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Effect of cement additions on the plastic density and workability of concrete

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ABSTRACT

This paper reports the effect of cement combinations containing Portland cement, fly ash, silica fume and metakaolin on the plastic density and workability of concrete. The results show that cement additions would reduce the plastic densities of Portland cement concrete with increasing content. However, while fly ash binary cement concretes had plastic densities less than 2400 kN/m^3, silica fume and metakaolin binary cement concretes had plastic densities equal to or greater than 2400 kN/m^3. However, at a total replacement level less than 55%, all the cement combination concretes achieved plastic densities between 2350-2450 kN/m^3. Since fly ash reduced superplasticiser dosage and silica fume and metakaolin increased superplasticiser dosage, the superplasticiser dosages of the ternary cement concretes reduced with increasing content of fly ash. The cement additions improved the cohesion and stability of concrete. However, due to their increased surface area, concrete becomes sticky resulting in poor finish with increasing content of silica fume and metakaolin. Also, metakaolin concretes had higher plastic densities and required higher superplasticiser dosage than silica fume concretes at equal replacement level.

Keywords: *cement additions; cement combinations; cohesion; finishability; plastic density; workability.*

1. Introduction

For good quality of workmanship, fresh properties of concrete like plastic density and workability are very relevant to contractors and concrete suppliers. While the plastic density could be used to assess the extent of the early strength of concrete, the workability could be used to assess the ease of handling and placing of concrete. Hence, these properties would assist in making appropriate decisions on handling (transportation), placing (including choice of formwork), compacting and finishing of concrete.

Also, for improved performance of concrete consistent with cost and environmental compatibility, the use of cement combination concrete has been supported by cement and concrete standards like BS EN 197- 1, BS 8500 and BS EN 206- 1. Due to its availability, low cost and quality standard, fly ash constitutes the primary pozzolana in blended cements[1]. Despite its slow early age performance, it generally contributes to later-age strength development[2] and improved resistance[3,4,5]. Also, its spherical shape[6,7] and the electronic dispersion of its fine particles[8] has resulted in reduced water demand[9] and improved workability of concrete[10]. Silica fume and metakaolin, due to their fineness, would generate more nucleation sites to accelerate hydration reactions[11,12,13] and enhance both early and later age performance of concrete[14,15,16] but their fine particle size and high reactivity would cause workability problems[17,18,19, 20]. While BS EN 197- 1 permits the use of fly ash of up 55%, silica fume and metakaolin because of their high costs could only be used, respectively, in small quantitites of about 5-10% and 5-15% by mass of cement[21,22]. However, when combined, these cement additions would compliment each other in concrete performance[10].

Hence, to support the use of cement combinations within these permitted limits, this paper investigated the effect of the binary and ternary combinations of the cement additions on the plastic density and workability of concrete.

2. Experimental materials

The cements used were Portland cement (PC, 42.5 type) conforming to BS EN 197- 1, siliceous or Class F fly ash (FA) conforming to BS EN 450, silica fume (SF) in a slurry form (50:50 solid/water ratio by weight) conforming to BS EN 13263 and a calcined natural pozzolana (metakaolin, MK) conforming to BS EN 197- 1. The properties of the cements are presented in Table 1. The aggregates consisted of 0/4mm fine aggregates and 4/10mm and 10/20mm coarse aggregates. The coarse aggregates were uncrushed and they come in varied shapes. The 4/10mm aggregates have rough texture and the 10/20mm aggregates were smooth. The properties of the aggregates are presented in Table 2.

Table 1: Physical and chemical properties of cements

PROPERTY	CEMENTS			
	PC	FA	MK	SF
Blaine fineness, m^2/kg	395	388	2588	*
Loss on ignition, % a)	1.9	6.1 b)	0.9	2.7
Particle density, g/cm^3	3.17	2.26	2.51	2.17
% retained by 45µm sieve b)	-	11.0	-	-
Particle size distribution, cumulative % passing by mass c)				
125 µm	100	100	100	100
100 µm	98.2	99.2	100	100
75 µm	93.2	96.5	99.8	100
45 µm	81.8	87.0	99.4	100
25 µm	57.1	66.2	96.0	98.8
10 µm	30.1	40.6	76.2	93.8
5 µm	13.5	24.1	50.7	87.5
2 µm	5.6	10.9	18.2	85.5
1 µm	2.9	4.8	4.7	78.7
0.7 µm	1.3	1.9	1.4	50.7
0.5 µm	0.2	0.3	0.1	10.5

* Fineness for SF = 15,000-30,000 m^2/kg[23]
a) In accordance with BS EN 196-2
b) In accordance with EN 450- 1
c) Obtained with the Laser Particle Sizer

The concrete mix proportions, for the cement combinations in Table 3, were based on the BRE Design Guide[24] using a normal weight of 2400 kN/m^3 and a free water content of 165 kg/m^3 to avoid excessively sticky mixes. Potable water (conforming to BS EN 1008) and a superplasticiser (conforming to EN 934-2) were used for mixing the concretes. To provide a uniform basis for comparing the superplasticiser dosages, concrete were produced to a consistence level of S2 (BS EN 206- 1) defined by a nominal slump of 50-90 mm.

Table 2: Physical properties of fine and coarse aggregates

PROPERTY	FINE AGGREGATES 1) 0/4 mm	COARSE AGGREGATES 1)	
		4/10 mm	10/20 mm
Shape, visual	-	Varied	Varied
Surface texture, visual	-	Rough	Smooth
Particle density 2)	2.6	2.6	2.6
Water absorption, % 3)	1.0	1.7	1.2
% passing 600 µm sieve	55.0	-	-

1) Aggregates were obtained from Wormit Quarry.
2) In accordance with BS EN 1097- 6
3) In accordance with BS EN 1097- 6, Laboratory-dry condition

3. Experimental method

To investigate the effect of cement combinations on workability, the superplasticiser dosages and extent of cohesion or stability and finishability of the concretes were assessed. The slump test which could be used to determine the capacity of concrete to hold water and coarse aggregates[25] has been used to assess the workability properties. The superplasticiser dosages for the cement combinations were determined at a consistence level of S2 defined by a nominal slump of 50-90 mm in BS EN 206- 1.

Concrete was prepared to BS EN 12390- 2 and slump test was carried out to BS EN 12350- 2. A dampened truncated cone (100mmΦ x 200mmΦ x 300mm) placed on a horizontal base plate and held firmly in position with the aid of the foot rests, was filled with fresh concrete placed in three layers, each approximately one-third of the height of the cone when compacted. Each layer was compacted with 25 strokes of the tamping rod (16mmΦ x 600mm) uniformly distributed over the cross-sections and depths of the layers. The top layer was over-filled and the excess, after tamping, was removed by the sawing and rolling movement of the compacting rod. After this, the spilled concrete was removed from the base plate and the cone was carefully lifted vertically and placed inverted next to the slumped concrete. The difference between the height of the mould and the highest point of the slumped concrete was then measured, to the nearest 5mm with the aid of a ruler, as the slump and the quantities of superplasticiser required at a consistence level of S2 were obtained for the mixes. Cohesion and finishability were visually assessed. Cohesion was assessed by the extent of the firmness or looseness of the slumped concrete when tamped many times with a rod. Finishability was assessed by the quality of finish.

Plastic density test was determined to BS EN 12350- 6 using the concrete mixes at a consistence level of S2. Concrete was compacted into a rigid and water-tight container of known volume and mass and weighed to determine its mass and hence its density. The container after being calibrated to obtain its volume and weighed to obtain its mass, was filled with fresh concrete in three layers to ensure the full compaction of the concrete. The container with its content, at each stage, was carefully compacted with the vibrating table while being held firmly against the table. The top surface of the concrete was smoothened with a steel float and skimmed with a straight edge. After cleaning the outside surface of the container, the container was weighed and the plastic density was calculated by dividing the mass of the concrete with the volume of the concrete.

4. Analysis and discussion of results

Table 3 shows that plastic density generally reduced with increasing water/cement ratio and increasing total content of the cement additions. Hence, compared with Portland cement, the addition of the cement additions reduced the plastic densities of concretes. However, while silica fume and metakaolin binary cement concretes achieved plastic densities greater than 2400 kN/m^3, the plastic densities of the fly ash binary cements were lower than 2400 kN/m^3. While the plastic densities of the ternary cement concretes were lower than 2400 kN/m^3 all the cement concretes at a total replacement level of less than 55% have plastic densities within the range of 2350 and 2450 kN/m^3 generally used for normal weight concrete. Metakaolin as a binary or ternary cement component produced concretes with higher plastic densities than silica fume at equal replacement level and this is probably due to its higher particle density (Table 1).

Table 3 shows that superplasticiser dosage reduced with increasing water/cement ratio. While fly ash, as a binary cement component, reduced superplasticiser dosage with increasing content, silica fume and metakaolin, as both binary and ternary cement component, increased superplasticiser dosage with increasing content at equal water/cement ratio. Also, the superplasticiser dosages of the ternary cement concretes reduced with increasing content of fly ash. Metakaolin required higher superplasticiser dosage than silica fume at equal replacement level. As silica fume is finer than metakaolin and should require higher content of superplasticiser than metakaolin at equal water/cement ratio, the higher superplasticiser dosages recorded for metakaolin concretes would therefore be due to the fact that the effect of angular shape of metakaolin supercedes the effect of the higher fineness of silica fume on water requirement.

Table 3: Superplasticiser dosage and plastic density of concrete at a consistence class S2 in BS EN 206-1 (defined by a nominal slump of 50-90 mm)

MIX COMBINATION	SUPERPLASTICISER DOSAGE AND PLASTIC DENSITY OF CONCRETE					
	w/c = 0.35		w/c = 0.50		w/c = 0.65	
	SP[a], %	PD[b], kN/m^3	SP[a], %	PD[b], kN/m^3	SP[a], %	PD[b], kN/m^3
100%PC	0.41	2420	0.33	2395	0.25	2385
80%PC+20%FA	0.37	2390	0.30	2375	0.23	2365
80%PC+15%FA+5%MK	0.43	2390	0.35	2375	0.26	2370
80%PC+15%FA+5%SF	0.40	2390	0.31	2375	0.24	2365
65%PC+35%FA	0.33	2370	0.27	2360	0.20	2355
65%PC+30%FA+5%MK	0.40	2370	0.35	2360	0.27	2355
65%PC+25%FA+10%MK	0.45	2375	0.39	2365	0.31	2360
65%PC+30%FA+5%SF	0.38	2365	0.29	2360	0.23	2355
65%PC+25%FA+10%SF	0.40	2365	0.35	2360	0.26	2355
45%PC+55%FA	0.31	2340	0.26	2340	0.19	2340
45%PC+45%FA+10%MK	0.38	2345	0.34	2345	0.27	2345
45%PC+40%FA+15%MK	0.41	2350	0.37	2345	0.28	2345
45%PC+45%FA+10%SF	0.36	2340	0.31	2340	0.24	2340
95%PC+5%MK	0.43	2415	0.35	2390	0.26	2380
90%PC+10%MK	0.47	2410	0.39	2390	0.29	2380
85%PC+15%MK	0.51	2405	0.43	2385	0.33	2375
95%PC+5%SF	0.43	2410	0.35	2390	0.26	2380
90%CEM I+10%SF	0.46	2400	0.38	2385	0.28	2375

a) % Superplasticiser (SP) is related to the total cement content.
b) Plastic density of concrete

The cohesion of the concrete mixes was also assessed as described earlier with the aid of the slumped concretes. Cohesion of concrete was observed to generally reduce with increasing water/cement ratio. Compared with Portland cement concrete, the use of cement additions was observed to result in improved cohesion and therefore stability of the concrete mixes at equal water/cement ratio. This is probably due to improved particle packing, improved viscosity or higher water needed by the fine materials (especially silica fume and metakaolin). Compared with the FA binary cement concrete, the higher fineness of silica fume and metakaolin also resulted in ternary cement concrete with higher cohesion. However, increasing cohesion was observed to have a negative effect on finishability. This is because the higher the cohesion, the higher the stickiness and the difficulty in obtaining a smooth finish.

5. Conclusion

The plastic density of concrete would reduce with increasing water/cement ratio and the replacement of Portland cement with cement additions would reduce the plastic densities of concretes with increasing content. While only the silica fume and metakaolin binary cement concretes achieved plastic densities of 2400 kN/m^3 or more, only the ternary and fly ash binary cement concretes at a total replacement levels less than 55% achieved plastic densities of 2350 kN/m^3 or more. Also, metakaolin due to its higher particle density produced concretes with higher plastic densities than silica fume at equal replacement level.

Superplasticiser dosage reduced with increasing water/cement ratio and while the addition of fly ash would reduce superplasticiser dosage, the addition of silica fume and metakaolin as both binary and ternary cement component would increase superplasticiser dosage with increasing content. Hence, the superplasticiser dosages of the ternary cement concretes reduced with increasing content of fly ash. Metakaolin requires higher superplasticiser dosage than silica fume at equal replacement level probably because the effect of the fineness and angular shape of metakaolin particles supersedes the effect of the higher fineness and spherical shape of silica fume particles on the water requirement of concrete.

The cohesion of the concrete reduced with increasing water/cement ratio and due to improved particle packing and higher viscosity, the use of cement additions would improve the cohesion and stability of concrete. Also, silica fume and metakaolin due to their higher fineness would result in concrete with higher cohesion, stickiness and poor finish than fly ash concrete.

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