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Sorptivity Of Cement Combination Concretes Containing Portland Cement, Fly Ash And Metakaolin

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ABSTRACT

To investigate the permeation resistance of cement combination concrete, this paper examined the sorptivity of Portland cement and some binary and ternary cement concretes containing fly ash and metakaolin at equal water/cement ratios and strengths. At equal water/cement ratio, fly ash binary cement concretes have higher sorptivity than Portland cement and while their sorptivity increased with increasing content of fly ash, they decreased with curing age. Metakaolin binary and ternary cement concretes have lower sorptivity than Portland cement and fly ash binary cement concretes at both early and later ages and their sorptivity reduced with increasing content of metakaolin up to 15%. At equivalent strengths, cement combination concretes generally have lower sorptivity than Portland cement and the sorptivity of the binary cement concretes reduced with increasing content of fly ash and metakaolin up to 55% and 10% respectively. While at a total replacement level of less than 55%, the ternary cement concretes only performed better than the fly ash binary cement concretes at a strength of 50 N/mm^2, at a total replacement level of 55%, the ternary cement concretes have lower sorptivity values than the fly ash binary cement concretes at all the strengths investigated.

Keywords: Cement additions; cement combination concrete; metakaolin; permeation resistance; sorptivity.

1. Introduction

The use of cement combination would lead to reduced cost and improved performance and environmental compatibility of concrete and it is supported by cement and concrete standards like BS EN 197- 1, BS 8500 and BS EN 206- 1. Cement combinations, by virtue of their delayed strength development at early ages, would be more suitable for mass concreting and concrete work in hot climate than Portland cement. With their long-term pozzolanic reaction with curing age, they would also be good for under-water concrete structures which are prone to water sorption.

Metakaolin is a highly reactive non-crystalline fine pozzolana and its fineness would result in closer packing of materials and reduced bleeding and pore size[1] and ensure more nucleation sites to accelerate hydration reactions[2], increase pore refinement[3, 4] and enhance the early and later age performance of concrete[5]. However, its high specific surface and chemical reactivity have caused workability problems in concrete[6] resulting in increased superplasticiser dosage of about 0.6% for every 5% increase in its content[5]. Hence, it is used as replacements between 5-15% by weight to increase the strength and reduce the permeability of concrete[7]. Due to its availability, low cost and quality control, fly ash constitutes the primary pozzolana for blended cements[8] and the use of gas-fired and co-combustion fly ash would ensure the availability of quality fly ash for future use in concrete[9]. Fly ash is characterised by low water demand and reduced water/cement ratio for equal consistence[10] and improved workability[11]. This is due to the spherical shape[12, 1] and electronic dispersion of its particles[13]. However, the reaction of fly ash requires a higher alkalinity of the pore water than metakaolin. Since this alkalinity would be reduced by metakaolin, the reactivity of fly ash in the presence of metakaolin would be reduced[14]. Also, while fly ash concrete has relatively poor characteristics at early ages[15], its pozzolanic reactivity improves with curing age to improve concrete resistance in aggressive media[16].

While fly ash is cheaper and would improve the workability of concrete than Portland cement and metakaolin, it would reduce hydration reactions at early ages. Hence, ternary combinations of metakaolin and fly ash would perform better than their binary combinations with Portland cement. This is because, while metakaolin would support early age performance, fly ash would continue to refine the properties of the hardened concrete as it matures[17]. Ternary cement combinations are also known to reduce admixture dosage[18].

Sorptivity measures the rate of water absorbed by hydraulic cement concretes and therefore the susceptibility of an unsaturated concrete to water penetration by absorption when no head of water exist. Minimising sorptivity is important in order to reduce the ingress of chloride or sulphate into concrete[19]. But while sorptivity would increase with increasing content of fly ash, the incorporation of metakaolin as binary and ternary cement component would lead to a marked reduction in sorptivity[17]. Despite their ability to perform better than Portland cement, cement combination concretes have been under-utilised in construction. While BS EN 197- 1 permits the use of metakaolin and fly ash of up to 15% and 55% respectively, data from the European Ready Mixed Concrete Organisation[20] show a cement addition content of less than 20% in ready-mixed concrete. Also, while concrete in practice is prescribed on the basis of strength, most researches in literature were conducted at equal water/cement ratio. Since at equivalent strengths, the use of cement combinations would result in better performance[21, 22], this paper examined the effect of cement combinations containing fly ash (up to 55% content) and metakaolin (up to 15% content) on the sorptivity of concrete at equal water/cement ratios and strengths.

2. Experimental Materials and Mix Proportions

The cements used were Portland cement (PC, 42.5 type), siliceous or Class F fly ash (FA) and metakaolin (MK). 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.

Potable water, conforming to BS EN 1008, was used for mixing, curing and testing the concrete specimens. In order to provide reasonably workable concretes and a uniform basis for comparing concrete performance at equal water content and water/cement ratio, a superplasticiser based on carboxylic ether polymer conforming to EN 934-2 was applied during mixing to achieve a consistence level of S2 defined by a nominal slump of 50-100mm in BS EN 206- 1. The yield corrected concrete mix proportions, to the nearest 5 kg/m^3, based on the BRE Design Guide[23], a fixed free water content of 165 kg/m^3 (to avoid an excessively sticky mix) and saturated surface-dry (SSD) aggregates are presented in Table 3 for 0.35, 0.50 and 0.65 water/cement ratios.

Table 1: Properties of Cements

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

a) In accordance with BS EN 196-2
b) In accordance with EN 450- 1
c) Obtained with the Laser Particle Sizer

Table 2: Properties of Fine and Coarse Aggregates

PROPERTY	AGGREGATES 1)		
	FINE	COARSE	
	0/4 mm	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

Table 3: Yield Corrected Mix Proportions of Concrete at a Fixed Free Water Content of 165 kg/m^3

MIX COMBINATION	w/c	MIX PROPORTION, kg/m³ CEMENTS CEM I	FA	MK	AGGREGATES 0/4 mm	4/10 mm	10/20 mm	Free Water	SP, % [a)]
100%PC	0.35	475	-	-	650	375	755	165	0.41
	0.50	330	-	-	740	385	770	165	0.33
	0.65	255	-	-	820	380	765	165	0.25
80%PC+20%FA	0.35	375	95	-	640	370	745	165	0.37
	0.50	260	65	-	735	385	765	165	0.30
	0.65	200	50	-	815	375	760	165	0.23
80%PC+15%FA+5%MK	0.35	375	70	25	640	370	745	165	0.43
	0.50	265	50	15	735	385	765	165	0.35
	0.65	200	40	15	820	375	760	165	0.26
65%PC+35%FA	0.35	305	165	-	635	365	740	165	0.33
	0.50	210	115	-	730	380	760	165	0.27
	0.65	165	90	-	815	375	755	165	0.20
65%PC+30%FA+5%MK	0.35	305	140	25	635	365	740	165	0.40
	0.50	210	100	15	730	380	760	165	0.35
	0.65	165	75	15	815	375	755	165	0.27
65%PC+25%FA+10%MK	0.35	305	115	45	635	365	740	165	0.45
	0.50	210	80	35	730	380	760	165	0.39
	0.65	165	65	25	815	375	755	165	0.31
45%PC+55%FA	0.35	205	255	-	625	360	730	160	0.31
	0.50	145	180	-	725	375	755	160	0.26
	0.65	110	135	-	810	370	750	160	0.19
45%PC+45%FA+10%MK	0.35	210	210	45	630	365	730	160	0.38
	0.50	145	145	30	725	380	755	160	0.34
	0.65	115	115	25	810	375	750	160	0.27
45%PC+40%FA+15%MK	0.35	210	185	70	630	365	730	160	0.41
	0.50	145	130	50	725	380	755	160	0.37
	0.65	115	100	40	810	375	750	160	0.28
95%PC+5%MK	0.35	450	-	25	645	375	750	165	0.43
	0.50	315	-	15	740	385	770	165	0.35
	0.65	240	-	15	820	380	760	165	0.26
90%PC+10%MK	0.35	425	-	45	645	375	750	165	0.47
	0.50	295	-	35	740	385	770	165	0.39
	0.65	230	-	25	820	380	760	165	0.29
85%PC+15%MK	0.35	400	-	70	645	370	750	165	0.51
	0.50	280	-	50	740	385	770	165	0.43
	0.65	215	-	40	820	380	760	165	0.33

a) % Superplasticiser (SP) required for consistence class 2 (BS EN 206-1) is related to the total cement content.

3. Experimental Methods

Concrete was prepared to BS EN 12390- 2 and the specimens were cast, cured under a layer of damp hessian covered with polythene for about 24 hours, demoulded and cured in water tanks maintained at about 20°C until the tests' dates. Tests were carried out on hardened concrete specimens to determine their cube compressive strength and sorptivity at equal water/cement ratios. The cube compressive strengths were obtained in accordance with BS EN 12390- 3 using 100mm cubes at the curing age of 28 days. Since absorption into concrete is a function of the drying temperature and immersion duration[24], sorptivity was determined with specimens oven-dried to constant mass at 105±5°C to ensure a uniform basis for the comparison and repeatability of the results. This is because it is generally believed that at this temperature the pozzolanic reactions of the cement additions would be stopped, the plastic shrinkage cracking associated with reduced bleeding that normally characterise the use of fine materials would be avoided and the microstructure of the test specimens would not be adversely affected to prevent the repeatability of the results.

Sorptivity was carried out in accordance with ASTM C1585- 05 using concrete specimens 100mm in diameter and about 50mm thick. After being cooled to room temperature in a dessicator, the oven-dried specimens were waxed on the side and covered on one end with a loose plastic sheet attached with masking tape to allow the entrapped air to escape from the concrete pores while at the same time preventing water loss by evaporation. After obtaining the initial mass, the test surface (i.e. uncovered end) of each sample was placed on two lines of roller support placed in water maintained at 3-5mm level above the top of the support throughout the duration of the test (Fig. 1).

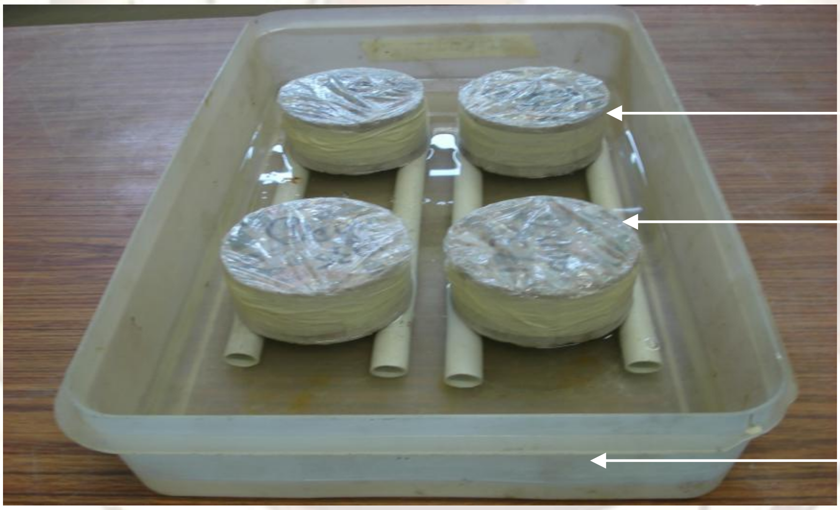

Figure 1: A typical sorptivity test set-up

The sorptivity test was conducted over six hours and the cumulative change in mass at specific intervals was determined. For each mass determination, the test specimen was removed from water and the surface was cleaned with a dampened paper towel to remove water droplets. The mass of the sample was then measured and the sample was replaced to continue the test. The cumulative change in mass at one minute, five minutes, ten minutes, 20 minutes, 30 minutes, one hour, two hours, three hours, four hours, five hours and six hours were used to obtain the respective cumulative absorption values, i, expressed by:

$$i = \frac{\Delta m}{A\rho} \qquad (1)$$

where Δm = cumulative change in mass due to water absorption,

A = cross-sectional area of test specimen, mm^2,
ρ = density of water.

It has been shown by Hall [29] that there exists a relation of the form:

$$i = St^{0.5} \text{ (Darcy's Law)} \qquad (2)$$

where S = sorptivity in mm/√min (1mm/√min = $1.29 \times 10^{-0.4}$ m/√s) and
t = time in minutes

Hence the cumulative absorption values were plotted against the square root of the times and sorptivity (the initial rate of water absorption) was obtained as the slope of the line that best fits the plot.

4. Analysis and Discussion of Results

Table 4 shows that the cube compressive strength of concrete reduced with increasing water/cement ratio and that while the addition of fly ash would reduce strength with increasing content, the addition of metakaolin as binary and ternary cement component resulted in improved strength at 28 days.

The sorptivity of fly ash binary cement concretes which were slightly higher than that of Portland cement concrete at 28 days reduced progressively such that at 180 days they became lower. This is because fly ash would require a higher level of alkalinity which increased progressively with the release of $Ca(OH)_2$ by the hydration reaction of Portland cement to improve the resistance of its concretes to sorption. Since the reductions at these ages increased with increasing content of fly ash, sorptivity would reduce at equal water/cement ratio with increasing content of fly ash. The Table also shows that the addition of metakaolin as binary and ternary cement component reduced the sorptivity of concrete at the test ages. The resistance of the ternary cement concretes to sorptivity also increased with increase in the total content of the cement additions. This must be due to the higher fineness of metakaolin (Table 2) resulting in more nucleation sites for $Ca(OH)_2$ and improved pozzolanic reactions to provide better packing between the cements and at the interface zones between the cement paste and the aggregates.

Table 4 shows that sorptivity of concrete reduced with increasing water/cement ratio and that equivalent sorptivity values of the concretes at equal water/cement ratio would be achieved at different ages and compressive strengths. Since concrete is usually specified in practice on the basis of strength at 28 days, the sorptivity of these concretes has been investigated at equivalent strength at 28 days. Being the range of strengths that would commonly be used in practice, the cube compressive strength and sorptivity of the concretes at the water/cement ratios of 0.35, 0.50 and 0.65 at 28 days (Table 4) were used, by interpolation, to obtain the sorptivity of the concretes at the equivalent strengths of 30, 40 and 50 N/mm^2 at 28 days (Table 5). These strengths also satisfy most of the strength requirements in BS EN 206-1 and BS 8500.

Table 4: Cube compressive strength and sorptivity of concrete at equal water/cement ratios

MIX	w/c	STRENGTH AT 28 DAYS, N/mm^2	SORPTIVITY x 10^{-4}, m/√s		
			28 Days	90 Days	180 Days
100%PC	0.35	80.0	200	160	135
	0.50	54.0	260	215	190
	0.65	38.5	335	295	260
80%PC +20%FA	0.35	72.0	205	155	120
	0.50	46.5	265	220	185
	0.65	30.0	345	300	255
80%PC +15%FA +5%MK	0.35	82.0	185	150	130
	0.50	53.0	245	205	170
	0.65	33.0	320	275	240
65%PC +35%FA	0.35	60.0	210	155	120
	0.50	35.0	270	220	180
	0.65	20.0	360	295	250
65%PC +30%FA +5%MK	0.35	64.0	185	145	120
	0.50	42.0	250	200	165
	0.65	24.0	340	275	235
65%PC +25%FA +10%MK	0.35	68.0	175	140	115
	0.50	43.0	240	195	160
	0.65	25.0	330	270	230
45%PC +55%FA	0.35	42.0	210	150	110
	0.50	24.0	275	210	155
	0.65	12.0	375	295	250
45%PC +45%FA +10%MK	0.35	47.0	115	90	70
	0.50	32.5	215	155	105
	0.65	18.5	325	240	175
45%PC +40%FA +15%MK	0.35	50.0	110	90	70
	0.50	33.0	180	130	100
	0.65	20.0	300	215	160
95%PC +5%MK	0.35	80.0	195	150	115
	0.50	56.0	240	185	135
	0.65	37.0	325	255	180
90%PC +10%MK	0.35	78.0	190	145	115
	0.50	54.5	220	175	130

	0.65	38.0	310	245	175
85%PC +15%MK	0.35	76.0	175	135	110
	0.50	54.0	215	170	125
	0.65	41.0	310	240	170

Table 5 shows that sorptivity reduced with increasing strength and all the cement combination concretes now have lower sorptivity values than Portland cement concrete at the equivalent strengths. Hence, the incorporation of the cement additions at equivalent strengths reduced the sorptivity of concrete. While the sorptivity of the fly ash binary cement concretes reduced with increasing content up to 55%, the sorptivity of the metakaolin binary cement concretes only reduced with increasing content up to 10%. At a total replacement level of less than 55%, metakaolin as a ternary cement component only performed better than the fly ash binary cement concretes at the strength of 50 N/mm^2. However, at a total replacement level of 55%, the addition of metakaolin, as a ternary cement component, resulted in concretes with sorptivity values lower than that of their respective fly ash binary cement concretes.

Table 5: Sorptivity of concrete at the equivalent strengths of 30, 40 and 50 N/mm^2 at 28 days

MIX COMBINATION	SORPTIVITY x 10^{-4}, m/√s		
	30 N/mm^2	40 N/mm^2	50 N/mm^2
100%PC	380	330	275
80%PC+20%FA	345	295	255
80%PC+15%FA+5%MK	330	300	255
65%PC+35%FA	295	255	230
65%PC+30%FA+5%MK	310	260	225
65%PC+25%FA+10%MK	305	250	220
45%PC+55%FA	250	215	180
45%PC+45%FA+10%MK	240	160	100
45%PC+40%FA+15%MK	200	150	110
95%PC+5%MK	365	310	260
90%PC+10%MK	355	300	235
85%PC+15%MK	400	320	235

5. Conclusion

At equal water/cement ratio, fly ash binary cement concretes have poor resistance against sorption and the resistance reduced with increasing content of fly ash. However, the resistance increased with increasing age such that at 180 days they became better than that of Portland cement concrete. Metakaolin binary and ternary cement concretes have better resistance to sorption than Portland cement and fly ash binary cement concretes at both early and later ages and their resistance increased with increasing content of metakaolin. The sorptivity of cement combination concrete is influenced by strength. Compared with Portland cement concrete, the sorptivity of the cement combination concretes were lower at the equivalent strengths and they reduced with increasing total content of fly ash and metakaolin as binary cement components up to 55% and 10% respectively. Metakaolin ternary cement concretes, at equivalent strength, would only perform better than the fly ash binary cement concretes at a total replacement level of 55%. Hence, if appropriately used, cement combination concrete would have higher resistance against sorption than Portland cement concrete and therefore would be preferred for concretes exposed to water and/or aggressive conditions.

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