EFFECT OF FLY ASH AND SILICA FUME ON THE SORPTIVITY OF CONCRETE

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Abstract

Despite their ability to perform better than CEM I, available data have shown that cement combination concetes have been under-utilised in construction. To investigate the permeation resistance of cement combination concrete, this paper examined the sorptivity of CEM I and some binary and ternary cement concretes containing fly ash and silica fume at equal water/cement ratios and strengths. At equal water/cement ratio, fly ash binary cement concretes have higher sorptivity than CEM I and while their sorptivity increased with increasing content of fly ash, they decreased with curing age. Silica fume binary and ternary cement concretes have lower sorptivity than CEM I and fly ash binary cement concretes at both early and later ages and their sorptivity reduced with increasing content of silica fume. At equivalent strengths, cement combination concretes generally have lower sorptivity than CEM I and they reduced with increasing total content of the cement additions.

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

1. Introduction

The use of cement additions has become an increasingly accepted practice in construction to improve concrete performance and contribute positively to the sustainability principle through the re-use of the supposed waste materials, reduced embodied carbon dioxide contents and improved environmental compatibility of their concrete. Silica fume, due to its fineness, would result in close packing of materials, reduced bleeding and reduced pore size[1] and generate more nucleation sites to accelerate hydration reactions[2]. Therefore, apart from filling up the voids existing between the coarser particles like the inert additives, it would chemically react in the pore water to produce materials which are capable of reducing the porosity within the resulting paste and at the interface transition zone between the paste and the aggregates[3]. Fly ash is cheaper and would improve the workability of concrete, but it would reduce hydration reactions at early ages. Fly ash and silica fume, complimenting each other, would react with $Ca(OH)_2$ to form additional calcium silicate hydrates which would increase density, refine the pore structure and reduce permeability to make concrete less susceptible to deterioration. The use of cement combinations is permitted by cement and concrete standards like BS EN 197-1, BS 8500 and BS EN 206- 1.

Fly ash is characterised by low water demand and reduced water/cement ratio for equal consistence[4] and improved workability[5] to ensure reduced bleeding and good workmanship in concrete. This is due to its spherical particle shape[6, 1] and electronic dispersion if enough of its fine particles are adsorbed on the surface of CEM I particles to cover and deflocculate them[7]. While fly ash concrete has relatively poor characteristics at early ages[8], its pozzolanic reactivity improves with curing age[9] to provide improved resistance in aggressive media in concrete[10, 11, 12]. Due to its availability, low cost and quality control, fly ash constitutes the primary pozzolana for blended cements[13] and the use of gas-fired and co-combustion fly ash would ensure the availability of quality fly ash for future use in concrete[14]. Silica fume possesses significant quantities of active silica and would accelerate cement hydration[15] to compensate for the slow rates of reactions of fly ash at early ages and enhance both early and later age performance of cement combination concrete. Silica fume, due to its packing action within the paste matrix and at the interface zone between the paste and the aggregates would result in reduced permeability[16, 8]. Ternary combinations of CEM I, a fast-reacting silica fume and a slow-reacting fly ash would offer significant advantages over binary combinations of these cement additions with CEM I. This is because silica fume would improve the early age performance of concrete while fly ash would continue to refine the properties of the hardened concrete as it matures[5, 9, 17, 18, 19]. Also, their ternary combination would result in reduced dosage of water reducing admixtures [20]. Sorptivity is a standard test for measuring the rate of absorption of water by hydraulic cement concretes and it determines 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[21]. Sorptivity would increase with increasing content of fly ash[22]. Compared with CEM I and fly ash binary cement concretes, the addition of silica fume as binary and ternary cement component would reduce sorptivity[23].

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 CEM I. Due to their long-term pozzolanic reaction with curing age, cement combinations would also be good for under-water concrete structures. While BS EN 197- 1 permits the use of silica fume and fly ash of up to 10% and 55% respectively, data from the European Ready Mixed Concrete Organisation show that the cement addition content (majorly GGBS and fly ash) was less than 20% of the total cement consumption in ready-mixed concrete. At equivalent strengths, the use of cement combinations could result in better performance[24, 25]. However, while concrete in practice is prescribed on the basis of strength, most researches in literature were conducted at equal water/cement ratio. Hence this paper, within the standard limits, examined the effect of cement combinations on the sorptivity of concrete at equal water/cement ratios and strengths.

2. Experimental Materials and Mix Proportions

The cements used were Portland cement (CEM I, 42.5 type) conforming to BS EN 197- 1, siliceous or Class F fly ash (FA) conforming to BS EN 450- 1 and silica fume (SF) in a slurry form (50:50 solid/water ratio by weight) conforming to BS EN 13263- 1. The physical and chemical 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 physical properties of the aggregates are presented in Table 2.

Table 1: Physical and chemical properties of cements

PROPERTY	CEMENTS		
	CEM I	FA	SF
Blaine fineness, m^2/kg	395	388	*
Loss on ignition, % a)	1.9	6.1 b)	2.7
Particle density, g/cm^3	3.17	2.26	2.17
% 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	100
45 μm	81.8	87.0	100
25 μm	57.1	66.2	98.8
10 μm	30.1	40.6	93.8
5 μm	13.5	24.1	87.5
2 μm	5.6	10.9	85.5
1 μm	2.9	4.8	78.7
0.7 μm	1.3	1.9	50.7
0.5 μm	0.2	0.3	10.5

* Fineness for SF = 15,000-30,000 m^2/kg[26]
a) In accordance with BS EN 196-2
b) In accordance with EN 450- 1
c) Obtained with the Laser Particle Sizer

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

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 low water/cement ratios and a fixed water content, 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[27], a 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 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/m^3							
		CEMENTS			AGGREGATES			Free Water	SP, % b)
		CEM I	FA	SF a)	0/4 mm	4/10 mm	10/20 mm		
100% CEM I	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%CEM I+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%CEM I+15%FA+5%SF	0.35	375	70	25	640	370	745	165	0.40
	0.50	260	50	15	735	380	765	165	0.31
	0.65	200	40	15	815	375	760	165	0.24
65%CEM I+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%CEM I+30%FA+5%SF	0.35	300	140	25	635	365	740	165	0.38
	0.50	210	100	15	730	380	760	165	0.29
	0.65	165	75	15	815	375	755	165	0.23
65%CEM I+25%FA+10%SF	0.35	300	115	45	635	365	740	165	0.40
	0.50	210	80	35	730	380	760	165	0.35
	0.65	165	65	25	815	375	755	165	0.26
45%CEM I+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%CEM I+45%FA+10%SF	0.35	205	205	45	625	360	730	160	0.36
	0.50	145	145	30	725	375	755	160	0.31
	0.65	110	110	25	810	370	750	160	0.24
95%CEM I+5%SF	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%CEM I+10%SF	0.35	425	-	45	645	370	750	165	0.46
	0.50	295	-	35	740	385	770	165	0.38
	0.65	230	-	25	820	380	760	165	0.28

a) Dry powder content.
b) % 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 20-24 hours, demoulded and cured in water tanks maintained at about 20^{o}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 at the water/cement ratios of 0.35, 0.50 and 0.65. Since absorption into concrete is a function of the drying temperature and immersion duration[28], sorptivity was determined with specimens oven-dried to constant mass at 105±5^{o}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 (Figure 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

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

where Δm = cumulative change in mass due to water absorption,
A = cross-sectional area of test specimen, mm^2 and
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 = $1.29\text{x}10^{-0.4}$ 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 silica fume as binary and ternary cement component resulted in improved strength at 28 days. Also, the sorptivity of fly ash binary cement concretes which were slightly higher than that of CEM I 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 CEM I 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 silica fume 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. The higher fineness of silica fume (Table 2) must have resulted in better packing between the cements and at the interface zones between the cement paste and the aggregates. Also, more nucleation sites would be provided by the finer silica fume for $Ca(OH)_2$ to improve the pozzolanic reactions and reduce the sorptivity values of concrete.

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 therefore at different compressive strengths. Concrete is specified in practice on the basis of strength and since at 28 days a substantial quantity of hydration would have taken place, the sorptivity of these concretes has been investigated at equivalent strength at 28 days. The cube compressive strength and sorptivity of the concrete at the curing age of 28 days at the water/cement ratios of 0.35, 0.50 and 0.65 (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) which happen to be the range of strengths that would commonly be used in practice. These strengths also satisfy most of the strength requirements in BS EN 206-1 and BS 8500.

Table 5 shows that sorptivity of concrete reduced with increasing strength and compared with CEM I, the incorporation of cement additions at equivalent strengths would reduce the sorptivity of concrete. This is because all the cement combination concretes now have lower sorptivity values than CEM I concrete at the equivalent strengths. The fly ash and silica fume binary cement concretes performed better than CEM I and their sorptivity values reduced with increasing content of the cement additions. At a total replacement level of 35-55%, the addition of silica fume, as a ternary cement component, resulted in concretes with sorptivity values lower than that of their respective fly ash binary cement concretes. However, at a total replacement level less than 35%, silica fume as a ternary cement component only resulted in further reduction in sorptivity at lower strengths as the situation reverted as the strength increased.

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

MIX COMBINATION	w/c	STRENGTH AT 28 DAYS, N/mm^2	SORPTIVITY x 10^{-4}, m/√s		
			28 Days	90 Days	180 Days
100% CEM I	0.35	80.0	200	160	135
	0.50	54.0	260	215	190
	0.65	38.5	335	295	260
80%CEM I+20%FA	0.35	72.0	205	155	120
	0.50	46.5	265	220	185
	0.65	30.0	345	300	255
80%CEM I+15%FA+5%SF	0.35	83.0	190	150	125
	0.50	55.0	245	200	165
	0.65	36.0	315	260	220
65%CEM I+35%FA	0.35	60.0	210	155	120
	0.50	35.0	270	220	180
	0.65	20.0	360	295	250
65%CEM I+30%FA+5%SF	0.35	65.0	170	130	100
	0.50	43.0	225	170	135
	0.65	26.0	300	230	180
65%CEM I+25%FA+10%SF	0.35	77.0	150	120	95
	0.50	49.5	190	155	125
	0.65	32.0	255	205	165
45%CEM I+55%FA	0.35	42.0	210	150	110
	0.50	24.0	275	210	155
	0.65	12.0	375	295	250
45%CEM I+45%FA+10%SF	0.35	57.0	95	80	70
	0.50	36.0	140	120	95
	0.65	22.0	250	170	125
95%CEM I+5%SF	0.35	78.0	120	100	85
	0.50	58.0	205	160	120
	0.65	41.0	300	235	175
90%CEM I+10%SF	0.35	82.0	115	95	80
	0.50	59.0	185	145	115
	0.65	45.0	270	210	170

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 CEM I concrete. Silica fume binary and ternary cement concretes have better resistance to sorption than CEM I and fly ash binary cement concretes at both early and later ages and their resistance increased with increasing content of silica fume. The sorptivity of concrete is influenced by strength. Compared with CEM I concrete, the sorptivity of the cement combination concretes were lower at the equivalent strengths and they reduced with increasing total content of the cement additions.

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% CEM I	380	330	275
80%CEM I+20%FA	345	295	255
80%CEM I+15%FA+5%SF	340	300	260
65%CEM I+35%FA	295	255	230
65%CEM I+30%FA+5%SF	285	235	205
65%CEM I+25%FA+10%SF	260	220	190
45%CEM I+55%FA	250	215	180
45%CEM I+45%FA+10%SF	175	125	105
95%CEM I+5%SF	370	305	250
90%CEM I+10%SF	360	290	235

References

[1] Mindess, S., Young, F. J. and Darwin, D., Concrete, Prentice-Hall, 2003, 644p.

[2] Mehta, P, K. and Aitcin P. C., Principles underlying production of high-performance concrete, Cement Concrete and Aggregates, 12, 1990, pp. 70-78.

[3] Korpa A., Kowald T. and Trettin R., Hydration behaviour, structure and morphology phases in advanced cement based systems containing micro and nanoscale pozzolanic additives, Cement and Concrete Research, 38 (7), 2008, pp. 955-962.

[4] Dhir R. K., McCarthy M. J. and Paine K. A., Use of fly ash to BS EN 450 in structural concrete, Thomas Telford, 2002, 878p.

[5] Thomas M. D. A., Shehata M. H., Shashiprakash S. G., Hopkins D. S. and Cail K., Use of ternary cementitious systems containing silica fume and fly ash in concrete, Cement and Concrete Research, 29 (8), 1999, pp. 1207-1214.

[6] Concrete Society, The use of GGBS and PFA in concrete, Technical Report No 40, The Concrete Society, London, 1991.

[7] Helmuth, R., Fly ash in cement and concrete, Portland Cement Association, Skokie, Illinois, 1987, 203p.

[8] Hassan, K. E., Cabrera, J. G., Maliehe, R. S., The effect of mineral admixtures on the properties of high- performance concrete, Cement and Concrete Composites, 22 (4), 2000, pp 267-271.

[9] Lam L., Wong Y. L., Poon C. S., Effect of fly ash and silica fume on compressive and fracture behaviours of concrete, Cement and Concrete Research, 28 (2), 1998, pp 271-283.

[10] Naik T. R., Singh S., Ramme B., Mechanical properties and durability of concrete made with blended fly ash, ACI Material Journal, 95 (4), 1998, pp 454-462.

[11] Dhir R. K., Jones M. R., Development of chloride-resisting concrete using fly ash, Fuel 78 (2), 1999, pp 137-142.

[12] Antiohos S. and Tsimas S., Chloride resistance of concrete incorporating two types of fly ashes and their intermixtures: The effect of active silica content, Supplementary paper- Proceedings of the 6th CANMET/ACI International Conference on Durability of Concrete, Thessaloniki, Greece, 2003.

[13] Antiohos S. K., Papadakis V. G., Chaniotakis E., Tsimas S., Improving the performance of ternary blended cements by mixing different types of fly ashes, Cement and Concrete Research, 37 (6), 2007, pp 877-885.

[14] Jones M. R., Sear L. K. A., McCarthy M. J. and Dhir R. K., Changes in coal fired power station fly ash: Recent experiences and use in concrete, Proc. Ash Technology Conference, UK Quality Ash Association, 2006.

[15] Langan B. W., Weng K. and Ward M. A., Effect of silica fume and fly ash on heat of hydration of Portland cement, Cement and Concrete Research, 32 (7), 2002, pp 1045-1051.

[16] Bentz D. P., Stutzman P. E. and Garboczi E. J., Experimental and simulation studies of the interfacial zone in concrete, Cement and Concrete Research, 22 (5), 1992, pp 891-902.

[17] Mehta P. K. and Gjorv O. E.,Properties of Portland cement concrete containing fly ash and condensed silica fume, Cement and Concrete Research, 12 (5), 1982, pp 587-595.

[18] Khan M. I., Lynsdale C. J. and Waldron P., Porosity and strength of PFA/SF/OPC ternary blended paste, Cement and Concrete Research, 30 (8), 2000, pp 1225-1229.

[19] Khan M. I. and Lynsdale C. J., Strength, permeability and carbonation of high-performance concrete, Cement and Concrete Research, 32 (1), 2002, pp 123-131.

[20] Bouzoubaa N., Bilodeau A., Sivasundaram v., Fournier B and Golden D. M., Development of ternary blends for high performance concrete, ACI Material Journal, 101 (1), 2004, pp 19-29.

[21] McCarter W. J., Ezirim H., Emerson M., Absorption of water and chloride into concrete, Magazine of Concrete Research, 44 (158), 1992, pp 31-37.
[22] Bai J., Wild S. and Sabir B. B., Sorptivity and strength of air-cured PC-PFA-MK concrete and the influence of binder composition on carbonation depth, Cement and Concrete Research, 32 (11), 2002, pp 1813-1821.
[23] Gonen, T. and Yazicioglu, S., The influence of mineral admixtures on the short and long-term performance of concrete, Building and Environment, 42, 2007, pp 3080-3085.
[24] Dhir R. K. and Byars E. A., PFA Concrete: Near surface absorption properties. Magazine of Concrete Research, 43 (157), 1991, pp 219-232.
[25] Dias W. P. S., Nanayakkara S. M. A. and Ekneligoda T. C., Performance of concrete mixes with OPC-PFA blends, Magazine of Concrete Research, 55 (2), 2003, pp 161-170.
[26] Holland, T. C., Silica Fume User’s Manual, Silica Fume Association, Lovettsville, VA 22180, USA, 2005.
[27] Teychenne D. C., Franklin R. E. and Erntroy H. C., Design of normal concrete mixes, 2nd Ed., amended by B. K. Marsh, Building Research Establishment, 1997, 42p.
[28] Lea F. M., Lea’s chemistry of cement and concrete, 4th Ed., Arnold, London, 1998.
[29] Hall C., Water sorptivity of mortars and concretes: A review, Magazine of Concrete Research, 41 (147), 1989, pp 51-61.