USE OF FINE FLY ASH IN DEVELOPING HIGH PERFORMANCE CONCRETE

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ABSTRACT. This paper briefly describes the major study undertaken to evaluate the suitability of processed fine fly ashes in developing high performance concrete. The two fine fly ashes used in the study were of low lime nature (ASTM, Class F) and sourced from different counties. In total over 3000 tests were carried out in determining the quality of ashes in terms of their physical and chemical characteristics (fineness, morphology, density, particle size distribution, loss-on-ignition, water requirement, strength factor, activity index, heat of hydration, bulk oxide composition and mineralogy) and the performance of concrete mixes produced in their fresh state (consistency and density) and hardened state (strength, drying shrinkage, initial surface absorption, air permeability, carbonation resistance and chloride ingress). The results obtained showed that fine fly ashes can, on their own, be used to produce high performance concrete and that the quality of such a concrete can be comparable to that produced using microsilica fume. Where fine fly ash is of lower quality, this can be compensated by using a tertiary blend with up to 5% silica fume.

Keyword: Fly ash, Metakaolin, Silica fume, Physical and chemical characteristics, Concrete, High performance, Strength, Durability related properties.

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INTRODUCTION

The concept of high performance concrete, as we know it, is in itself not entirely new. Many books [1] and technical papers [2] have been written and conferences, seminars and workshops held on this subject since the early 1990's. Indeed, in 1997 the Council of Scientific and Industrial Research (CSIR), in implementing the Government of India's United Nations Development Fund Umbrella Programme, organised an International Workshop in order to promote high performance concrete and its applications in India. One of the authors (R. K. Dhir) was invited to speak at this Workshop on trends towards holistic approach to material selection for high performance concrete [3]. Likewise, the fundamentals of producing high performance concrete are not entirely new either – they are aimed at, in the first place, selecting and harnessing potential of materials for making concrete in order to optimise its design performance, such as consistence in terms of slump, compressive strength, or durability in terms of resistance to chlorides ingress. Ideally, such an approach to concrete design should be cost effective and routinely useable.

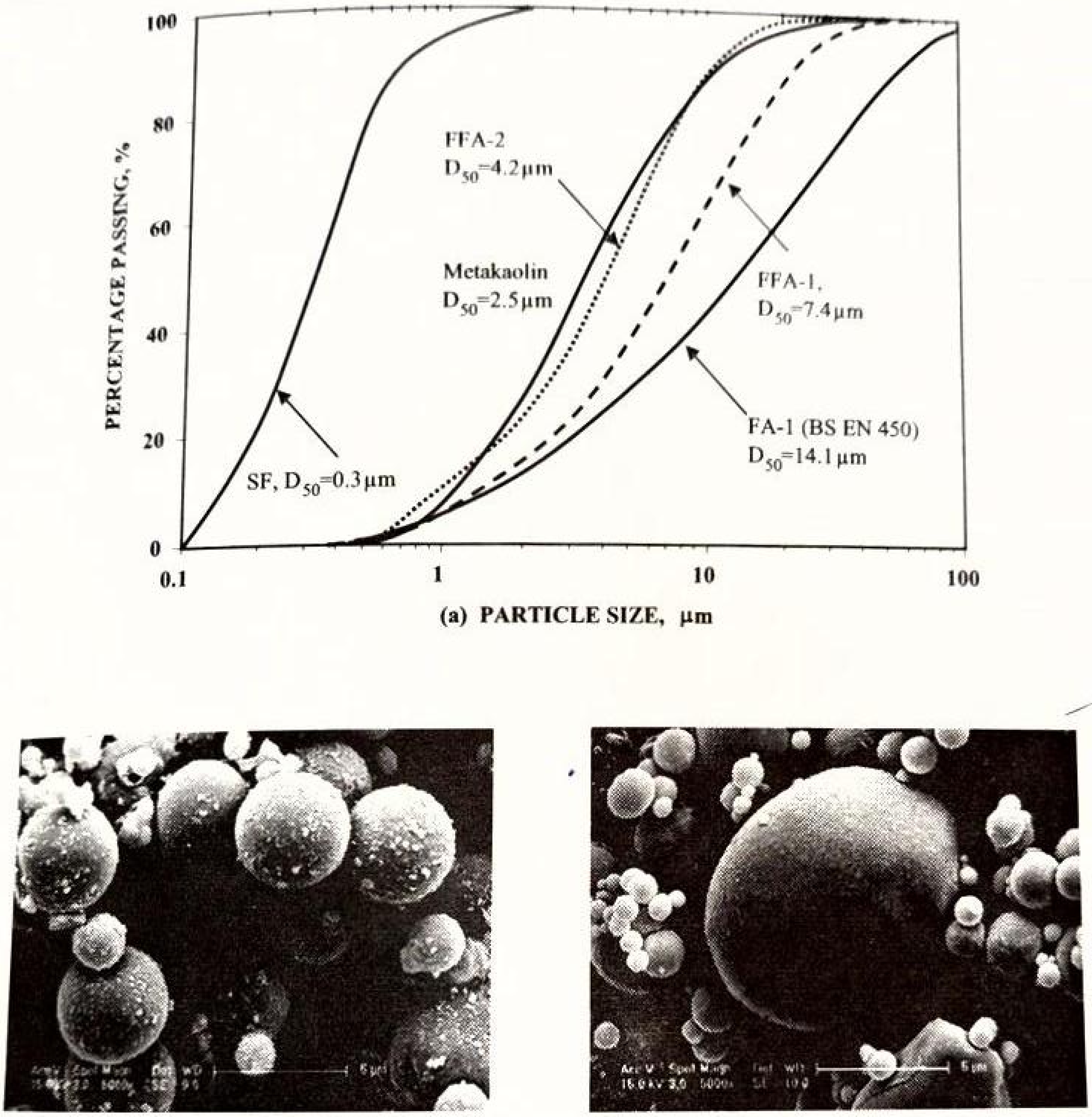
Notwithstanding the significance of the above, it was not until the use of chemical admixtures, in particular those designed to reduce considerably the water demand of concrete mixes (i.e. superplasticisers, high range superplasticisers) became routely accepted, that the use of high performance concrete came into vogue. Indeed, the use of a superplasticiser is an essential requirement for designing high performance concrete as it allows controlling its water content and thereby manipulating the quality of cement paste of the concrete mix. For example, (i) reducing the concrete mix water content whilst maintaining its consistence (workability) will improve the quality of the cement paste in the mix (i.e. porosity and thereby strength and impermiability leading to improvements in the resistance of concrete to the ingress of harmful species) through lowering its water/cement ratio or (ii) alternatively allowing the use of ultrafine fillers/additions such as ground limestone (inert material), microsilica fume (reactive pozzolanic material) can be used to improve cement paste quality through improving its particle packing density, without having to increase mix water content and thereby increasing water/cement ratio which would have negated the beneficial effect of improving the quality of cement paste and hence that of concrete.

Although, until option (ii) above came into consideration and became a possibility, microsilica fume has commonly been associated with high performance concrete (particularly for durability). Basically there is no reason whatsoever why other fine pozzolanic materials such fly ash and ground granulated blastfurnace slag could not be considered for such applications. Indeed, limited amount of work that has been reported [4 -7] suggests that fine fly ashes can potentially be used for producing high performance concrete, particularly when such materials, contrary to microsilica fume, on their own are unlikely to increase the water demand of concrete mix [7].

This paper reports briefly a comprehensive study undertaken to establish the potential for using fine fly ashes (FFAs) in developing high performance concrete mixes in terms of the strength (HSC) and durability (HDC), in comparison to the more commonly used materials such as silica fume (SF) and metakaolin (MK). Additionally, the use of tertiary blends of FFA incorporating SF, and MK were also investigated to determine their potential use in developing high performance concrete mixes.

EXPERIMENTAL PROGRAMME

The most important point to note here is that two fine fly ashes were used (FFA-1 and FFA-2) and that they were obtained from two different countries. Whilst both these fine fly ashes were of low lime nature (ASTM, Class F), they were of different fineness and to certain extent morphology, as can be seen from Figure 1.



(b) Fine Fly Ash FFA-1, mag: 5000×

(b) Fine Fly Ash FFA-2, mag: 5000×

Figure 1 Physical characteristics of fine fly ash, (a) particle size distribution (b) surface morphology

Additionally, silica fume (SF) and metakaolin (MK) were used for comparison. The Portland cement used was 43.5 MPa strength grade. A normal fly ash (FA-1) conforming to BS EN450 – type S (11) was also used as an additional reference material. These cementitious materials, where applicable conformed to the relevant European/British standards and British Board of Agrement [8-11]. The physical and chemical characteristics of these materials are given in Table 1 and Figure 1.

Table 1 Characterisation of the Cementitious Materials Used

PROPERTIES	CEMENTITIOUS MATERIALS					
	PC	FA-1*	FFA-2	FFA-1	SF	MK
(a) Physical Properties						
Density (g/cm^3)	2.99	2.14	2.31	2.20	2.20	2.60
Fineness – 45 μm retention (%)	—	5.9	0	1.0	0	0
Fineness – Blaine (cm^2/g)	3550	4285	5600	5345	200000	29960
Fineness – PSD (cm^2/g)	4450	5625	10370	8285	20900	15755
Setting time (hh:mm)	02:05	02:25	02:41	02:16	—	—
LOI (%)	—	2.08	0.44	2.21	2.29	1.34
Particle Size Distribution (Laser method, also see the Figure 1)						
D_{90} (μm)	34.24	47.22	12.71	25.38	22.29	8.07
D_{50} (μm)	12.38	14.07	4.25	6.92	1.05	1.90
D_{10} (μm)	1.64	1.85	0.99	1.18	0.55	0.69
(b) Water Requirement and Activity						
Water requirement	100	91	84	89	—	—
Strength Factor	1.00	0.81	1.00	0.88	—	—
Activity index	100	83	106	91	—	—
(c) Chemical Compositions (%)						
CaO	62.70	7.19	2.46	4.41	0.81	0.01
SiO_2	21.32	51.22	46.38	50.32	95.51	56.77
Al_2O_3	5.86	27.30	29.82	31.78	0.76	39.87
Fe_2O_3	3.62	3.60	5.96	3.56	0.25	0.51
MgO	2.39	1.35	0.879	1.13	0.64	0.29
MnO	0.10	0.04	0.04	0.05	0.04	0.01
TiO_2	0.32	1.38	1.48	1.53	0.00	0.00
K_2O	0.70	1.55	1.22	1.24	0.86	1.82
Na_2O	0.21	0.58	0.24	0.32	0.34	0.096
SO_3	2.99	0.46	0.59	0.46	1.22	0.00
(d) Mineralogical Components (%)						
C_3S	41.2	—	—	—	—	—
C_2S	19.9	—	—	—	—	—
C_3A	7.8	—	—	—	—	—
C_4AF	15.4	—	—	—	—	—
Quartz	1.0	8.6	7.6	5.07	—	1.8
Mullite	0.9	23.4	24	21.1	—	—
SiC	—	—	—	—	Trace	—
Illite	—	—	—	—	—	3.3
Sandine	—	—	—	—	—	9.8
Amorphous	7.3	63.0	67.1	66.3	<100	85.1

* to EN 450 (Type S) (11)

The coarse aggregates used were crushed gravel in two fractions, having maximum size of 20 and 10 mm [12] and were combined in the ratio of 2 to 1 respectively. The fine aggregate was a natural sand of medium grade [12].

The superplasticiser used to control the consistence of concrete at a constant water content of 160 l/m^3 conformed to BS EN934-2 [13]. This water content was adopted to reflect the use of water contents by the readymixed concrete industry worldwide.

Test Procedures

The tests were carried out in accordance with the methods listed in Table 2 [11, 14-23].

Table 2 Test Methods Used

TEST ITEMS	TEST METHOD
(a) Cements: Physical Characterisation	
Density	BS EN 196 [14]
Fineness	BS EN 196 [14] BS EN 450 [11]
Particle Size Distribution	MALVERN Laser Method
Setting Time	BS EN 196 [14], BS EN 450 [11]
LOI	BS EN 196 [14], BS EN 450 [11]
Morphology	Scanning Electron Microscope
Paste Water Requirement	BS EN 196 [14]
Strength Factor	BS EN 450 [11]
Activity Index	BS EN 450 [11]
(b) Cements: Chemical Characterisation	
Bulk Oxide Composition	XRF analysis
Mineral Composition	XRD analysis
(c) Fresh Concrete	
Consistence	BS EN 12350 [18]
Plastic Density	BS 1881: Part 107 [19]
(d) Hardened Concrete	
Compression Strength	BS EN 12390 [20]
Drying Shrinkage	BS 1881 [21]
ISAT	BS 1881-208 [22]
Air Permeability	Dundee method [24]
Accelerated Carbonation	Dundee Method [27]
Rapid Chloride Permeation	AASHTO (ASTM 1202) [23]

TEST RESULTS AND DISCUSSION

Consistence (Slump)

This was measured using the slump test as described in BS EN 12350: Part 20 [18] and the results obtained, using a fixed amount of water at 160 l/m^3 and the dosage of superplasticiser (SP) fixed at a level (0.25% by mass of cement) that was required to produce the corresponding concrete mix with silica fume having a slump of 50mm, are shown plotted in Figure 2(a). From this it can be seen that:

- The consistence of concrete, measured as slump, increases with increasing percentage addition of FFA with the use of both the fine fly ashes.
- At 20% addition, increase in slump with fine fly ashes (FFAs) is much greater than the corresponding increase with fly ash to BS EN 450: type S (FA-1).
- The consistence of concrete with FFA-2 is approximately twice of that obtained with FFA-1, at all levels of addition.

To visualise the potential impact of this improved consistence with fine fly ashes, a set of mixes were designed with constant cement content (400 kg/m^3) and superplaticiser dosage (0.25% by mass of cement) as before, but in this case, for each mix the slump was kept constant at 50mm by controlling the amount of water used. The water demand of the mixes thus established are shown plotted in Figure 2(b), from which the following observations can be made:

- Water demand of mixes reduces with increasing percentage addition of FFA, with considerably higher water reductions being achieved with FFA-2 than with FFA-1.
- Fine fly ashes (FFAs) are more effective in reducing the water demand of concrete mixes than fly ash to BS EN450 (FA-1).

The practical implications of the results shown in Figure 2(b), are that unlike silica fume or metakaolin, which essentially require the use of a superplasticiser to maintain the design slump of the mix, fine fly ashes can in fact improve the mix consistence and thereby for a given slump offer the possibility of reducing its water content and thus leading to further improving the quality of concrete

The other point of interest that emerges from these results is that all fine fly ashes are not equally effective and that in this case the superior performance of FFA-2 compare to FFA-1 is due to its better particle shape, surface texture and being finer than FFA-1 (Figure 1).

In summary, given the results of Figure 2, it follows that FFAs can potentially be suited for producing high performance concrete and that this potential will vary with the ability of fine fly ash to effect water reduction in a concrete mix.

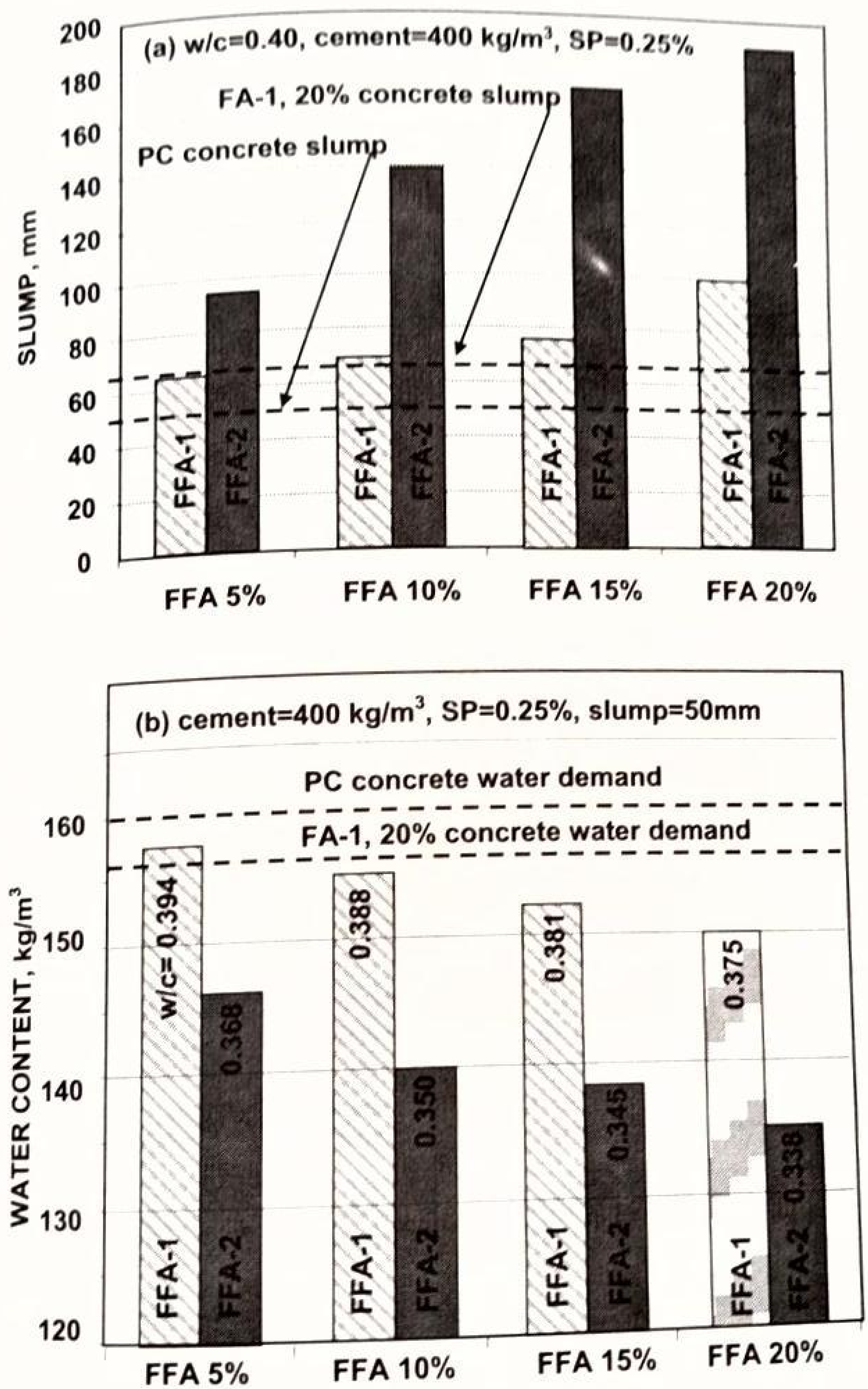


Figure 2 Comparison between FFA-1 and FFA-2 (a) Slump measurements (B) WATER REQUIRED TO PRODUCE CONCRETE MIXES OF GIVEN CONSISTENCE

COMPRESSIVE STRENGTH

All strength tests were carried out in accordance with BS EN 12390 [20]. Extrapolated results for concrete mixes, corresponding to a total cement content of 400 kg/m^3 of binary cement combinations with the following as presented in Table 3:

(i) FFA-1 and FFA-2 additions at 5, 10, 15 and 20%,
(ii) SF at 5 and 10%,
(iii) MK at 10 and 15% and
(iv) FA-1 at 20%,

It should be noted that all mixes have similar consistence of 50 mm slump and superplasticiser dose of 0.25% by mass of cement, but using different amount of water are given in Table 3. It should be noted that these results allow the effect of both the material reactivity and water demand to be considered together. From the results given in Table 3, the following observations can be made:

Table 3 Strength Development Comparison in Binary at Same Consistence

	STRENGTH DEVELOPMENT, N/mm^2				
	3 days	7 days	28 days	60 days	90 days
PC at w/c=0.40	41.5	49.0	59.0	64.0	65.5
5% Replacement					
FFA-1, 5% at w/c=0.394	42.0	50.5	61.5	66.5	68.5
SF 5% at w/c=0.413	44.0	53.5	65.5	70.0	71.5
FFA-2, 5% at w/c=0.368	47.0	55.5	66.5	71.5	73.5
10% Replacement					
FFA-1, 10% at w/c=0.388	43.0	51.5	63.5	69.0	71.5
SF 10% at w/c=0.425	41.0	51.5	65.0	70.0	72.0
MK 10% at w/c=0.438	37.0	47.5	60.5	65.5	68.0
FFA-2, 10% at w/c=0.350	50.5	59.5	71.5	77.0	79.5
15% Replacement					
FFA-1, 15% at w/c=0.381	43.5	52.5	65.5	71.5	74.0
MK 15% at w/c=0.438	35.5	45.0	58.0	63.5	65.5
FFA-2, 15% at w/c=0.345	51.0	60.0	73.5	79.5	82.0
20% Replacement					
FFA-1, 20% at w/c=0.375	44.0	53.0	66.5	73.0	75.5
FA-1, 20% [EN450] at w/c=0.388	41.5	49.5	60.5	65.4	67.5
FFA-2, 20% at w/c=0.338	52.5	61.0	75.0	81.5	84.0

1) Concrete made with fine fly ash (FFA-1) develops higher strength than the corresponding concrete made with PC, with the difference in strength increasing with FFA-1 content and age at testing.

2) At the same levels of replacement, concrete made with FFA-1 develops lower/higher strength than the corresponding concretes made with SF/MK. However, when compared at 20% FFA-1 level, fine fly ash produces concrete that is equal to or than that with up to 10% SF and considerably better than with up to 15% MK.

3) Strength of concrete made with fine fly ash FFA-2 is considerably higher than that made with FFA-1, with the difference between the two sets of concrete increasing with fine fly ash content and age at testing.

4) At 20%, FFA-1 develops higher concrete strength at all ages than FA-1, indicating that FFA-1 can be used to produce concrete having strength of similar order to that obtained with SF, whilst FFA-2 can be used to develop concrete with compressive strength higher than SF.

Drying Shrinkage

The drying shrinkage results of concrete mixes, tested in accordance with BS 1881[19], up to 16 weeks are given in Table 4. As can be seen, the drying shrinkage values are essentially similar for all cement combinations (composite cements) used in this study.

Initial Surface Absorption

The ISAT results obtained in accordance with BS 1881: Part 208 is given in Table 4. It can be seen from these results that:

- Concrete made with FFA-1 performs lightly better/better/similar than the corresponding concrete incorporating SF/MK/ FA-1.
- Concrete made with FFA-2 performs slightly better than that made with FFA-1, up to 10% addition levels and thereafter both concretes perform similarly.
- 10% addition of fine fly ashes is an optimum figure for initial surface absorption of concrete.

Air Permeability

The air permeability test [24] gives a better measure of the structure of concrete (hardened cement paste).The results obtained are given in Table 4 and the main points to note are that:

- The optimum effect of fine fly ashes is realised with 10% addition.
- At this addition level, FFA-2 performs similar to SF and both materials achieve the lowest air permeability value of 0.9m2x10-17.
- At all levels of addition, FFA-2 performs slightly better than FFA-1.
- The performance of MK comes out to be the worst.

Chloride Diffusion

This was assessed using the rapid chloride permeability test, RCPT [23]. Although recognised by the authors as a highly unreliable and unsuitable as a research tool, this test was adopted in this study because of speed with which the tests can be completed.

The results obtained are given in Table 4. and unfortunately they turn out be fairly inconclusive, other than that fine fly ashes can be used effectively in developing concrete with sufficient resistance to chloride ingress. Indeed, given the chemical nature of fly ash per say, and the weight of information suggesting its suitability for use in chloride environment [25, 26], it should be reasonable to deduce from the results in Table 4 that fine fly ashes improve concrete resistance to chloride ingress and that concrete made with fine fly ashes could be expected to give similar performance to SF in this respect.

Table 4 Other Properties Comparisons in Binary at Same Consistence

	PROPERTIES				
	ISAT10, ml/m^2×10^2	k_{int}, m^2×10^{-17}	ASTM Chloride, Coulombs	8 Weeks Carbonation, mm	12 Weeks Shrinkage, %
PC at w/c=0.40	35.5	3.6	Moderate	5.4	0.053
5% Replacement					
FFA-1, 5% at w/c=0.394	30.5	1.8	Moderate	5.3	0.058
SF 5% at w/c=0.413	31.5	1.1	Low	4.5	0.055
FFA-2, 5% at w/c=0.368	29.5	1.6	Moderate	4.0	0.055
10% Replacement					
FFA-1, 10% at w/c=0.388	29.0	1.2	Moderate	5.3	0.058
SF 10% at w/c=0.425	31.0	0.9	Low	9.4	0.054
MK 10% at w/c=0.438	35.5	1.9	Low	8.2	0.059
FFA-2, 10% at w/c=0.350	28.0	0.9	Low	3.5	0.055
15% Replacement					
FFA-1, 15% at w/c=0.381	30.5	1.2	Low	5.9	0.056
MK 15% at w/c=0.438	37.5	2.4	Low	9.0	0.057
FFA-2, 15% at w/c=0.345	30.0	1.0	Low	4.4	0.054
20% Replacement					
FFA-1, 20% at w/c=0.375	32.5	1.3	Low	6.9	0.055
FA-1, 20% [EN450] at w/c=0.388	37.2	1.9	Moderate	8.7	0.056
FFA-2, 20% at w/c=0.338	32.0	1.2	Low	5.6	0.054

Carbonation Resistance

The carbonation results obtained up to 16 weeks using the method developed at the University of Dundee [27] are given in Table 4. It can be seen that the carbonation of concrete made with fine fly ashes is lower than the corresponding concrete made with fly ash to BS EN450, as well as silica fume and metakaolin and that between the two fine fly ashes FFA-2 performs somewhat better than FFA-1.

OVERALL OBSERVATIONS

Overall, the results in Tables 3 and 4 suggest that:

Whilst both fine fly ashes can be used to produce concrete having strength of similar order to that obtained with MK and SF, fine fly ash FFA-2 can produce strengths greater than those obtained with the use of SF.

In terms of durability related properties, whilst the use of both fine fly ashes can be suitable and the use of FFA-1 can be developed for some aspects to produce concrete of similar performance to that made with SF and MK; fine fly ash FFA-2 would be more effective in such a use.

EFFECT OF SF OR MK ON FFA-1 BINARY CEMENT COMBINATION AT EQUAL CEMENT CONTENT AND CONSISTANCE

Of the two fine fly ashes, FFA-1 was, all round, found to be less effective than FFA-2, which performed as well or better than SF or MK. To further enhance the performance of fine fly ashes, where required, it was decide to study the effect of introducing SF or MK into a binary cement combination of PC/FFA-1.This combination was chosen because of its lower performance compared with FFA-2.

The previous results obtained in this study suggested that best results may be obtained with concrete containing FFA-1 between 15 to 20% and therefore it was decided to select levels of 15 to 20% as a reference to determine the effect of including SF or MK within a total of 15 to 20% in tertiary blends. In each case cement content was kept at 400 kg/m^3, superplasticiser dosage at 0.20% and consistence at 50mm slump (therefore water content is allowed to vary in each mix)

The results obtained are shown plotted in Figure 3, comparing them with those obtained with FFA-2 at 10% addition considered as being able to give optimum performance. From the examination of Figure 3, it can be seen that in general terms the performance of FFA-1 can be further improved using of about 5% SF in combination with FFA-1 at 10 or 15 %. Overall, including cost consideration, the combination FFA-1 at 10% with SF at 5% could be considered as the optimum combination.

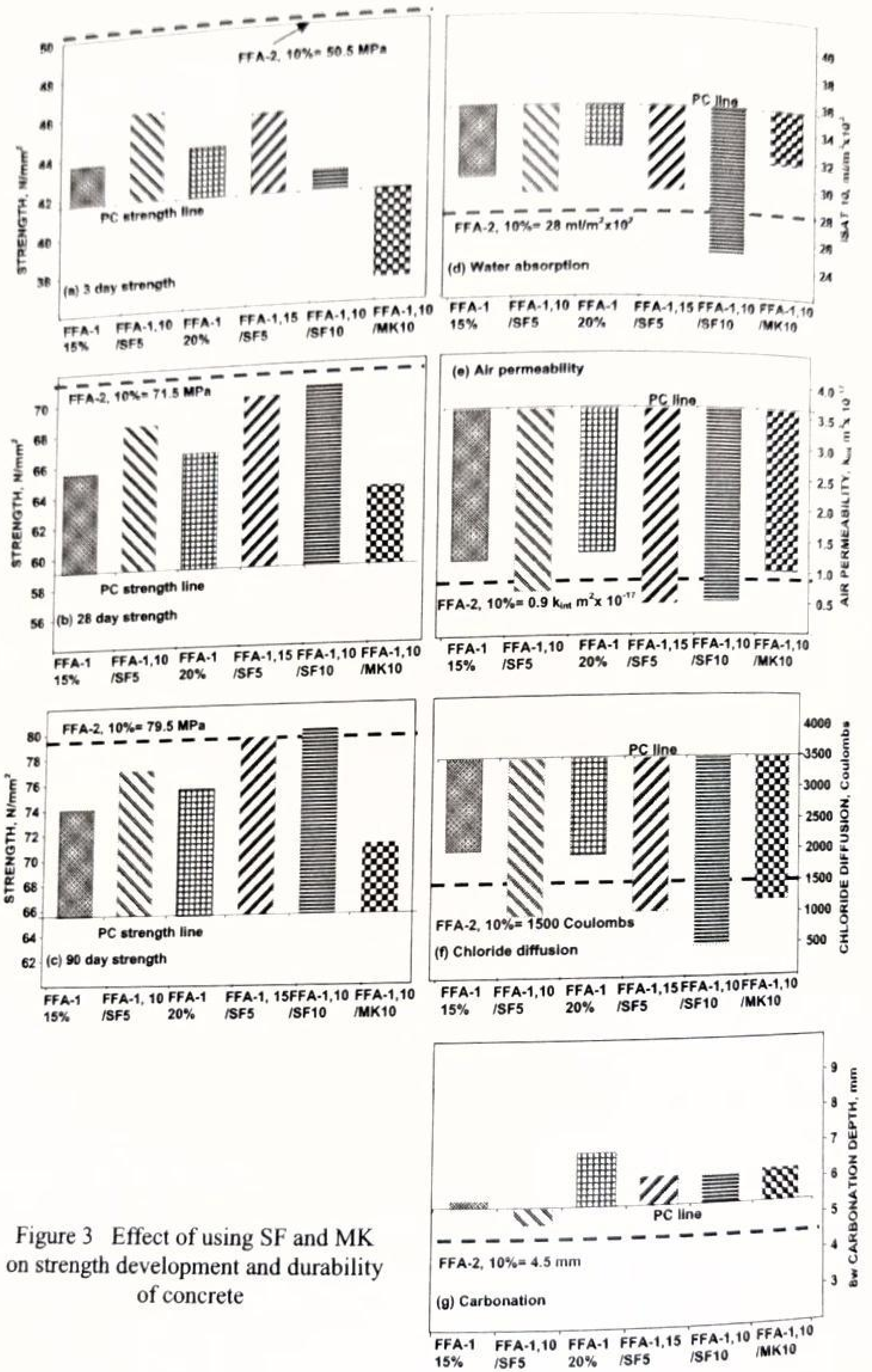


Figure 3 Effect of using SF and MK on strength development and durability of concrete

CONCLUSIONS

1. Processing fly ash to greater fineness than the BS EN 450 specification will make it more effective in improving the performance of concrete, but the magnitude of this effect will be determined by the fineness and physical and chemical characteristics of the material. This is supported by the test results obtained for two fine fly ashes tested, where fine fly ash FFA-2 was found to be of better quality (Table 1) and accordingly produced concrete with better performance than fine fly ash FFA-1.

2. Notwithstanding the above, the results show that fine fly ash FFA-1 is a better quality material than the corresponding BS EN 450 fly ash from the same source and as such FFA-1 can be used to produce concrete of high performance quality.

3. Fine fly ashes of quality similar to that of FFA-2, are suitable for producing high performance concrete, both in terms of its strength and durability, of quality comparable to or better than that produced with microsilica fume. Thus fly ash processed to quality similar to that of FFA-2 merits their use in par with silica fume.

4. When used at higher addition level or combined with 5% SF, fine fly ash of FFA-1 (lower quality than FFA-2) can also be used to produce high performance concrete of quality comparable to that produced with microsilica fume. This concept of tertiary (triple) blend cement is well suited for the production of high performance concrete.

REFERENCES

1. SHAH S P and AHMED S H. High Performance Concrete. New York: McGraw-Hill, 1994.

2. JONES M R, McCARTHY M J and DHIR R K. Chloride resistant concrete. Concrete 2000: Economic and Durable Construction through Excellence, E & F N Spon, Ed. R K Dhir and M R Jones, 1993, pp.1429-1444.

3. DHIR R K. Towards a holistic approach to material selection for high performance Concrete. Proc. TCDC Int. Workshop on Advances in High Performance Concrete Technology and its Applications, 1997, pp I 1-18.

4. BUTLER, W B. Superfine fly ash in high strength concrete. Concrete 2000, Eds. R K Dhir and M R Jones, 1993, pp 1825-1831.

5. CORNELISSEN, H A W., HELLEWAARD, R E. and VISSENS, J L J. Processed fly ash for high performance concrete, CANMET/ACI Conference, Wisconsin, USA, 1995,pp 67-81

6. DHIR, R K., JONES, M R. and BOOTH, A P J. Feasibility of Processing PFA to Improve It's Quality for Use in Concrete, Internal Report, University of Dundee, 1998, 321 pp

7. SEEDAT, E Y. A surfine pozzolanic class F fly ash for superior concrete, Ash Resources, South Africa, 2000, 16 pp.

8. BRITISH STANDARDS INSTITUTION, prEN 13263: Silica fume for concrete - Definitions, requirements and conformity control, 1988.

9. BRITISH BOARD OF AGRÉMENT, Metakaolin, and Agrément certified (98/3540).

10. BRITISH STANDARDS INSTITUTION, BS EN 197-1, Cement - Composition, specifications and conformity criteria for common cements. London, 2000

11. BRITISH STANDARDS INSTITUTION, BS EN 450 Fly ash for concrete - Definitions, requirements and quality control, London, 1995.

12. BRITISH STANDARDS INSTITUTION, BS EN 12620, Aggregate for Concrete, London, 2002.

13. BRITISH STANDARDS INSTITUTION, BS EN 934-2, Admixtures for concrete, mortar and grout. Concrete Admixtures. Definitions and requirements. London, 1998.

14. BRITISH STANDARDS INSTITUTION, BS EN 196-1, Methods of testing cement. Determination of strength, London, 1995.

15. BRITISH STANDARDS INSTITUTION, BS EN 196-3, Methods of testing cement. Determination of setting time and soundness, London, 1995.

16. BRITISH STANDARDS INSTITUTION, BS 812-2, Testing aggregates, Part 2. Methods of determination of density, London, 1995.

17. BRITISH STANDARDS INSTITUTION, BS EN 933-1, Tests for geometrical properties of aggregates, Part1. Determination of particle size distribution – sieving method, London, 1997.

18. BRITISH STANDARDS INSTITUTION, BS EN 12350-2, Testing fresh concrete – Part 2: Slump test, London, 2000.

19. BRITISH STANDARDS INSTITUTION, BS 1881: Part 107, Testing concrete – Method for determination of density of compacted fresh concrete, London, 1983.

20. BRITISH STANDARDS INSTITUTION, BS EN 12390-3, Testing hardened concrete, Part 3: Compressive strength of test specimens, London, 2002.

21. BRITISH STANDARDS INSTITUTION, BS 1881: Testing concrete – Determination of drying, shrinkage and moisture movement, London, 1986.

22. BRITISH STANDARDS INSTITUTION, BS 1881: Part 208, Recommendations for the determination of the initial surface absorption of concrete, London, 1996.

23. ASTM C 1202, Standard Test Method for Electrical Indication of Concrete Ability to Resist Chloride Ion Penetration, 1997.

24. DHIR, R K., HEWLETT, P C & CHAN, Y N. Near surface characteristics of concrete: Intrinsic permeability. Magazine of Concrete Research, 41 (147), June 1989, pp 87-97. Discussion 42 (152), 1990, pp 187-188, 1990

25. DHIR, R K, MCCARTHY, M J & JONES, M R Cement Additions. Concrete Production and Performance in Aggressive Environments. Keynote Paper. Proceedings of International Conference, Concrete in Hot and Aggressive Environments, Bahrain, 27-29November 2006.

26. DHIR R K. Specifying concrete durability: Are we getting there? Proc. Joint Symposium on Concrete and Bridge Research in Ireland, Eds.E.Cannon, R. West and P. Fanning, National University of Ireland, Galaway, December, 2008, pp 3-14.

27. DHIR, R K., JONES, M R & MUNDAY, J G L. A practical approach to studying carbonation of concrete. Concrete 19 (1), October, pp 32-34, 1985