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Flow behavior of freshly mixed quaternary blended high performance concrete using modified slump cone test

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ABSTRACT

This paper focusses on the flow behavior of quaternary blended HPC using modified slump cone test. 49 HPC mixes including control mix were developed incorporating mineral admixture combinations of metkaolin, slag and fly ash up to 92.5% replacement levels. Semi-empirical models were proposed for yield stress and plastic viscosity as the function of the slump and slump time. It was found that the fluidity of concrete increased moderately and the plastic viscosity and yield stress decreased noticeably, when mineral admixture combinations were substituted partially for cement. Out of 49 HPC mixes, the quaternary HPC mix developed with 57.5% cement, 7.5% metakaolin, 25% slag, and 10% fly ash, gives a minimum yield stress of 878 Pa and plastic viscosity of 179 Pa.s.

Introduction

Over the last two decades, the High-Performance Concrete (HPC) technology has been the important subject in concrete research since HPC has unique properties and numerous advantages in practical applications. Among them, the workability (i.e., easy placing and consolidation) is one of the most representative characteristics. For this reason, the use of such concrete is spreading worldwide quickly (Tsong Yen et al, 1999). Researchers treat fresh concrete as fluid and use fluid rheology methods to identify and describe concrete behavior. Concrete as a fluid is most often assumed to behave like a Bingham fluid with good accuracy. In Bingham model, flow is defined by two parameters: yield stress and plastic viscosity. Yield stress gives the quantitative measure of initial resistance of concrete to flow and plastic viscosity governs the flow after it is initiated. Yield stress is the contribution of the skeleton (i.e.) it is a manifestation of friction among solid particles. Plastic viscosity is the contribution of suspending liquid that results from viscous dissipation due to the movement of water in the sheared material. Plastic viscosity appears to be controlled essentially by the ratio of solid volume to the packing density of granular mixture, including aggregates and cement (Aminul Islam Laskar, Sudip Talukdar, 2008).

The incorporation of mineral admixtures is now an important technique in improving the fluidity, strength, durability, etc., properties of concrete. Although many researchers have reported on the pozzolanic effect of mineral admixtures, as well as the micro-filling effect of the fine mineral powders. The role of the much finer mineral powders, incorporated in HPC, involves not only their hydraulicity or pozzolanic effect and their micro-filling effect but also their surface activity (Yun-Xing Shia et al. 2004). Since the mid-nineties, a significant increase in the production of blended concretes incorporating Portland cement and two (in the case of ternary) or even three (in the case of quaternary) supplementary cementitious materials has occurred. The advantages of these types of concretes compared to the respective binary systems motivated considerable research in this field (S.K. Antiohos et al. 2007, J. Bai et al. 2000, G. Menendez et al 2003, C.J. Lynsdale and M.I. Khan, 2000). Zongjin Li et al (2003) chose the combination of metakaolin and slag and implemented research on the physical and mechanical properties of Portland Cement (PC) containing metakaolin or a combination of metakaolin and slag and its effect on the amount of superplasticizer used in concrete. The result of this study indicates that the incorporation of 10% MK and 20% or 30% ultra-fine slag together into PC, not only improved the fluidity of blended cements, but also the 28-day compressive strength of the cement was enhanced . R.P.Khatri et al., 1995 under took a study to compare mechanical properties as well as fresh concrete properties containing silica fume, fly ash and ordinary Portland cement

The rheometer developed by the Laboratoire Central des Ponts et Chausse´es (LCPC), France the BTRHEOM rheometer allows the quantitative determination of the yield stress and the viscosity of plastic concretes (Chiara F. Ferraris and Francois, 1998, de Larrard et al. 1997, de Larrard et al. 1996, and Hu et al. 1995).

A survey of the state of the art shows that none of the current field tests (in distinction to rheometers) is able to assess the plastic viscosity of the fresh concrete. However, this parameter is of increasing importance in modern concretes (Chiara F. Ferraris, 1999). For high-performance concretes, it frequently constitutes the critical parameter that controls pumpability and ease of finishing (Tanigawa, Y and Mori, H, 1989).

Tanigawa et al.1989, 1991 performed standard slump cone test to measure the slump as a function of time. They found that the slump-time curve could be simulated by finite element analysis of the fresh concrete assuming that the concrete is a Bingham material. The slump-time curve depends on both the yield stress and the plastic viscosity. Since the final slump is

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related directly to the yield stress, it is reasonable to assume that the time dependence of slump is likely to be controlled by the plastic viscosity. Considering that the slump test is currently the only field test in the world for most practitioners, the test procedure was modified slightly to make possible measurements of both the yield stress and the plastic viscosity of fresh concrete. This paper describes the modification made to the standard slump cone test apparatus, test procedure and calculation to determine both the yield stress and the plastic viscosity.

An extensive literature review has been carried out to identify the rheological behavior of HPC mixes consisting of different mineral admixtures. The literature review shows the studies on rheological behavior of fresh high performance concrete mixes consisting of only binary and few ternary blended mineral admixtures up to a maximum replacement level of about 70% but there were minimal research reported with quaternary blended HPC along with metakaolin. As the cement prices are hiking up for few years by keeping economic and sustainability towards the environment point of view in mind, an attempt has been made to study the rheological behavior of HPC mixes consisting of quaternary blends (i.e.) for example 30% cement, 40% slag, 15% FA, 15% MK.

Experimental Procedure

Properties of materials

(i) Cement and mineral Admixtures

Ordinary Portland Cement (PC) of 53 grade confirming to IS 12269-1987 was used for this study. The specific gravity and Blaine specific surface area of PC were 3.12 and 2250 cm^2/gm respectively. Metakaolin (MK) supplied by English India Ltd, Trivandrum, India was used in the study. Its specific gravity and Blaine specific surface area were 2.51 and 5300 cm^2/gm respectively. Ground Granulated Blast Furnace Slag (SL) supplied by M/S Nandi cements Pvt.Ltd, Bangalore, India was used for this research. Its specific gravity and Blaine specific surface area were 2.94 and 4320 cm^2/gm respectively. Fly ash (FA) Class F, supplied by Tamil Nadu Papers Ltd, Karur, India, was used for this study. Its specific gravity and Blaine specific surface area were 1.90 and 3450 cm^2/gm. The chemical composition of PC, MK, SL and FA are shown in Table 1.

(ii) Aggregates

Dry and clean, locally available river sand conforming to grading zone-II as per IS: 383-1970 was used in concrete mixture. Its specific gravity was 2.65 with 1% absorption. Locally available coarse aggregate from quarry was used and they are rather rounded in shape with a maximum size of 12.5 mm size. The specific gravity and water absorption of coarse aggregate were 2.79 and 0.3% respectively.

(iii) Superplasticizer (SP)

Modified polycarboxylic ether based High Range Water Reducing Admixture (HWRA) GLENIUM B233 was used as superplasticizer (SP) at various dosages to maintain the workability of fresh concrete. The specific gravity of super plasticizer is 1.09 ± 0.01 at 25^0C.

(iv) Water

Water conforming to the requirements of IS: 456-2000 is found to be satisfactory for making concrete. It is generally stated that water fit for drinking is suitable for making concrete. For the present research, potable water free from salts is used for concrete mixing and curing.

Concrete mixture proportions

The absolute volume method of design was used to determine the HPC mix proportions for each mix per cubic meter. Air content for HPC was assumed as 1.5%. Unit water and sand percentage were derived considering the properties of coarse and fine aggregates, quantity of mineral admixtures and superplasticizers. 49 mix proportions (one control + 48 quaternary blends) were arrived at after having done many trials at a constant water/binder ratio (w/b) of 0.35 and a constant total binder content of 400 kg/m^3. The HWRA polycarboxylic ether based super plasticizer (GLENIUM-B233) with 34% solids was employed to achieve the desired slumps. The optimum dosage of SP for all HPC mixes was determined by conducting Marsh cone test.

Marsh Cone Test

This is a simple field laboratory test to find the optimum dosage of superplasticizers for a HPC mix. Marsh cone is a conical brass vessel, which has a smooth aperture of 5 mm diameter at the bottom. The profile of the apparatus is shown in Figure 1. Take 2 kg of cement, proposed to be used in the experiment. Take one litre of water (w/c = 0.35) and superplasticizer 0.6% by weight of binder. Mix them thoroughly in a mechanical mixer for two minutes. Take one litre slurry and pour it into Marsh cone duly closing the aperture with a finger. Start a stop watch and simultaneously remove the finger. Find out the time taken in seconds, for complete flow out of the slurry. The time in seconds is called the “Marsh Cone Time”. Repeat the test with different dosages of plasticizer. Plot a graph connecting Marsh cone time in seconds and dosages of plasticizer or super plasticizer. The dosage at which the Marsh cone time is lowest is called the saturation point. The dosage is the optimum quantity of superplasticizer for that particular binder. The Marsh cone tests were conducted for 49 binders of different HPC mixes and corresponding super plasticizer dosages were determined (Aitcin PC, 1998) and shown in Table 2. Figure 2 shows the Marsh Cone flow times for different dosages of superplasticizer to determine the compactabilty of PC53 grade with superplasticizer.

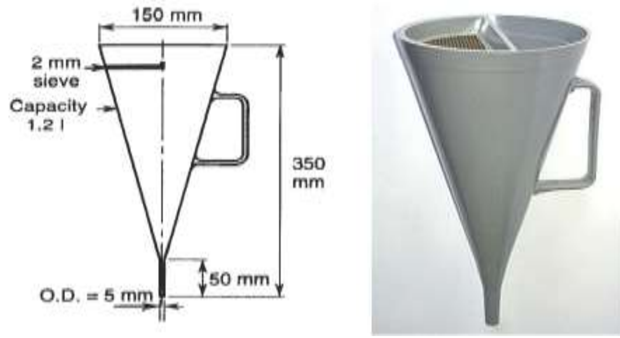

Fig. 1- Marsh Cone Viscometer

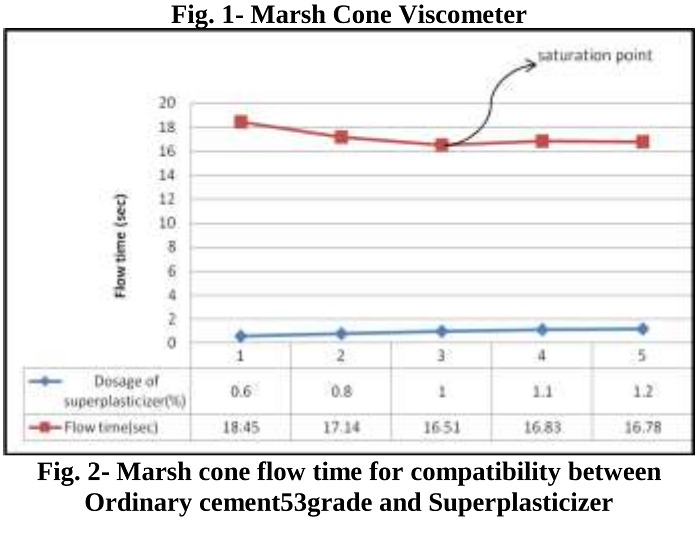

Fig. 2- Marsh cone flow time for compatibility between Ordinary cement53grade and Superplasticizer

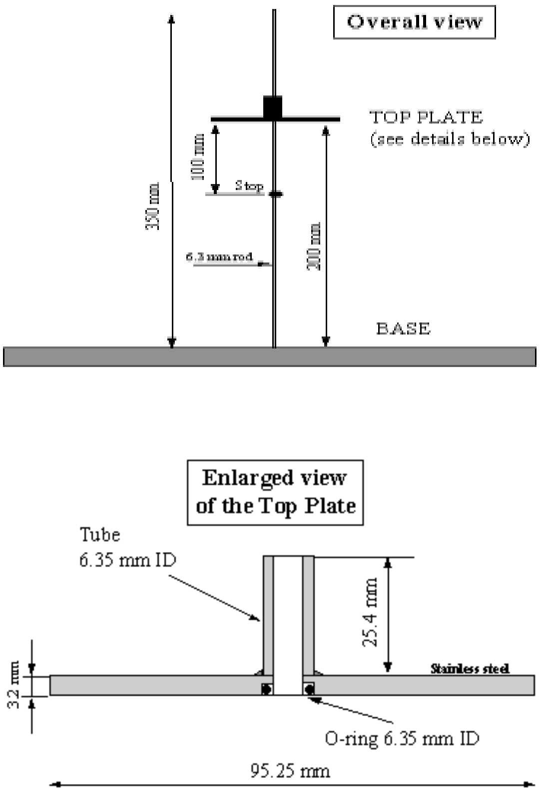

Fig. 3- Rod and top plate in the modified slump apparatus

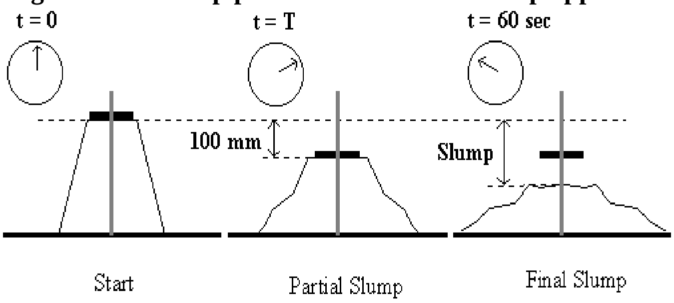

Fig. 4- Schematics of the modified slump cone test. T is the "slump time"

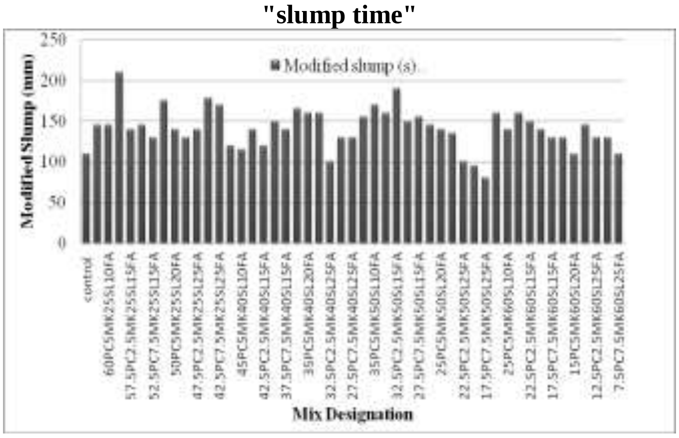

Fig. 5- Effect of mineral admixtures content on the modified slump of quaternary HPC mixes

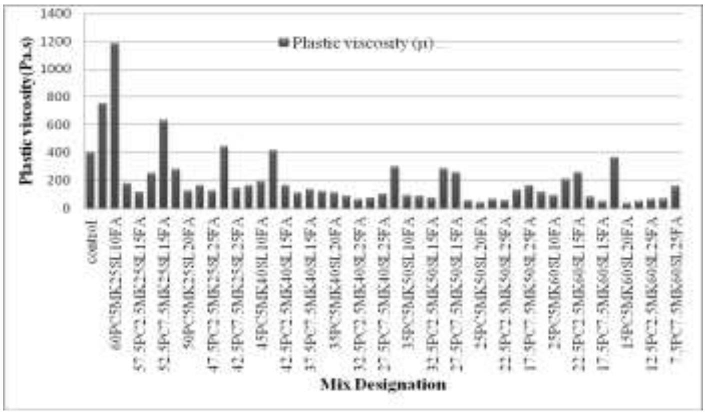

Fig. 6- Plastic viscosity of HPC mixes with quaternary blends

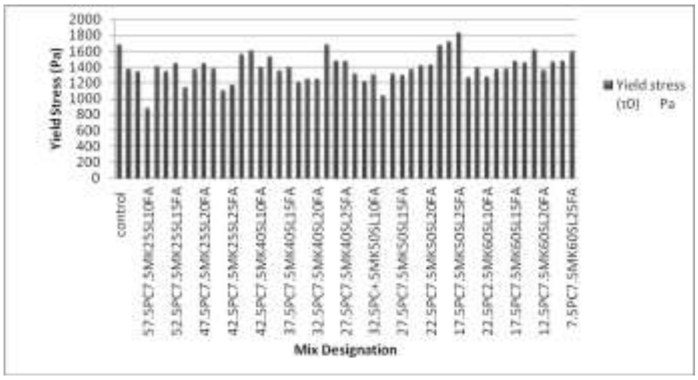

Fig. 7- Yield Stress of quaternary blended HPC mixes

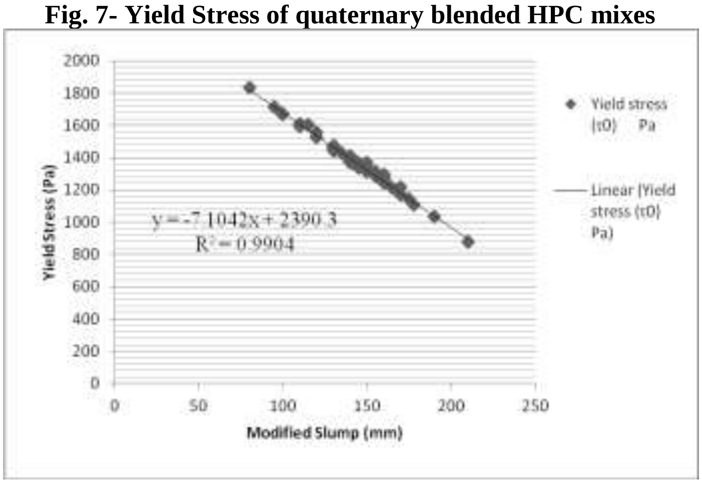

Fig. 8- Correlation between Yield Stress and modified slump of quaternary HPC mixes.

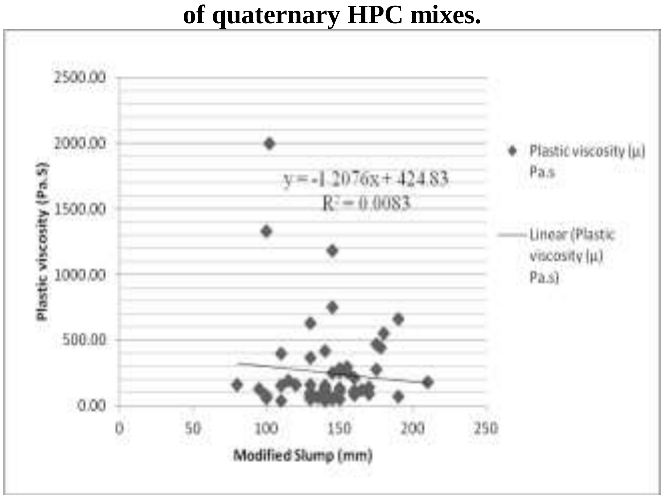

Fig.9- Correlation between Plastic Viscosity and modified slump of quaternary blended HPC mixes.

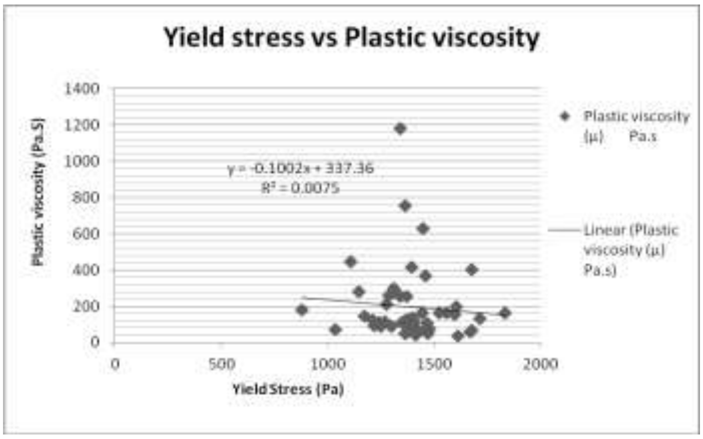

Fig. 10- Correlation between the Bingham characteristics of quaternary blended HPC mixes

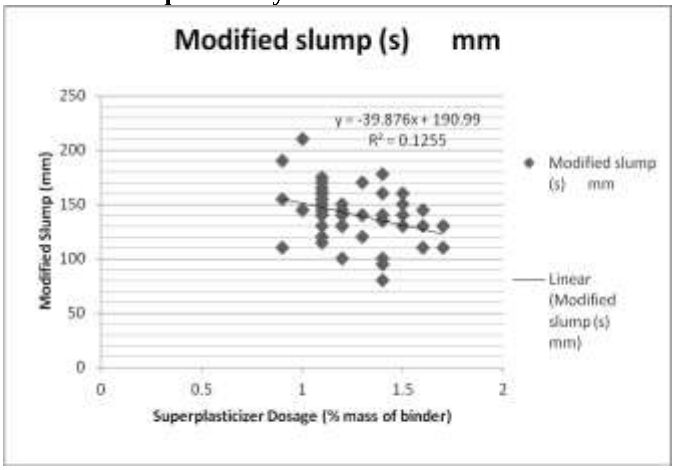

Fig. 11- Correlation between superplasticizer dosage and modified slump for quaternary blended HPC mixes.

Methodology

The HPC mixes were mixed in a laboratory vertical axis-pan mixer of 40L capacity, AIMIL make. After thorough dry mixing of ingredients in the pan mixer, half of the mixture of measured water and superplasticizer was added to mix and mixing was continued for 2 minutes. Then, remaining half of the water- superplasticizer mixture was poured into pan mixer and mixing was done for another 3 minutes. The mixing time for the concretes with HWRA was longer due to addition of some mineral and chemical admixtures.

The slump was measured in accordance with ASTM Test Method C 143-90, except that the apparatus was provided with an axial vertical rod and a stainless steel disk that could slide down the rod. This plate was placed on top of the concrete cone. The effect of these modifications on the final slump was found to be negligible.

(i) Procedure for Measuring the Slump Time by Modified Slump Cone Test

Figure 3 and Figure 4 show the Modified slump cone apparatus and method of measurement of modified slump. Various components required to conduct the modified slump cone test are given below:

- A horizontal base to which the rod is attached.
- A standard mould for the slump test (ASTM C 143-90).
- A sliding disk (the upper plate).
- A rubber O-ring seal, the purpose of which is to prevent finer particles from interfering with the fall of the disk.
- A rod to consolidate the concrete.
- A small trowel to finish the upper surface of the concrete.
- A ruler graduated in ‘mm’ to measure the slump.
- A stopwatch which could be read to the nearest 0.01 second.

The concrete was placed in the same manner as in the standard slump test (ASTM C 143-90). The various steps are as follows:

The rod of the base is cleaned with petroleum jelly and mould inside is moistened before placing it on the base. After ensuring that the axis of mould coincides with the rod, concrete is filled in three layers into mould and each layer is rodded for 25 times. Excess concrete on the top of mould is struck off using a trowel. The disk is slided along the rod until contact is made with the surface of the concrete and then, mould is raised vertically while starting the stopwatch. While the concrete is slumping, continually observe the disk (through the top of the mould) and stop the stopwatch as soon as the disk stops moving. Once the slump has stabilized, or no later than one minute after the start of the test, removes the disk and the slump is measured with the ruler (Ferraris CF, 1999). Slump time is the time taken by the disc to slide down vertically along the rod by 100mm when concrete is subsiding.

(ii) Estimation of the Fundamental Rheological Parameters on the Basis of the Modified Slump Cone Test

Based on the slump and Finite Element analysis of the slump cone test, Hu proposed a general formula relating the slumps to the yield stress, τ_0 in the following form.

$$\tau_0 = (\rho/270) \times (300\text{-}s) \quad (1)$$

where

‘ρ’ is density of concrete expressed in kg/m^3,

τ_0 is yield stress in Pa and‘s’ is the slump expressed in mm

The following equation is the improved Hu’s model for yield stress,

$$\tau_0 = (\rho/347) \times (300\text{-}s) + 212 \quad (2)$$

A Semi Empirical Formula to Evaluate Plastic Viscosity:

If we consider concretes having the slumps lower than 260mm, the Plastic Viscosity, μ can be given by the following equation

$$\mu=\rho\times T\times 1.08\times 10^{-3}(s-175) \quad \text{for } 200 < s < 260\text{mm} \quad (3)$$

$$\mu=25\times 10^{-3}\times \rho\times T \quad \text{for } s < 200\text{mm} \quad (4)$$

where

μ is Plastic Viscosity, T is the slump time

From these equations, the plastic viscosity can be estimated from the unit mass, the final slump (in mm), and the partial slump time in seconds (Chiara F. Ferraris and Francois de Larrard, 1998).

Results and discussions

The modified slump test as described was performed on quaternary blended concretes and the partial slump times (or simply slump times) are measured. The modified slump values of these concretes covered a range from 80 to 210 mm and slump times range between 0.58 and 18.72 seconds as shown in Table 3.

Concrete fluidity

Figure 5 shows the slumps of HPC with different quaternary blends containing varied contents of combinations of mineral admixtures. It can be seen that the changes in the fluidity of the concretes were closely related to the types of mineral admixtures and their contents.

For quaternary blends of 43.5% replacement, the concrete reached the highest slump of 210mm. In most of the quaternary blended mixes, slumps exhibited an increase; the increase was obviously smaller as compared to control mix. The results suggest that the fluidity of the concrete depends on the types of mineral admixtures and their contents.

Table 1-Chemical composition of Cement and Mineral Admixtures

Chemical composition %				
Compound	**Cement**	**Metakaolin**	**Fly Ash Class F**	**Slag**
SiO_2	20.10	51.60	48.53	35.34
Al_2O_3	4.51	41.30	24.61	11.59
Fe_2O_3	2.50	0.64	7.59	0.35
CaO	61.30	0.52	9.48	41.99
MgO	1.00	0.16	2.28	8.04
Loss on ignition	2.41	0.72	0.93	0.45

The mineral admixture powders can have a dispersion effect and increase greatly, the fluidity of concrete through adsorbing superplasticizer on their surfaces and forming electric double layers (Yun-Xing Shi et al., 2004). Therefore, the fluidifying effect of fine mineral powders should not be considered to be only a micro filling effect alone. These experimental results also confirm that the dispersion effect is more effective in enhancing the fluidity of concrete in some cases and is related to the vitreous phase.

Analysis of Rheological properties

After the fluidity measurement was conducted for each batch of concrete, the plastic viscosity and yield stress of the concrete were determined using the semi-empirical formulae based on the slumps from modified slump cone test.

Quaternary blends

Table 3 shows the ranges of the two Bingham constants: the yield stress varied from 878 Pa to 1832 Pa, the plastic viscosity from 37 to 1182 Pa.s. Figure 6 and Figure 7 show that the variation trends of yield stress and plastic viscosity correlate the slump values of corresponding concretes. That is, higher the slump value with lower slump time, and then, lower is the yield stress and viscosity.

In PC-MK-SL-FA quaternary blended concretes, very fine particles of MK filled the spaces made by bigger particles of PC, SL, FA, and absorbed SP, formed a gel, resulting in reducing friction forces of cementitious materials. The combined effect of SL and FA is to increase the yield stress and viscosity but decreasing when SL content is higher with lower content of FA and higher SP dosage. In quaternary system, the MK did not influence so significantly on other components for increasing the yield stress and the plastic viscosity. These systems could be controlled, with their rheological parameters by each mineral admixture and dosages of super plasticizers.

Figure 6 and Figure 7 show that for each type of quaternary blended concrete, the plastic viscosity decreased progressively and yield stress also lowered as the percentage replacement levels increased (except HPC3 mix). The HPC45 mix developed with 15% PC, 5% MK, 60% SL, and 20% FA had the lowest plastic viscosity (i.e. 37 Pa.s). This is attributed due to the influence of MK on higher proportions of SL present in mix and effect of higher SP dosage which induces a dispersion force among cementitious particles and increases flowability, thereby decrease in plastic viscosity and yield stress. The HPC3 mix (60% PC, 5% MK, 25% SL, 10% FA) had the highest value of viscosity (i.e. 1182 Pa.s) might be due to the influence of MK and FA on other components and less hydration reactivity of SL due to lesser SP dosage comparably, resulting increase in plastic viscosity and yield stress. However, in most of the cases of 25% FA based quaternary mixes; plastic viscosity was smaller than other quaternary mixes. It can be postulated from the results that the incorporation of higher proportions of SL in quaternary concretes can be a contributing factor for decreasing the viscosity and yield stress.

Correlation between rheological parameters and fluidity of concrete slump versus plastic viscosity and yield stress

The correlations between modified slump values and viscosity as well as yield stress are shown in Figure 8 and Figure 9. From the Figure 8, it is evident that the relationship between yield stress (x-axis) and modified slump (y-axis) of quaternary concretes, were more linear with R^2 value = 0.9904. The R^2 value reveals the excellent relationship between yield stress and slump and very useful to predict the flow properties of mixes. It is noted that there is no correlation between the plastic viscosity and modified slump as shown in Figure 9.

It can be seen that there is no correlation between the two Bingham parameters as shown in Figure 10. In particular, it can be noted from Table 3 that for concretes having the same slump value, the plastic viscosity can vary from one value relative to other value.

Figure 11 shows relationship between superplasticizer dosage (x-axis) and modified slump (y-axis). It is noted that increase in SP dosage in the mix is resulting increase in slump values when compared to HPC without Mineral Admixtures (MAs).

It can be seen that as the viscosity decreases, quaternary blended concretes showed a higher increment in the slump value than those with control concrete. The concrete with quaternary system had a higher fluidity and the slump values also seemed to have a tendency to decrease with increasing yield stress but a clear relation between slump and the yield stress cannot be seen.

From the above results, it can be suggested that the relationship between the fluidity of concrete and the rheological parameter can be notably influenced by incorporating varied mineral admixture powders with different contents. This may be attributed to the surface chemical and physical effects, which are also associated with the vitreous contents of the mineral admixtures. The effects of fine mineral powders on the properties of fresh concrete depend on various factors such as specific surface area, size distribution, surface texture, and particle size distribution of the powders, as well as the types of cement, SP content, etc.

Summary And Conclusions

Rheological properties of HPC were studied incorporating MK, SL and FA in quaternary combinations. Cement was replaced on weight basis at different replacement levels and rheological performances of concrete mixes were studied. Following conclusions are derived from the present work:

1. The modified slumps of HPC mixes with quaternary blends increased in proportion to the percentage replacement levels and SP dosages. The fluidity of the concrete depends on the types of MAs and their contents.
2. For control concrete without MAs, the yield stress and the plastic viscosity are much improved as the dosage of SP increases in the range up to 1.7% by weight of cement. The dosage of SP was the main factor for improving the rheological properties.

Table 2-Mix proportions of HPC with quaternary blends

Mix Number	Mix Id	w/b ratio	PC53(kg/m^3)	MK(kg/m^3)	Slag(kg/m^3)	FA(kg/m^3)	Water(kg/m^3)	Sand(kg/m^3)	CA(kg/m^3)	SP %	SP(kg/m^3)
HPC1	Control	0.35	400	0	0	0	143.5	756	1194	0.9	3.3
HPC2	62.5PC2.5MK 25SL10FA	0.35	250	10	100	40	143.5	744	1176	1.0	3.7
HPC3	60PC5MK25SL 10FA	0.35	240	20	100	40	143.5	744	1174	1.0	3.7
HPC4	57.5PC7.5MK 25SL10FA	0.35	230	30	100	40	143.5	743	1173	1.0	3.7
HPC5	57.5PC2.5MK 25SL15FA	0.35	230	10	100	60	143.5	740	1169	1.1	4.0
HPC6	55PC5MK 25SL15FA	0.35	220	20	100	60	143.5	739	1167	1.1	4.0
HPC7	52.5PC7.5MK 25SL15FA	0.35	210	30	100	60	143.5	738	1166	1.1	4.0
HPC8	52.5PC2.5MK 25SL20FA	0.35	210	10	100	80	143.5	736	1162	1.1	4.0
HPC9	50PC5MK 25SL20FA	0.35	200	20	100	80	143.5	735	1160	1.2	4.4
HPC10	47.5PC7.5MK25SL20 FA	0.35	190	30	100	80	143.5	734	1159	1.2	4.4
HPC11	47.5PC2.5MK 25SL25FA	0.35	190	10	100	100	143.5	731	1155	1.4	5.1
HPC12	45PC5MK 25SL25FA	0.35	180	20	100	100	143.5	730	1154	1.4	5.1
HPC13	42.5PC7.5MK 25SL25FA	0.35	170	30	100	100	143.5	730	1152	1.3	4.8
HPC14	47.5PC2.5MK 40SL10FA	0.35	190	10	160	40	143.5	743	1174	1.1	4.0
HPC15	45PC5MK 40SL10FA	0.35	180	20	160	40	143.5	742	1172	1.1	4.0
HPC16	42.5PC7.5MK 40SL10FA	0.35	170	30	160	40	143.5	742	1171	1.2	4.4
HPC17	42.5PC2.5MK 40SL15FA	0.35	170	10	160	60	143.5	739	1167	1.3	4.8
HPC18	40PC5MK 40SL15FA	0.35	160	20	160	60	143.5	738	1165	1.1	4.0
HPC19	37.5PC7.5MK 40SL15FA	0.35	150	30	160	60	143.5	737	1164	1.1	4.0
HPC20	37.5PC2.5MK 40SL20FA	0.35	150	10	160	80	143.5	734	1160	1.1	4.0
HPC21	35PC5MK 40SL20FA	0.35	140	20	160	80	143.5	734	1159	1.1	4.0
HPC22	32.5PC7.5MK 40SL20FA	0.35	130	30	160	80	143.5	733	1157	1.1	4.0
HPC23	32.5PC2.5MK 40SL25FA	0.35	130	10	160	100	143.5	730	1153	1.2	4.4
HPC24	30PC5MK 40SL25FA	0.35	120	20	160	100	143.5	729	1152	1.2	4.4
HPC25	27.5PC7.5MK 40SL25FA	0.35	110	30	160	100	143.5	728	1150	1.2	4.4
HPC26	37.5PC2.5MK 50SL10FA	0.35	150	10	200	40	143.5	742	1172	1.1	4.0
HPC27	35PC5MK 50SL10FA	0.35	140	20	200	40	143.5	742	1171	1.1	4.0
HPC28	32.5PC7.5MK 50SL10FA	0.35	130	30	200	40	143.5	741	1170	1.1	4.0
HPC29	32.5PC2.5MK	0.35	130	10	200	60	143.5	738	1165	0.9	3.3

	50SL15FA										
HPC30	30PC5.0MK 50SL15FA	0.35	120	20	200	60	143.5	737	1164	1.2	4.4
HPC31	27.5PC7.5MK 50SL15FA	0.35	110	30	200	60	143.5	736	1163	0.9	3.3
HPC32	27.5PC2.5MK 50SL20FA	0.35	110	10	200	80	143.5	734	1159	1.2	4.4
HPC33	25PC5MK 50SL20FA	0.35	100	20	200	80	143.5	733	1157	1.4	5.1
HPC34	22.5PC7.5MK 50SL20FA	0.35	90	30	200	80	143.5	732	1156	1.4	5.1
HPC35	22.5PC2.5MK 50SL25FA	0.35	90	10	200	100	143.5	729	1152	1.4	5.1
HPC36	20 PC5MK 50SL25FA	0.35	80	20	200	100	143.5	728	1150	1.4	5.1
HPC37	17.5 PC7.5MK 50SL25FA	0.35	70	30	200	100	143.5	728	1149	1.4	5.1
HPC38	27.5PC2.5MK 60SL10FA	0.35	110	10	240	40	143.5	742	1171	1.4	5.1
HPC39	25PC5MK 60SL10FA	0.35	100	20	240	40	143.5	741	1170	1.3	4.8
HPC40	22.5PC7.5MK 60SL10FA	0.35	90	30	240	40	143.5	740	1168	1.5	5.5
HPC41	22.5PC2.5MK 60SL15FA	0.35	90	10	240	60	143.5	737	1164	1.5	5.5
HPC42	20PC5MK 60SL15FA	0.35	80	20	240	60	143.5	736	1163	1.5	5.5
HPC43	17.5PC7.5MK 60SL15FA	0.35	70	30	240	60	143.5	736	1162	1.5	5.5
HPC44	(17.5PC2.5MK 60SL20FA	0.35	70	10	240	80	143.5	733	1157	1.6	5.8
HPC45	15PC5MK 60SL20FA	0.35	60	20	240	80	143.5	732	1156	1.6	5.8
HPC46	12.5PC7.5MK 60SL20FA	0.35	50	30	240	80	143.5	731	1155	1.6	5.8
HPC47	12.5PC2.5MK 60SL25FA	0.35	50	10	240	100	143.5	728	1150	1.7	6.2
HPC48	10PC5MK 60SL25FA	0.35	40	20	240	100	143.5	728	1149	1.7	6.2
HPC49	7.5PC7.5MK 60SL25FA	0.35	30	30	240	100	143.5	727	1148	1.7	6.2

Table 3-Modified Slump and Rheological Parameters of Quaternary blended HPC mixes

Mix No.	Mix Id	Modified slump (s) mm	Density (ρ) kg/m^3	Slump time (T) sec	Yield stress (τ_0) Pa	Plastic viscosity (μ) Pa.S
HPC1	control	110	2676	6.00	1677	401
HPC2	62.5PC2.5MK25SL10FA	145	2580	11.70	1364	755
HPC3	60PC5MK25SL10FA	145	2525	18.72	1340	1182
HPC4	57.5PC7.5MK25SL10FA	210	2568	2.79	878	179
HPC5	57.5PC2.5MK25SL15FA	140	2584	1.80	1403	116
HPC6	55PC5MK25SL15FA	145	2528	4.00	1341	253
HPC7	52.5PC7.5MK25SL15FA	130	2518	10.00	1446	630
HPC8	52.5PC2.5MK25SL20FA	175	2588	4.30	1144	278
HPC9	50PC5MK25SL20FA	140	2508	2.00	1368	125

HPC10	47.5PC7.5MK25SL20FA	130	2512	2.60	1443	163
HPC11	47.5PC2.5MK25SL25FA	140	2537	2.00	1382	127
HPC12	45PC5MK25SL25FA	178	2549	6.97	1108	444
HPC13	42.5PC7.5MK25SL25FA	170	2559	2.25	1171	144
HPC14	47.5PC2.5MK40SL10FA	120	2597	2.50	1559	162
HPC15	45PC5MK40SL10FA	115	2610	3.00	1603	196
HPC16	42.5PC7.5MK40SL10FA	140	2565	6.50	1395	417
HPC17	42.5PC2.5MK40SL15FA	120	2531	2.56	1525	162
HPC18	40PC5MK40SL15FA	150	2624	1.66	1346	109
HPC19	37.5PC7.5MK40SL15FA	140	2571	2.11	1397	136
HPC20	37.5PC2.5MK40SL20FA	165	2565	1.89	1210	121
HPC21	35PC5MK40SL20FA	160	2554	1.76	1242	112
HPC22	32.5PC7.5MK40SL20FA	160	2570	1.35	1249	87
HPC23	32.5PC2.5MK40SL25FA	100	2538	1.03	1675	65
HPC24	30PC5MK40SL25FA	130	2580	1.17	1476	75
HPC25	27.5PC7.5MK40SL25FA	130	2562	1.62	1467	104
HPC26	37.5PC2.5MK50SL10FA	155	2627	4.54	1310	298
HPC27	35PC5MK50SL10FA	170	2680	1.39	1216	93
HPC28	32.5PC+7.5MK50SL10FA	160	2691	1.30	1298	87
HPC29	32.5PC2.5MK50SL15FA	190	2592	1.12	1034	73
HPC30	30PC5MK50SL15FA	150	2546	4.44	1313	283
HPC31	27.5PC7.5MK50SL15FA	155	2575	4.00	1288	258
HPC32	27.5PC2.5MK50SL20FA	145	2596	0.85	1372	55
HPC33	25PC5MK50SL20FA	140	2600	0.63	1411	41
HPC34	22.5PC7.5MK50SL20FA	135	2550	1.03	1425	66
HPC35	22.5PC2.5MK50SL25FA	100	2528	0.90	1669	57
HPC36	20 PC5MK50SL25FA	110	2540	2.07	1603	131
HPC37	17.5PC7.5MK50SL25FA	100	2555	2.56	1685	164
HPC38	27.5OPC2.5MK60SL10FA	160	2615	1.75	1267	114
HPC39	25PC5MK60SL10FA	140	2545	1.48	1385	94
HPC40	22.5PC2.5MK60SL10FA	160	2632	3.19	1274	210
HPC41	22.5PC2.5MK60SL15FA	150	2682	3.82	1371	256
HPC42	20PC5MK60SL15FA	140	2535	1.30	1381	82
HPC43	17.5PC7.5MK60SL15FA	130	2570	0.76	1471	49
HPC44	17.5PC2.5MK60SL20FA	130	2540	5.76	1456	366
HPC45	15PC5MK60SL20FA	110	2555	0.58	1611	37
HPC46	12.5PC7.5MK60SL20FA	145	2574	0.76	1362	49
HPC47	12.5PC2.5MK60SL25FA	130	2545	1.03	1459	66
HPC48	10PC5MK60SL25FA	130	2565	1.08	1469	69
HPC49	7.5PC7.5MK60SL25FA	110	2525	2.47	1595	156

3. In this study, the most of quaternary blended HPC mixes incorporating MK, SL and FA combinations exhibited slight decrease in yield stress compared to control mix without MAs while the plastic viscosity of the concretes are gradually decreasing in proportion to the increasing replacement levels of MAs. The quaternary blended HPC mixes with 25% FA showed plastic viscosity lesser than other quaternary HPC mixes.
4. The quaternary HPC mix developed with 57.5% PC, 7.5% MK, 25% SL, and 10% FA is found to yield the most suitable rheological performance with moderate plastic viscosity and the lowest yield stress.

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