide, Na ₂ O %	0.21	0.052	0.20	0.38	0.081	
Potassium oxide, K ₂ O %	0.49	0.998	0.561	2.02	0.19	
Loss of ignition %	0.8	3.36	1.09	2.1	0.57	

Table 2

Percentage of ingredients for consistency and setting times.

Series	Cement mixes	(gm)			Standard	IS/FS (min)		
		OPC	FA	SF	GGBS	MK	Consistency	
Control	OPC100%	400	0	0	0	0	32	150/220
G 1								
1	OPC70% SF 5% FA20% GGBS5%	280	80	20	20	0	29.5	160/215
2	OPC70% SF 7.5% FA15% GGBS7.5%	280	60	30	30	0	31	170/245
3	OPC50% SF 10% FA30% GGBS10%	200	120	40	40	0	33	185/245
4	OPC50% SF 15% FA20% GGBS15%	200	80	60	60	0	33	180/225
5	OPC50% SF20% FA15% GGBS15%	200	60	80	60	0	32.5	190/305
G 2								
1	OPC70% SF 5% FA20% MK5%	280	80	20	0	20	32.5	165 / 280
2	OPC70% SF 7.5% FA15% MK7.5%	280	60	30	0	30	33	155/235
3	OPC50% SF 10% FA30% MK10%	200	120	40	0	40	35	160/220
4	OPC50% SF 15% FA20% MK15%	200	80	60	0	60	38	158/215
5	OPC50% SF 20% FA15% MK15%	200	60	80	0	60	38.5	170/295

age of three tests. Once the standard consistency had been established the setting time was determined.

Two periods of times are used to assess the setting behavior. These are called "initial setting time" and "final setting time". The initial setting time was recorded as per IS: 4031 part-5. A needle of 1 mm square is used to penetrate into the paste at every 10 min intervals till the index scale shows 5 + 0.5 mm from the bottom of the mold. For determining the final setting time, the needle has been replaced of the Vicat's apparatus by the needle with an annular attachment. Released needle at every 30 min intervals till the needle makes an impression on the test block. Initial and final set value was recorded at an average of three tests.

3. Results and discussions

3.1. Standard consistency

3.1.1. Standard consistency of OPC-FA-SF-GGBS

The result of standard consistency tests for the quaternary binder OPC-FA-SF-GGBs at different percentage levels are shown in Fig. 1. A study (Nochaiya et al., 2010) reported that in ternary binder, with OPC-FA-SF at 20FA10SF and 30FA10SF, with the replacement of OPC, the requirement of water increases with the increasing percentage levels of SF due to its very high fineness. It is also reported that in binary binder with the increasing percentage level of FA, the water demand is decreasing. It was found that while adding GGBS with FA and SF in replacement of OPC to make quaternary binder, the water demand is again decreasing in quaternary binder. GGBS exhibit some properties that are similar to OPC, like the surface area of GGBS, which is almost equivalent to OPC. Reduction in water demand from 3% to 5% is recorded with the use of GGBS. The overall standard consistency for quaternary binder OPC-FA-SF-GGBS was found almost similar to OPC for all replacement levels.

3.1.2. Standard consistency of OPC-FA-SF-MK

The quaternary binder that consists of OPC-FA-SF-MK requires more water with the increasing percentage level of SF and MK. Studies (Snelson, 2011; Bai and Gailius, 2009) have revealed that replacement of OPC with

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Figure 1. Standard consistency of quaternary (OPC-FA-SF-GGBS/MK) binder paste.

MK increases the water demand with the increasing level of MK in binary binder. Studies also indicate that OPC-FA acted same as OPC. That means FA does not demand much water due to its spherical size. Immediately adding MK with this binary binder and converting into ternary binder, the consistency started increasing. This indicates that quaternary binder with MK shows almost same result as in binary and ternary binder with MK. But results of consistency in quaternary binder along with SF and MK is slightly more due to the high surface area of SF and MK, they demand more water but addition of FA, recompense the water demand and consistency can be deal within limit. The quaternary mix combinations 50%OPC + 20%FA + 15%SF + 15%MK and 50%OPC + 15%FA + 20% SF + 15%MK demand more water and their consistency is higher than other combinations. These combinations cannot be fruitful for the construction materials which can decrease the mechanical and durability properties of mortar and concrete.

3.2. Setting time

3.2.1. Initial and final setting time of OPC-FA-SF-GGBS

The setting times of the quaternary binders containing mineral admixtures are given in Figs. 2 and 3. It was observed that the common effect of the FA, SF, GGBS and MK has lengthened the setting times of quaternary binders. The observed retardation in setting times can be mainly due to the combined effect of lower cement content. Berg and Kukko (Berg and Kukko, 1991) reported that setting time retards in binary binder with the addition of fly ash, if high carbon content is available. It is also reported that the setting time of OPC–FA reduces with the addition of SF and the addition of GGBS along with OPC, FA and SF retard the setting time. Rao (Rao, 2003) studied the effect of silica fume on the setting time of cement paste. It was observed that initial setting time decreased with the increase in silica fume content. At smaller contents, the setting time of cement paste did not affect much. However, at higher SF contents, the initial setting time was significantly decreased. The final setting time seem to be not influenced by silica fume. The pozzolanic action of silica fume seems to be very active at early hours of hydration.

Due to the addition of GGBS the hydration process takes longer time and retards the setting time. However, it does not impact on final setting time so much. As per IS: 4031 part-5, the final setting time should be within 600 min.

3.2.2. Initial and final setting time of OPC-FA-SF-MK

The addition of MK along with OPC, FA and SF accelerate the setting time of quaternary binder. However, A study (Snelson, 2011), shows that the addition of MK, replaced with OPC, accelerate the initial and final setting time of binary binder, while in ternary binder (Mehta and Monteiro, 1993) along with OPC, FA and SF the setting time decreases. In quaternary binders formed using OPC, FA, SF and MK the setting time escalates due to excessive fineness of SF and MK, which results in dense microstructure, thereby resulting in accelerated setting time. However at 5%, 7.5%, 10% and 15% replacement level of SF and MK smooth reduction in setting time is recorded. At 20% SF and 15% MK replacement with OPC and FA, the setting time shows disorder.

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Figure 2. Initial setting times of quaternary (OPC-FA-SF-GGBS/MK) binder paste.



Figure 3. Final setting times of quaternary (OPC-FA-SF-GGBS/MK) binder paste.

Table 5	
Estimated cost of each binder constituents.	

OPC	50 KG	4.51\$ (in US dollar)
GGBS	50 KG	2.26 \$ (in US dollar)
FA	50 KG	Industrial by product freely available
MK	50 KG	Industrial by product freely available
SF	25 KG	7.51 \$ (in US dollar)

3.2.3. Estimated binder cost

The cost of each binder composition is estimated on the basis of different binder constituents and their percentage

within the binder. The estimated cost of each constituent is based on the existing market cost and it is illustrated in Table 3 and 4.

4. Conclusions

The results show that all the supplementary cementitious materials have their own different effects on both standard consistency and setting times of quaternary binders.Following conclusions can be drawn from the study:

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Table 4		
Cost of developed	binder composites.	

Series	Cement mixes	(gm)					Cost of materials	Cost per tonne in
		OPC	FA	SF	GGBS	MK	per tonne in Indian rupees	US dollars
Control	OPC100%	400	0	0	0	0	7000 Rs.	105.32 \$
G 1								
1	OPC70% SF 5% FA20% GGBS5%	280	80	20	20	0	6047.86 Rs.	91\$
2	OPC70% SF 7.5% FA15% GGBS7.5%	280	60	30	30	0	6624.73 Rs.	99.68 \$
3	OPC50% SF 10% FA30% GGBS10%	200	120	40	40	0	5774.7 Rs.	86.89 \$
4	OPC50% SF 15% FA20% GGBS15%	200	80	60	60	0	6949.72 Rs.	104.57 \$
5	OPC50% SF20% FA15% GGBS15%	200	60	80	60	0	7949.94 Rs.	119.62 \$
G 2								
1	OPC70% SF 5% FA20% MK5%	280	80	20	0	20	5049.63 Rs.	75.98 \$
2	OPC70% SF 7.5% FA15% MK7.5%	280	60	30	0	30	5124.73 Rs.	77.11 \$
3	OPC50% SF 10% FA30% MK10%	200	120	40	0	40	3800 Rs.	57.18 \$
4	OPC50% SF 15% FA20% MK15%	200	80	60	0	60	3950 Rs.	59.43 \$
5	OPC50% SF 20% FA15% MK15%	200	60	80	0	60	3950 Rs.	59.43 \$

- 1. Replacement of OPC by 30% with FA, SF and GGBS has very limited influence on the consistency, but replacement impact on consistency increases as it reaches 50%, however an increase in consistency was recorded within standard limit and almost similar to the OPC. These findings suggest that supplementary cementitious materials have almost negligible impact on consistency.
- 2. Standard consistency in quaternary binder (OPC-FA-SF-MK) increases with increasing percentage levels of MK, owing to the high surface area of MK and high levels of water demand. These findings revealed that by controlling the percentage level of MK in binder, both water and standard consistency requirements can be addressed.
- 3. 30% replacement of OPC by FA, SF and GGBS has little control on consistency. Partial replacement of OPC (50%) by FA, SF and GGBS increased consistency. But that is also in limit and almost similar to OPC. This suggests that the properties of FA and GGBS i.e. absorption/adsorption are similar to OPC. However in place of ternary (OPC-FA-SF) binder setting properties increase in quaternary concrete (OPC-FA-SF-GGBS) with the addition of GGBS. This indicates that increasing amount of pozzolanic materials increases the hydration process, hence increasing time period. The advantage of delayed setting times allowing concrete to be worked for longer periods meaning time delays, including delays in transport, between mixing and using concrete are less critical. These types of combination also help to reduce the risk of cold joints in larger concrete pours.
- 4. Standard consistency in quaternary binder (OPC-FA-SF-MK) increases with the increasing percentage levels of MK. This is recognized to the high surface area of the MK and high level of water demand. Setting time of quaternary binder increases at lower replacement of MK. Initial and final setting time decreases with the

higher amount of MK in quaternary binder. The silica fume and metakaolin are highly reactive, and small size of particles speeds up the reaction with calcium hydroxide.

- 5. Overall effect of FA, SF, MK and GGBS on standard consistency, an initial and final setting time in quaternary binder is to retard the setting time. The influence of increasing the levels of GGBS is to provide greater retardation in the setting time, due to less content of C_3A .
- 6. These types of binders are useful for the manufacturing of RMC concrete where longer time is needed for placing the concrete.
- 7. Based on the cost analysis these binders are very economic. If these types of combinations are used in RMC plant then construction cost can be reduced manifold.

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