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A COMPARATIVE STUDY OF THE EFFECTS OF SILICA FUME, METAKAOLIN AND PFA ON THE AIR CONTENT OF FRESH CONCRETE

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Introduction

The raw materials needed for the manufacture of Portland cement (PC) are available in most parts of the world, and the energy requirements for its production may be considered to be relatively modest. Nevertheless the use of alternative binders or cement replacement materials, has become a necessity for the construction industry because of the economic, environmental and technological benefits derived from their use. Furthermore recent years have seen increased concerns regarding the depletion of raw materials, energy demands and the consequent environmental damage. These concerns have led to wider utilization of existing cement replacement materials and further search for other less energy intensive materials. Many of these mineral admixtures are industrial by-products, and are considered as waste. When used as a partial cement replacement material, typically in the range of 20 to 60% by mass, the energy and cost savings are substantial. From an environmental point of view mineral admixtures are playing an undisputed role. They are responsible for substantial “environmental unloading” because their disposal can be hazardous to the environment and higher utilisation of them can result in reduction of greenhouse gas emissions attributed to the cement industry.

Two of the revolutionary developments in concrete technology in the last century have been produced by air entraining agents (AEAs) and superplasticizers [1]. Superplasticizers or high range water reducing admixtures (HRWRAs) are concrete admixtures which can be mainly used either to increase the workability of fresh concrete at a given mix composition or to reduce the amount of mixing water and water/cement (w/c) ratio for a given workability in order to increase strength and durability. For instance to compensate for the loss of workability in mixes like those containing pozzolanic materials such as condensed silica fume (CSF) and metakaolin (MK) or even increase the water reduction effect of pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) we normally use superplasticizers. Due to addition of superplasticizers the slump increase at a given mix composition can be 150-200 mm and the reduction of mixing water at a given slump can be up to 30%, both depending on the method of addition, dosage and type of admixture used. Presently the most important HRWRAs available are based on condensed melamine sulfonated formaldehyde (MSF) or naphtalene sulfonated formaldehyde (NSF) in the form of 40% aqueous solution to facilitate an accurate, reliable and automatic dispensing at the batching plant. The optimum dosage of commercial superplasticizers is in general in the range 1-2% by mass of cement. The main action of the molecules of such superpalsticizers is to wrap themselves around the cement particles and give them a highly negative charge so that they repel each other [2]. This results in deflocculation and dispersion of cement particles with the resulting improvement in workability.

It is widely recognized that most pozzolans when used correctly in concrete increase its durability [3]. Thus when durability is of paramount concern, concrete should always incorporate pozzolanic materials. An important aspect of durability is freeze-thaw: the resistance of concrete to alternate cycles of freezing and thawing. Superplasticizers can also be useful as far as freeze-thaw is concerned. They can be used to reduce the amount of mixing water without changing the cement content in order to reduce the w/c ratio and therefore not only increase strength and reduce sorptivity and water absorption but also improve freeze-thaw durability. They are capable of allowing reduction in w/c ratio to the low levels (0.40-0.45) required for frost resistant concrete of appropriate workability by American and European specifications.

Air entraining agents are admixtures which are capable of forming air bubbles dispersed throughout the cement matrix that binds the aggregates. After compaction, normal concrete is likely to contain about 1-2% air by volume, this accidentally entrapped air being unevenly distributed and consisting of bubbles of irregular size and shape. Air entraining agents introduce a controlled amount of air in the form of millions of bubbles of uniform size and uniformly distributed throughout the concrete mix. There is another distinctive difference between air voids accidentally entrapped in concrete and the deliberately entrained air bubbles. The latter are very much smaller, typically 50μm in diameter whereas the former can be as large as the familiar, albeit undesirable, pockmarks on the formed surface of concrete. Numerous types of air entraining agents are commercially available with the vinsol resin based products being the most common ones. The optimum dosage for AEAs is usually below 1% by mass of cement.

The presence of entrained air in fresh concrete has a pronounced effect on its properties. One of these is workability, which is improved. For adequate workability, the aggregate particles must be spaced in a way that they can move past one another with relative ease during mixing and placing. In this respect, the entrained air voids are often thought of as millions of tiny ball bearings in the concrete, making the mix more workable [2]. Entrained air also eliminates or minimises segregation and subsequent bleeding. Although there are also other advantages to be realised, the principal reason behind the use of air entrainment agents is the improvement that they impart to the concrete’s resistance to frost action and to its deterioration due to repeated freezing and thawing. A given volume of air and an appropriate spacing factor are required to produce an adequate air bubbles system to protect concrete from freezing and thawing. Because the damaging action of freezing and thawing involves expansion of water on freezing and associated osmotic processes, it is logical to expect that, if excess water can readily escape into adjacent air-filled voids, damage to the concrete will not occur. This is the underlying principle of improved frost resistance by air entrainment.

Research objectives

Studies on air entrainment and freeze-thaw durability of CSF concrete have been conducted mainly after 1980. There have been significant additions to knowledge in this system but certain aspects of it still require attention. A lot of work has also been carried out on air entrainment and freeze-thaw in concrete containing PFA. However there is reluctance to combine PFA with air entraining agents since there is uncertainty about their interaction. Furthermore, little information is available on the influence of PFA on the development of the air void system in hardened concrete or on the evaluation of the performance of such concrete under freeze-thaw conditions [4]. Metakaolin is a relatively new material and its effects on the properties of concrete have been well established during the past few years [5-9] but some durability aspects of MK concrete, including freeze-thaw, have not yet been investigated.

This paper examines the influence of admixture dosages on the air content of the fresh concrete in relation to various partial replacement levels of PC by CSF, MK or PFA. It reports the findings of a study of the inter-relationships between the effects of a recently developed highly efficient superplasticizer (HRWRA) and air entraining admixture on the workability and air content in concrete containing CSF, MK or PFA. The findings will be used to select a range of mix properties for further investigative studies examining the response of such concretes to freeze-thaw environments. The behaviour will be investigated in terms of the concrete’s pore size distribution and air bubble systems, its microstructure, expansion and water absorption.

State of knowledge on air entrainment and pozzolans

In general, more AEA is required to entrain a specified volume of air in PFA concrete as compared to non-PFA concrete, and the cause of this is said to be the adsorption of air entraining agent by unburnt carbon in the PFA [10,11]. It has however been reported that some PFAs make it difficult or impossible to entrain a specified amount of air [12].

Gebler and Klieger [13] showed that a different amount of air entraining agent is usually needed for a particular air content with PFAs of different characteristics. If the quantity of organic substances, carbon content and LOI of the PFA increases, then more AEA is required for a specified air content. Carette and Malhotra [14] have published considerable data on air-entrained concrete incorporating a variety of PFAs. Investigations dealing with air-entrainment and freeze-thaw durability of PFA concrete have been recently reported by Dhir et al [4]. The results demonstrate that the admixture demand of PFA concrete was higher than that of PC only concrete. In addition it was found that air contents of up to 4.5% (using vinsol resin type air entraining agents) in concretes containing PFA required a factor of 2 increase in the admixture demand. Sturrup, Hooton and Glendenning [10] studied the effects of PFA on the air content of concrete in the laboratory and found that entrapped air is reduced by about 0.5% by the PFA and that the total air content required to obtain adequate durability is reduced as compared to concrete not containing PFA.

According to Carette and Malhotra [15] the dosage of air-entraining admixture to produce a required volume of air in concrete usually increases with increasing amounts of CSF due to the very high surface area of silica fume and to the effect of carbon when the latter is present. In another series of experiments Carette and Malhotra [16] found that for low water/binder ratio (w/b = 0.40) the replacement of cement by CSF in superplasticized concrete led to an increased need for AEA, to maintain the same air content. The authors concluded that entrainment of more than 5% air is difficult in concrete incorporating high amounts of CSF, even in the presence of a superplasticizer.

Toutanji [17] performed an experimental study on the properties of CSF concrete containing air-entraining agent. The CSF content ranged from 0 to 20% by mass of the binder (PC+CSF).The fresh mix properties were characterized by slump and air content tests. The test results showed that air entrainment improved the workability of CSF concrete, however the effectiveness of air entrainment reduced with increasing CSF content. It was also found that the increase in air content in both control and CSF concrete due to addition of air entrainment decreases with increasing air-entraining agent. More specifically, employing a dosage of 0.05% (as percentage of the binder) has considerably more effect on air content than increasing the dosage from 0.05 to 0.10%. Sabir and Kouyiali [18] have shown that in using a fixed dosage of air entraining agent, the resulting volume of air decreased appreciably with increasing CSF content. The air content reduced from 6.6% for the control mix to 4.4% for the mix incorporating 12% CSF. Virtanen [19] found that CSF concrete needed a higher dosage of air entraining agent than the control mix, to reach a given air content, but the dosage was less than that required for concrete containing PFA and GGBS. In a further test series Virtanen [20] investigated high quality concrete for bridge edge beams, containing 0 to 16% CSF, and different dosages of AEA. In agreement with other researchers, for a given dosage of air entraining agent an increase in CSF content resulted in reduced air content in the fresh mix. Carette et al. [21] reported that the required dosage of air-entraining admixture increased with the amount of CSF, especially for concrete made with a w/b ratio of 0.40 against others with w/b ratios of 0.5 and 0.6. To the author’s knowledge no studies have been conducted on MK concrete to establish the relationships between the dosage of air entraining agent and the air content in the fresh concrete.

Experimental investigation

Materials

The cement used throughout this investigation, was class 42.5 N Portland cement complying with the requirements of BS 12 [22]. The CSF was supplied by Elkem Materials Ltd and the slurry was composed of a mass ratio of CSF solids to water of 1:1. The PFA was supplied by Ash Resources Ltd and the MK was supplied by ECC International. Details of the main physical and chemical properties of the PC and binder materials are given in Table 1.

The fine aggregate was natural sea-dredged sand from the Bristol Channel. The sieve analysis performed in accordance to BS 812: Section 103.1 [23] showed that the sand complied with grades C and M of BS 882 [24]. The coarse aggregates employed were 10 mm maximum size crushed limestone supplied by a local quarry. The limitation on the maximum size of coarse aggregates was imposed by the sorptivity testing systems which will be employed in the later part of this investigation. The gradings of fine and coarse aggregates are given in Table 2.

A comprehensive range of concrete mixtures was found to be achievable using a more recently developed water reducing admixture, i.e. “Adva Flow”. Adva Flow (AF) is a synthetic carboxylated polymer based clear liquid superlasticizer complying with BS 5075: Part 3 [25].

Darex AE3, a pale yellow liquid air entraining agent, was used. This conforms to the requirements of BS 5075: Part2 [26] for air entraining admixtures and it is based on the salt of an ether sulphate. Table 3 gives descriptions of the water reducing and air entraining admixtures employed in the current investigation. AF was found to be a more effective and stable admixture when used in combination with the air entraining agent. Careful control, however, was found to be crucial as slight alterations in the dosages of the superplasticizer can cause very significant changes in workability.

Table 1 Properties of PC, CSF, PFA and MK used in the study

Property	PC	CSF	PFA	MK
Oxide composition: %				
SiO_2	20.00	85-98	49.8	52.1
Al_2O_3	4.30	1.5	26.4	41.0
Fe_2O_3	2.30	3.0	9.3	4.32
CaO	64.00	0.7	1.4	0.07
MgO	2.20	2.0	1.4	0.19
SO_3	3.00	-	0.8	-
Na_2O	0.16	1.0	1.5	0.26
K_2O	-	3.0	3.5	0.63
TiO_2	-	-	1.0	0.81
Cl	-	-	0.01	-
C	-	3.0	-	-
LOI	2.80	-	4.9	0.6
Mineral Composition: %				
C_3S	61.7			
C_2S	11.4			
C_3A	7.6			
C_4AF	6.8			
Physical properties:				
Colour	Grey	Grey	Black	White
Specific gravity	3.08-3.14	1.40	2.30	2.5
Bulk density: Kg/m^3	1000-1450	200-300	1000	300
Specific surface: m^2/Kg	360	15000-30000	300-600	12000

Table 2 Grading of fine and coarse aggregates

Coarse aggregate		Fine aggregate	
Sieve size (mm)	Percentage retained	Sieve size	Percentage retained
10	1.4	5mm	10.7
5	98.5	2.36mm	28.3
2.36	99.6	1.18mm	36.2
		600µm	45.1
		300µm	84.6
		150µm	99.3

Table 3 Properties of chemical admixtures used in the study

Admixture	Description/technical information from manufacturers
Daracem SP1 (superplasticizer)	Based on the salt of a polymeric naphthalene sulphonate. Supplied as dark brown liquid. Specific gravity = 1.19 at 20°C. Recommended addition rate: 500ml-1500ml per 100Kg of cement
Adva Flow (AF) (superplasticizer)	Synthetic Carboxylated polymer. Supplied as a clear liquid. Specific gravity = 1.06 at 20°C. Recommended addition rate: 200ml-1000ml per 100Kg of cement.
Darex AE3 (air entraining agent)	Based on the salt of an ether sulphate. Supplied as a pale yellow liquid. Specific gravity = 1.005 at 20°C. Recommended addition rate: 60ml-400ml per 100Kg of cement.

Mix proportions and mix design

Several mixtures were prepared to investigate the roles played both by superplasticizer and air entraining agent on the properties of the fresh concrete. A constant binder mix design method was used in the development of the proportions of the required concrete mixes. All the mixes were in the proportions binder : sand : 10mm aggregate of 1 : 1.6 : 3.1, and had a constant binder content of 380 Kg/m^3 and a w/b ratio of 0.45. In addition to the control (PC only) mixes, 10% and 20% replacement of cement by mass was adopted for mixes incorporating CSF or MK, whereas three replacement levels of 20, 30 and 40% by mass were employed for those incorporating PFA. The mix proportions for the mixtures employed in the present work are given in Table 4. The superplasticizer and air entraining admixture are expressed as a percentage by mass of the binder.

Table 4 Mix proportions, w/b = 0.45, b = 380 Kg/m^3, w = 171 Kg/m^3

	binder %				Concrete mix proportions: Kg/m^3					
					binder				aggregate	
	PC	CSF	PFA	MK	PC	CSF	PFA	MK	Sand	10mm
Control	100	-	-	-	380	-	-	-	663.1	1284.8
PC+CSF	95	5	-	-	361	19	-	-	660.7	1280.1
	90	10	-	-	342	38	-	-	658.2	1275.4
	85	15	-	-	323	57	-	-	655.8	1270.7
	80	20	-	-	304	76	-	-	653.4	1265.9
PC+PFA	80	-	20	-	304	-	76	-	655.3	1269.7
	70	-	30	-	266	-	114	-	651.4	1262.1
	60	-	40	-	228	-	152	-	647.5	1254.5
PC+MK	95	-	-	5	361	-	-	19	661.6	1281.9
	90	-	-	10	342	-	-	38	660.1	1279.0
	85	-	-	15	323	-	-	57	658.7	1276.1
	80	-	-	20	304	-	-	76	657.2	1273.2

Specimen preparation and testing

Mixing was performed in a rotary pan mixer in a room with an ambient temperature of 20±5 and relative humidity >50% in compliance with BS 1881: Part125 [27]. The PC, PFA and/or MK were blended together by hand until a uniform colour was achieved. First the aggregates were placed and spread evenly in the pan. One third of the prescribed amount of water was then added to the pan and the mixer was operated for 30s. The contents were kept covered in the pan to avoid loss of water by evaporation. After 1 min the blend was added and spread in an even layer over the aggregates. Mixing was recommenced and continued for 30s. Another third of the mixing water was thoroughly mixed with the air entraining agent added to the pan and then mixing continued for an additional minute. Any material adhering to the mixer blades was then scraped off into the pan. Finally the superplasticiser was mixed with the remaining third of water, and added to the pan for a further one minute of mixing. A slight modification was made to the above mixing procedure in the case of PC-CSF concrete because of the water in the slurry. In this case the second third of water was halved. The first half was blended with CSF and added to the pan. Then the second half was mixed with the air entraining agent and was added to the ingredients in the pan, followed by one minute of mixing.

For each replacement level of the various pozzolanic materials used, several dosages of air entraining agent were used to achieve a comprehensive assessment of the effect of air entrainment agent on the slump, compacting factor and air content of the fresh concrete. The slump, compacting factor and air content tests were performed in accordance with BS 1881: Parts 102, 103 and 106 respectively [28-30]. Tests for air content were carried out within 15 minutes of mixing, following slump and compacting factor tests. As frost resistance can be achieved both through the use of high strength concrete and through the use of air entrainment, it was decided to consider both compressive strength and air content as variables in this study. For this reason, twelve 100mm cubes; three for each of the curing ages of 7,14,28 and 90 days, were prepared for compressive strength tests. Compaction of test specimens was accomplished using a vibration table. All the test samples were kept in their steel moulds covered with cling film for 24 hours, then were demoulded and cured in water at 20 °C until they reached the testing age.

Results and discussion

Dosage requirements for air entraining agent

A comparison of the effect of CSF and MK on the dosage of air entraining agent needed to attain 7.5±0.6 % air content of the fresh mix is shown in Figure 1. A constant amount of superplastisizer of 0.35% by mass of the binder was adopted for both CSF and MK mixes. The dosage of air entraining admixture required to produce a given volume of air in concrete containing more than 5% CSF or MK, as partial mass replacement for PC, increases markedly with increasing amounts of CSF or MK. The admixture requirement rises very sharply for increase in CSF or MK content from 15 to 20%, indicating even higher air entraining admixture demand for higher amounts of the two pozzolanic materials. The trend of this increase is identical for both CSF and MK concretes. However the CSF concrete is more demanding in air entraining agent than MK concrete. This is primarily due to the higher specific surface of CSF which leads to more air entraining agent being adsorbed and fewer molecules of the agent available to be adsorbed at the air-water interfaces. The carbon content of CSF (Table 1) will also contribute to this additional adsorption. The measured slumps for these mixtures were in the ranges 45-210 mm and 50-210 mm for the CSF and MK concretes respectively. Figure 2 shows the variations in the slump with the level of pozzolanic replacements. The results demonstrate the higher water demand of CSF as compared to MK, as the replacement level increases. The inconsistency in the results obtained for the 20% replacements is attributed to specimen variability.

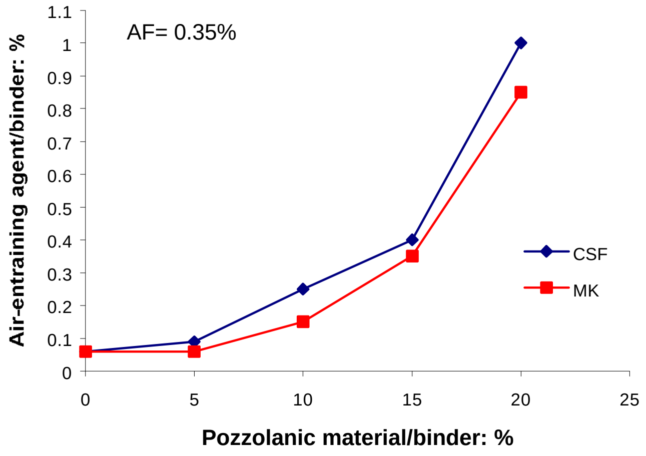

Figure 1 Comparison of the effect of CSF and MK on the dosage of air entraining agent to obtain 7±1 % air content in the fresh concrete

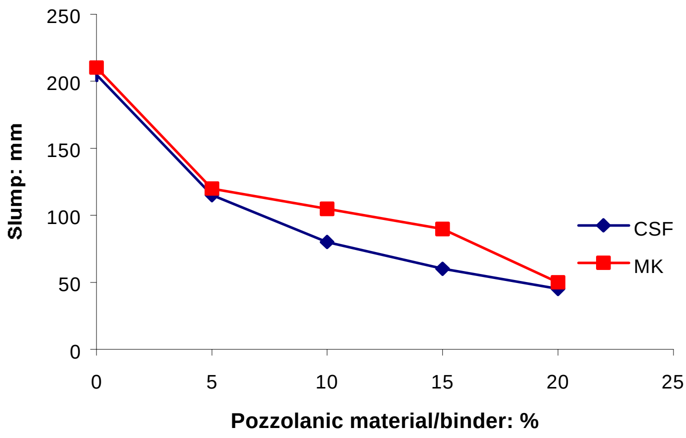

Figure 2 Comparison of the effect of CSF and MK on the slumps obtained for concretes shown in Figure 1

Dosage requirements for superplasticizer

In the next series of tests a large number of mixtures were made in an attempt to investigate mixtures which have the same workability and air contents. The relationships obtained between the superplasticizer dosage requirement and the levels of CSF or MK to produce a slump of 100±20 mm and air content of 6±1 % are given in Figure 3. In agreement with the air entrainment dosage requirements (Figure 1), CSF is also more demanding in superplasticizer compared to MK. The results presented in Figure 3 were achieved under a constant dosage of air entraining agent (0.06%) and the target air content was achieved even at the higher cement replacement levels. This suggests that the presence of superplasticizer enhances the ability of the air entraining agent to entrain air in concrete containing these two pozzolanic materials possibly by competing with the latter for surface adsorption sites.

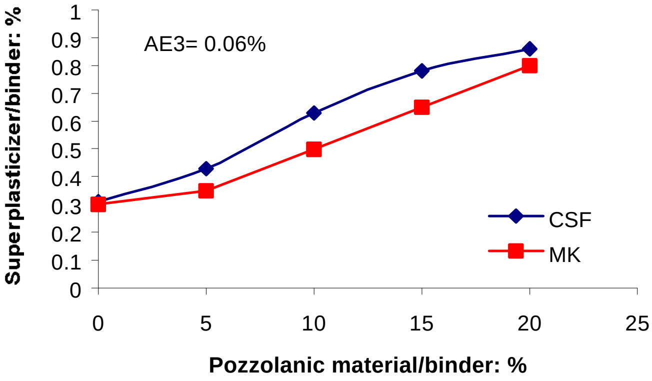

Figure 3 Comparison of the effect of CSF and MK on the dosage of superplasticizer required to obtain 6±1 % air content and 100±20 mm slump in the fresh concrete

Air content of fresh concrete

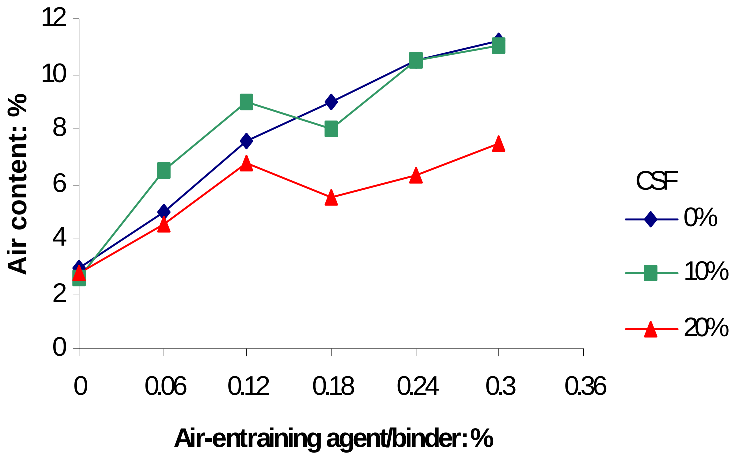

Figure 4 Effect of air entraining agent on air content of control and CSF concrete with 0.3 and 0.5% of superplasticizer respectively

Figure 4 gives the variations in the measured air contents in the control and CSF concrete with increasing dosage of air entraining agent. The results clearly demonstrate the efficiency of the admixture in entraining air in all the concretes investigated. It is seen that sharp rises in the air contents are obtained for dosages up to 0.12%. Dosages greater than 0.12% have less influence on air content in the case of 20% CSF whereas the air content of the control and 10% CSF concretes show continuous increase. A similar behaviour was encountered by Carette and Malhotra [23] who found it difficult to entrain more than 6% air in concretes with 20% CSF.

It is interesting to note that all the concretes without air entraining agent had the same volume of naturally entrapped air. Generally, because of the filler effects of the very small CSF particles, its use in concrete results in a more densified matrix with reduced entrapped air. It is thought that in the present study the expected reduction in the air content caused by the CSF is compensated for by the additional superplasticiser used as compared to that in the control. Superplasticisers are known, sometimes, to result in more air being entrapped in the system. The increased entrapped air due to the superplasticiser is also manifest in the 10% CSF concretes in which air entraining agent is added. This effect, however, reduces when the CSF level is increased to 20%, where the absorption effects, described above, due to the fine CSF particles play a more significant role in reducing the measured air content of the fresh concrete. It is to be emphasised that both the 10 and 20% CSF concretes contained the same amount of superplasticiser as a fraction of the total binder, i.e. 0.5%. The sharp reductions in the air contents of the CSF concretes with 0.18% air entraining agent (or increases at 0.06%), may be indications of instability or may be a result of sample variability. The results shown in Figure 4 give good indications as to the dosages of the air entraining agent required to obtain the desired air contents in the fresh concrete. For example in order to entrain 6% air, dosages of air entraining agent of 0.06 and 0.12% are required for 10% CSF and 20% CSF concretes, respectively. Higher levels of air contents, although undesirable because of the associated reductions in the strength of the hardened concrete, will require much more widely differing dosages.

Figure 5 gives the variations in the measured air contents of MK concrete with increasing air entraining agent. Again as with CSF concrete, the results show the efficiency of the admixture in entraining air in such concretes. It is seen that steady increases in the air contents are obtained for dosages up to 0.24%. This optimum limit is significantly greater than the limit of 0.12% dosage exhibited by CSF concrete.

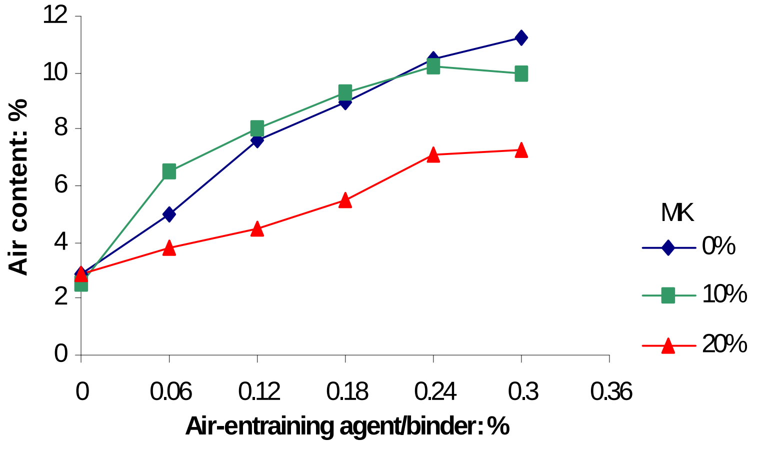

Figure 5 Effect of air entraining agent on air content of control and MK concrete with 0.3 and 0.5 % superplasticizer respectively

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Again as with the CSF concretes, MK concretes and the control concrete without air entraining agent exhibit the same volume of naturally entrapped air. This is due to the role of the increased level of superplasticiser, from 0.3 to 0.5%, in entrapping air in the system. The increased entrapped air due to the superplasticiser is also manifest in the concretes dosed with air entraining agent as portrayed by the 10% MK concrete which exhibits almost identical air contents to those of the control. The role of the superplasticiser (at a dosage of 0.5% of binder mass) in entrapping additional air over and above accidental air normally entrapped, diminishes in extent as the MK level increases to 20%. At such high levels of MK the increased adsorption of the admixture by the greater specific surface of the binder becomes dominant resulting in reduced air contents. It is observed that MK concrete gives more consistent changes in air content, with increasing air entrainment agent, than those obtained for CSF concrete. All the measurements presented in this study were made by the candidate himself using the same equipment and under the same operating conditions. For these reasons it is found difficult to attribute the lack of consistency in the results obtained for the CSF concrete (Figure 4) as being due to variability of controls. Rather it is thought that the behaviour is an indication of some instability that is inherent to the system examined. It is planned to repeat some of the tests to confirm this. If the results of these tests reproduce the observations already made, then it would appear that the admixtures used are more compatible with MK than they are with CSF. According to Figure 5, 6% air content in the fresh concrete requires dosages of approximately 0.06 and 0.20% air entraining agent in the 10 and 20% MK concretes, respectively. The results also indicate that it would be difficult to entrain air in excess of about 6%, (though normally not desirable) in 20% MK concrete even with high dosages of air entraining agent. In the case of 10% MK, air contents in excess of 10% may be entrained. Similar results were encountered in the case of the CSF concretes. This behaviour is attributed to the dispersal effects when high dosages of air entraining agent are used in conjunction with high pozzolan levels, leading to greater adsorption rates.

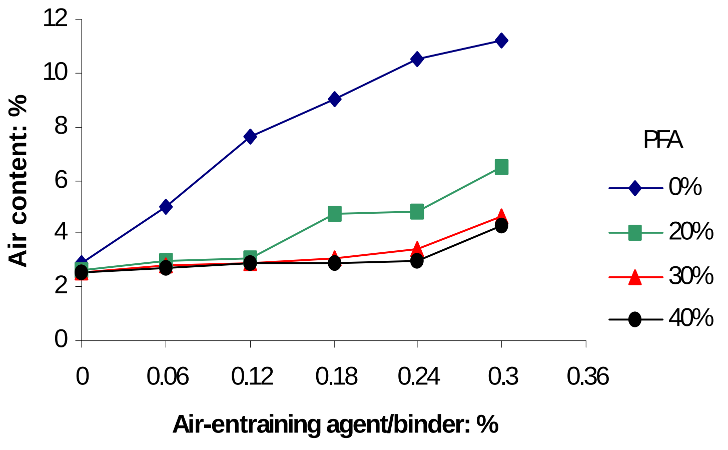

Figure 6 Effect of air entraining agent on air content of control and PFA concrete with 0.3% of superplasticizer

Figure 6 shows the large reductions in the air content caused by the incorporation of PFA, irrespective of the dosage of the air entraining agent. This reduction increases as the PFA level increases for all dosages of the admixture. Although moderate increases in air content are obtained for the 20% PFA concrete, albeit at the cost of high dosages of the admixture, little or no gain in air content is exhibited by the 30 and 40% PFA concretes. This may be due to the absorption effects caused by the unburnt carbon that is present in PFA (LOI=4.9%). These results indicate that at low levels (up to 0.18%) the admixture acts more effectively as a lubricating rather than an air entraining agent.

In Figure 7 a direct comparison of the results for the slump, compacting factor and air contents for the control and the 20% CSF, MK and PFA concretes is made. It is pointed out that the control and PFA concretes contained 0.3% superplasticiser compared to a dosage of 0.5% in the CSF and MK concretes.

The results show that all pozzolans have a negative effect on the volume of air entrained in the fresh concrete. The greatest reductions in the air contents are exhibited by the PFA concretes for all dosages of air entraining agent, 0 - 0.3%. CSF and MK appear to cause similar reductions in air contents for all dosages of air entraining agent with the exception of the CSF concrete with 0.12% dosage which shows a sharp rise in the measured air content.

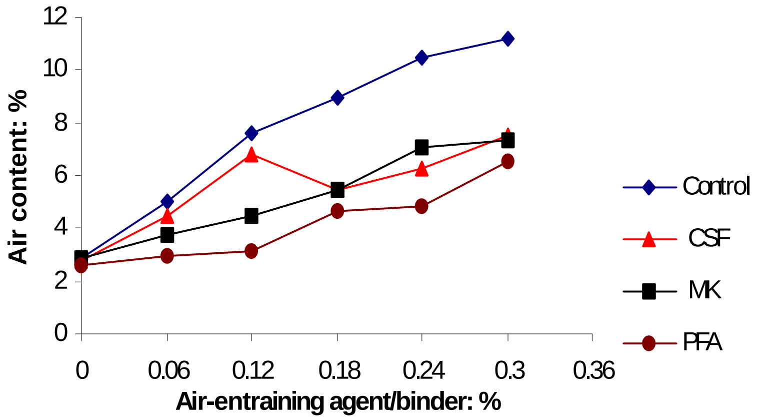

Figure 7 Comparison of the effect of air entraining agent on air content of control and 20% CSF, MK and PFA concrete

Compressive strength and air content

Table 5 summarises the results for the compressive strength reductions at each of the ages of 7, 14, 28 and 90 days corresponding to increases in the air contents for concretes incorporating CSF, MK or PFA.

Table 5 Effect of increase in air content on reduction in compressive strength

Concrete	Air content increase %	Reduction in strength: %			
		7 days	14 days	28 days	90 days
Control	210	25	26	27	32
10% CSF	304	43	43	41	41
10% MK	300	35	33	33	33
20% MK	152	25	25	24	20
20% PFA	150	18	21	24	25
30% PFA	84	18	16	14	10
40% PFA	72	4	4	5	9

For example when the air content in 10% CSF concrete increases by 304% i.e. from 2.6 to 10.5% there is a reduction in the 28-day compressive strength of 41%. The reduction in the 28-day strength of the 10% MK concrete corresponding to an increase in the air content of 300%, i.e. from 2.5 to 10% is 33%. Similar effects are produced in the PFA concretes. For example an increase in air content of 150%, i.e. from 2.6 to 6.5% in 20% PFA concrete gives a reduction in the 28 day strength of 24%. The results show that irrespective of the curing time, the percentage reductions in strength due the increase in air content are more or less the same for all concretes considered in the present study.

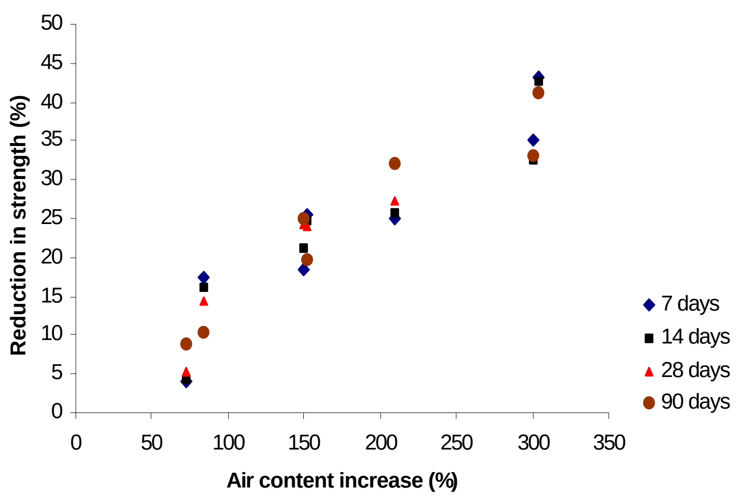

Figure 8 Percentage strength reduction versus percentage air content increase for concretes under investigation at different curing ages

Figure 8 gives a plot of the percentage reductions in strength with percentage increases in the air content of concretes incorporating CSF, MK or PFA. It can be seen that the relationship between the percentage reductions in strength and the percentage increases in strength is almost linear with the exception of those reductions corresponding to small increases in the air content of the fresh concrete.

Conclusions

The following conclusions may be drawn from the work reported in this paper:

1) For a given slump and air content CSF has more demand for superplasticiser and air entraining admixtures than MK.

2) The superplasticiser enhances the performance of the air entraining admixture and/or itself plays a secondary role in entraining air to the fresh concrete.

3) A three fold increase in slump is produced in control and 10% CSF concretes by adding 0.12% of air entraining admixture. Although further additions of the admixture lead to increased slump in the control, little benefit in workability is exhibited by the CSF concrete. This is attributed to the greater diffusion of the air entraining agent and consequent adsorption of the admixture by the very fine CSF particles.

4) Up to 0.12% air entraining admixture results in steep rises in the air content of superplasticised CSF concrete. The benefits of higher levels of the admixture diminish, particularly in the concretes with high CSF contents (20%). The superplasticiser plays an important role in increasing the air content of low level CSF concrete.

5) Up to 0.24% air entraining admixture results in a steady increase in the air content of MK concrete. This is compared to a limit of 0.12% for CSF concrete.

6) Non-air entrained control, CSF and MK concretes all have the same volume of naturally entrapped air (approximately 2%). This is attributed to the role played by the additional superplasticiser used in the CSF and MK concretes.

7) PFA causes large reductions in the air content of fresh concrete, irrespective of the dosage of the air entraining admixture.

8) The compressive strength of all concretes show systematic and more or less linear reductions with increasing air contents (2 to 10%) of the fresh concrete.

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