PFA FOR CONCRETE: MIX PROPORTIONING AND STRENGTH DEVELOPMENT

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Synopsis

This paper describes an investigation on mix design of concrete incorporation highly percentage of pulverized fuel ash (pfa) as a cement replacement in concrete. Studies are also made on the strength development of OPC/superplasticised pfa concrete designed for a specified workability and 28 days strength equivalent to that of the corresponding OPC concrete covering a very wide range of pfa usage (from 30% to 70%), water: cement ratio and age at test. Mixes designed by partial but direct replacement of 70% of pfa and water. cement ratio of 0.3 and a superplasticizer dosage of 2% by weight of cement + pfa, shows a slightly lower strength compared to OPC at earlier age but the concrete achieves comparable strength to OPC concrete at later ages. Such a concrete also exhibits highly workable properties with no detrimental effects on the quality of the concrete.

Keywords: admixtures, compressive strength, flexural strength, fly ash, workability, mix proportioning, water-cement ratio, superplasticizer.

Introduction

The use of fly ash (pfa) as a pozzolanic material in combination with portland cement for making concrete was first demonstrated in 1937 by Davis et al[1]. They in the most comprehensive investigation undertaken on the subject of concrete at that time, studied the effects of fly ash incorporation on a wide range of concrete properties. They suggested that with fly ashes of a certain quality, up to 50% substitution of fly ash for cement would be made in concrete mixes. However, their work attracted very little attention from practising engineers until 1948, when the United States Bureau of Reclamation decided to use fly ash in the concrete of Hungry Horse Dam.

Since then, direct economic factors coupled with an increasing awareness of the need to protect the environment and conserve energey have combined to focus attention on the utilization of fly ash in concrete. A great deal of research aimed at understanding the properties of OPC/Pfa concrete has been undertaken[2] and the beneficial effects of fly ash in concrete are well known[3]. Inspite of these, the present position is that although fly ash consumption has increased steadily throughout the world, with several countries producing standard specification for its use in concrete[4], its application in concrete is still very small. There are a number of reasons for resistance to its more widespread use; this include in the author's opinion being the inadequacy of the methods of proportioning concrete incorporating fly ash, and inconclusive and sometimes conflicting results have been produced from studies into various properties of OPC/Pfa concrete.

The research undertaken at Faculty of Civil Engineering UTM and Sheffied University to study the behaviour of mortar and concrete incorporating pfa has been conducted using high percentage of pfa ranging from 30% to 70% as a partial replacement of cement by weight. The pfa is defined by B.S. 3892 (1982)[5] as "a solid material extracted by electrical or mechanical means from the flue gases of boilers fired with pulverized coal".

Object of Preliminary Mix Design

The basic mix design used in this study was arrived at after a series of trial mixes utilising pfa. The basic objectives of the mix design are as follows:

a) to establish whether a high amount of the portland cement could be substituted by pfa, with no detrimental effects on the quality of the matrix in both the fresh and hardened states.

b) to produce the final mix product of high workability with a compressive strength of 40-45 N/mm^2 at 28 days. The requirement of good workability was essential, to allow the matrix to penetrate through layers of mesh reinforcement, even after the inclusion of the fibres in thin cement sheet production[6].

From an economic point of view, any direct substitution of cement by pfa would result in less expensive material, since pfa is an essentially waste material and considerably cheaper than portland cement. This in a way would off-set, to some extent the increased cost due to the incorporation of the more expensive admixtures in the mix.

A superplasticizing agent was used in the mix to increase the flow characteristics and accelerate the early strength development. The final mix proportions used for the test series were chosen on the basis of the best flow and strength characteristics.

Materials

Cement

Ordinary portland cement was used in all mixes employed in this work. The cement was considered to comply with B.S. 12 (1978)[7]. Table 1 shows the chemical composition of the cement used.

Table 1 Chemical analysis of ordinary portland cement

Constituents	Concentration in weight (%)
Silica SiO_2	19.8
Alumina as Al_2O_3	5.6
Iron as Fe_2O_3	2.4
Potassium as K_2o	0.58
Calcium as CaO	65.9
Sodium as Na_2O	0.29
Sulphur as SO_3	2.8
Loss on ignition	1.2
Insoluble residue	0.4
Free lime	0.9
Lime saturation factor	100.4
Lime combination factos	98.9
Silica ratio	2.48
Alumina ratio	2.33
Tricalcium silicate (C_3S)	65.1
Dicalcium silicate (C_2S)	7.6
Tricalcium aluminate (C_3A)	10.8
Tetracalcium alumina ferrite (C_4AF)	7.3

Fine Aggregate

The fine aggregate used in mortar matrix was washed natural river sand. The grading curve shown in Figure 1 lies within zone three of the grading limits of B.S. 882, 1201 Part 2: (1973)[8]. Table 2 shows the details of the sieve analysis and the fineness modulus of the sand. Sampling and testing were carried out in accordance with B.S. 812: Part 1 (1975)[9]. All sand was thoroughly dried in a mechanical drier before use. Throughout this investigation, the sand was sieved through 2.36 mm standard size sieve before use. This was considered necessary to allow the matrix to penetrate through several layers of mesh with fibres included, and also because the size of the thin sheet produced[6]. The sieve analysis is shown in Table 3 and the fineness modulus of this sand was 1.98.

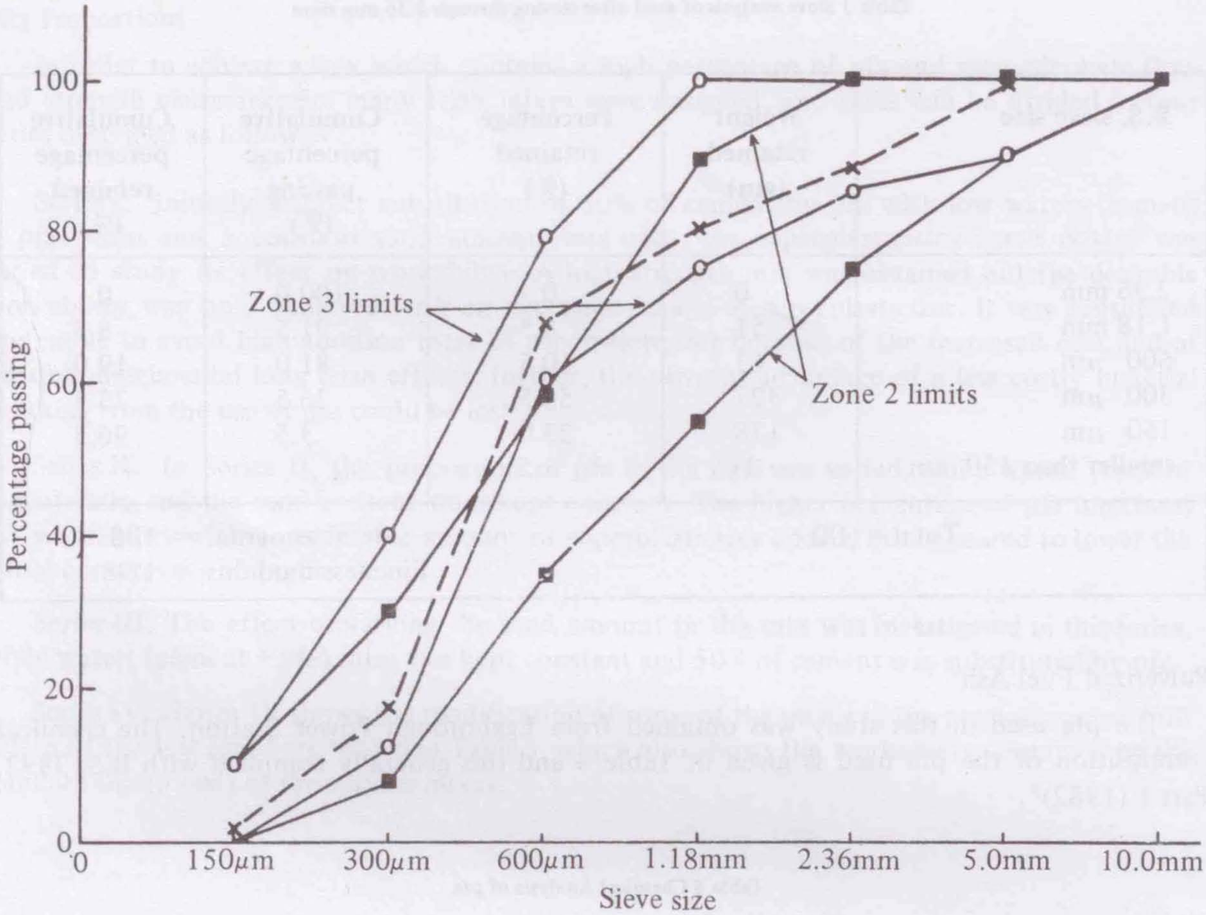

Figure 1 Grading curve for sand

Table 2 Sieve analysis of sand

B.S. sieve size	Weight retained (gm)	Percentage retained (%)	Cumulative percentage passing (%)	Cumulative percentage retained (%)
10.0 mm	0	0	100	0
5.0 mm	3	0.5	99.5	0.5
2.36 mm	67	11.2	88.3	12.0
1.18 mm	49	8.2	80.1	20.0
600 μm	72	12.0	68.1	32.0
300 μm	303	50.5	17.6	82.5
150 μm	96	16.0	1.6	98.5
smaller than 150 μm	10	1.6	–	–
Total = 600				Total = 246 Fineness modulus = 2.46

Table 5

Series II

$$\frac{w}{c + pfa} = 0.30$$

$$\frac{s}{c + pfa} = 1.8$$

SP = 2.0%

except M10 where,

$$\frac{w}{c + pfa} = 0.28$$

SP = 1.8%

Specimen	c/pfa	slump (mm)
M6	$\frac{60}{40}$	110
M4	$\frac{50}{50}$	130
M7	$\frac{40}{60}$	140
M8	$\frac{30}{70}$	collapse
M9	$\frac{100}{0}$	5
M10	$\frac{30}{70}$	35

Series III

$$\frac{w}{c + pfa} = 0.30$$

$$\frac{c}{pfa} = \frac{50}{50}$$

SP = 2.0%

Specimen	$\frac{s}{c + pfa}$	slump (mm)
M11	1.6	150
M4	1.8	130
M12	2.0	0

Table 5

Series IV					
Specimen	$\frac{w}{c+pfa}$	$\frac{c}{pfa}$	$\frac{s}{c+pfa}$	SP %	slump (mm)
M13	0.35	$\frac{40}{60}$	1.8	2.0	collapse
M14	0.30	$\frac{40}{60}$	1.8	1.8	50
M15	0.28	$\frac{30}{70}$	1.8	2.0	125
M16	0.32	$\frac{30}{70}$	1.8	0.0	10
M17	0.30	$\frac{100}{0}$	2.0	0.0	0

Note:

* percentage by weight of cement + pfa

** more than 300 mm slump

w = water, c = cement, pfa = pulverized fuel ash, s = sand

SP = Superplasticizer

When superlasticizer is used, $\frac{w}{c+pfa}$ denotes the actual water added.

Mixing Procedure

Several batches were mixed with different pfa percentage replacing equal amounts of cement by weight. Whenever pfa was used, the term 'cement' in this context means the combination of portland cement and pfa as cement eplacement. All batches were mixed in a rotating type mixer.

Bleeding is inevitable for concrete especially of high slump values. A mixing method of producing mortar of low bleeding was adopted. To reduce bleeding of cement paste, it has been shown by Hayakawa et al[11] that premixing cement with water of about 25% of the weight of cement was very effective. After cement and a part of water had been mixed for 120 seconds, remaining water was added, and then mixed for 90 seconds. By applying this method to mortar and premixing cement with sand and water of about 25% of the weight of cement, mortar of a very low bleeding can be produced. After mixing sand and a part of water which was controlled to obtain water content of 25% of the specific weight of cement for 30 seconds, cement was added and mixed for 120 seconds. Then the remaining water was poured in and mixed for 90 seconds. Whenever superplasticizer was used, the second pouring of water was mixed for 60 seconds and finally admixture was added and mixed for another 60 seconds, giving a total mixing time of 4.5 minutes.

Casting, Curing and Testing

With every mix, eighteen 100 mm cubes were cast for mortar matrix giving a total of 300 cubes being cast and tested for the trial mixes. All specimens were cast in steel moulds covered with a thin layer of mineral oil to facilitate easy demoulding. The moulds, which were placed on a vibrating table, were filled to overflow and after compaction by means of the vibrating table, the excess mortar was removed and the surface finished with a trowel. All the specimens were demoulded after 24 hours and stored in a fog room (20°C ±, 100% Relative Humidity) until the date of testing. They were then tested in compression at a stress rate of 15 N/mm^2 according to BS 1881: Part 4 (1970)[12].

Test Results and Discussion

The compressive strength of trial mixes for normal weight mortar matrix is shown in Table 6. From Series I and Figure 2, it is seen that the higher dosage of sulperplasticizer increases the workability, reducing the early strength of the mix and increasing later strength development. The substitution of cement by pfa results in a reduction in the rate of strength development, when comparisons are being made at a constant water: cementitious component ratio. This reduction is proportional to the amount of pfa being introduced into the mix as can be seen in Table 6, Series II, where the strength of the pfa mixes is compared to the strength of all cement mortar (M9). Figure 3 shows the strength attained by mixes containing various percentage of pfa at the ages of 1 to 180 days.

Increasing the amount of sand in the mix, eventhough this will result in increased compressive strength, appeared to produce a non-workable mix, as shown in Table 5 and Table 6, Series III.

Introducing pfa to the mixes enhanced the workability. The reason being the inertness of pfa particles during early hydration, help to create more free water available. A comparison of the workabilities of the various mixes can be seen in Table 5, Series II, from which it can be established that by increasing the percentage of pfa in the mix the workability increases.

At this stage, it is necessary to recall the main objectives for which the mixes have been designed as described in Section 2. With reference to the above requirements, trial mix M5 in Series I and trial mix M8 in Series II gave satisfactory results. The trial mixes in Series IV, more specifically, mixes M14 and M15 (as the modification of M4 and M8 respectively) mostly fulfil the above requirements. However, by reducing the amount of cement and superplasticizer in the mix M14, resulted in reduced strength and workability. Similarly, by reducing water: (cement + pfa) ratio in mix M15, the workability, which is the main criteria in the design, was reduced remarkably. Thus, the final mix chosen was trial mix M8 with (0.3: 0.7) :1.8 [(cement: pfa): sand] with a water: (cement + pfa) ratio of 0.30 and a superplasticizer dosage of 2% by weight of cement + pfa.

The mix proportions of mortar matrix were as follows:–

Material	Weight per m^3 of fresh mortar (kg)
cement	219
pfa	512
fine aggregate	1315
fee water	219
superplasticizer	15
	2289 kg/m^3

slump: collapse (more than 300 mm)
dry density of mix: 2170 kg/m^3 at 28 days

Table 6 Compressive strength of trial mixes for mortar mix

Series I

	Compressive strength (N/mm²)					
Mix	1d*	3d	7d	28d	90d	180d
M1	10.2	20.9	29.9	38.7	52.2	64.8
M2	10.0	22.6	32.8	46.3	60.5	68.4
M3	9.9	22.8	37.7	52.3	72.0	74.1
M4	9.8	23.9	38.5	53.0	72.8	75.0
M5	8.8	25.4	39.5	54.4	73.5	76.2

* age in days

Series II

	Compressive strength (N/mm²)					
Mix	1d	3d	7d	28d	90d	180d
M6	10.3	28.7	40.5	55.5	73.0	78.5
M4	9.8	23.9	38.5	53.0	72.8	75.0
M7	7.3	21.5	30.5	46.0	68.5	75.5
M8	6.8	19.9	27.9	43.5	64.5	76.4
M9	39.2	48.0	59.5	69.5	73.2	79.3
M10	5.9	16.4	22.8	38.9	55.6	60.6

Series III

	Compressive strength (N/mm²)					
Mix	1d	3d	7d	28d	90d	180d
M11	8.6	22.6	36.0	52.3	64.5	73.0
M4	9.8	23.9	38.5	53.0	72.8	75.0
M12	16.7	30.5	41.7	57.9	73.8	79.5

Series IV

	Compressive strength (N/mm²)					
Mix	1d	3d	7d	28d	90d	180d
M13	3.9	14.0	22.4	36.3	52.5	65.2
M14	10.2	24.2	29.9	46.9	63.8	70.5
M15	7.0	21.2	28.9	46.0	65.5	77.5
M16	4.8	10.0	17.0	27.1	49.1	54.1
M17	25.5	40.5	51.8	61.6	63.5	66.4

The finally chosen mix was repeated many times as control mix during the course of this work, to ensure that no adverse strength development arises due to the introduction of high amounts of pfa and superplasticizer. The results produced were fairly consistent. Therefore, it can be stated that pfa and superplasticizer are suitable for use in conjunction with cement even at high amounts, (70% pfa in the present investigation).

The most interesting point that can be noted from the test series is that the compressive strength of all the mixes at the age of 180 days has increased as compared to the 28 day strength. It was observed that this increase related to the admixture content and the pfa percentage of the mixes. From the results of Series I and Series IV, it can be seen that the lower the superplasticizer dosage, the greater is the increase in strength over the period of 28-180 days, with the 180 day strength reaching 100% greater than the 28 day strength in mix M16.

It can also be noted that for the mixes which contained high amounts of pfa, the percentage increase of the 180 day strength relative to the 28 day strength was greater than that in the mixes with lower amount of pfa. Mix M8 which has 70% pfa gave 180 day strength of 76% greater than the 28 day strength, whereas mix M6 with 40% pfa, the 180 day strength is 141% of the 28 day strength. Mix M9, without pfa, only gave 180 day strength of 14% greater than the 28 day strength. The above conclusions are better illustrated in Figure 2 and Figure 3, which show the development of compressive strength of various mixes with time. The strength development of the mix up to the age of 1½ years is shown in Figure 4.

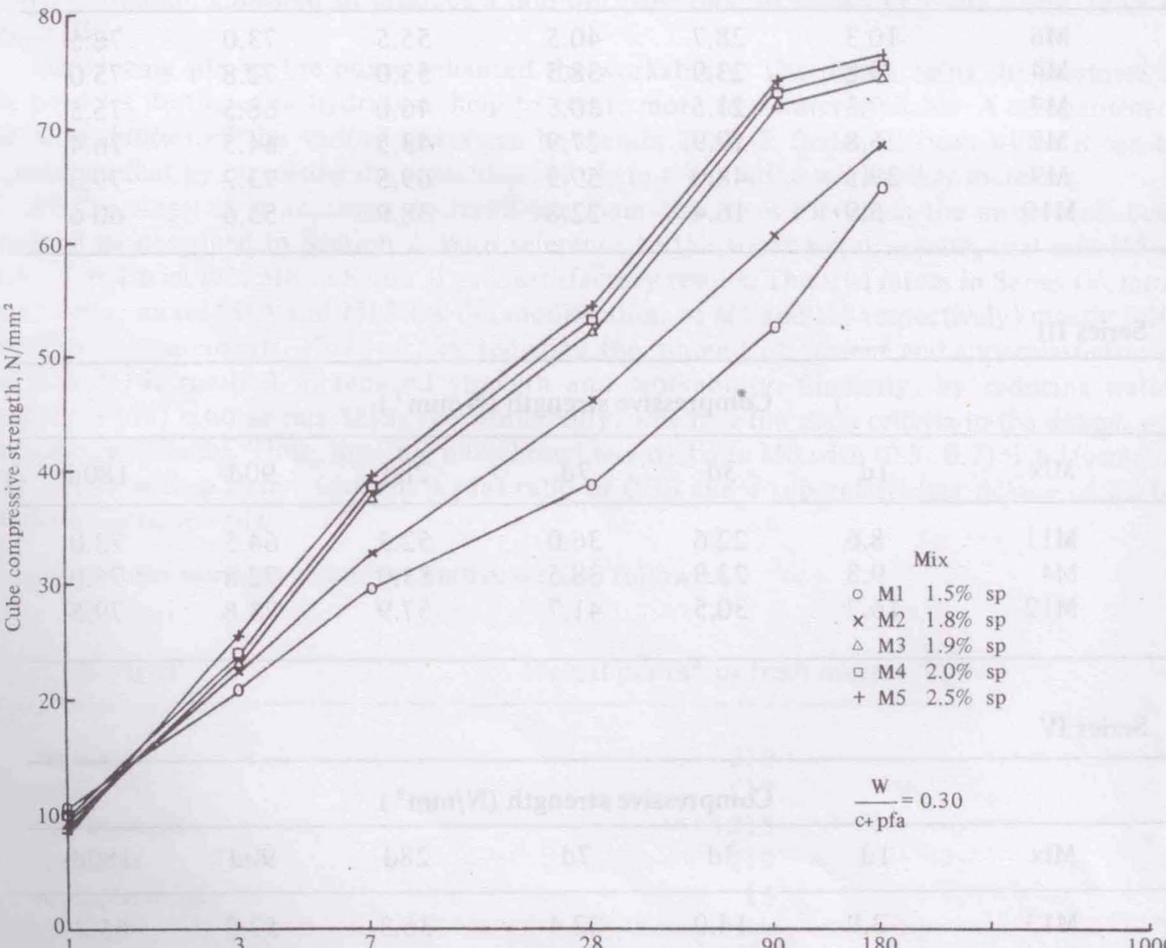

Figure 2 Compressive strength of series I specimens with time (normal weight mortar matrix)

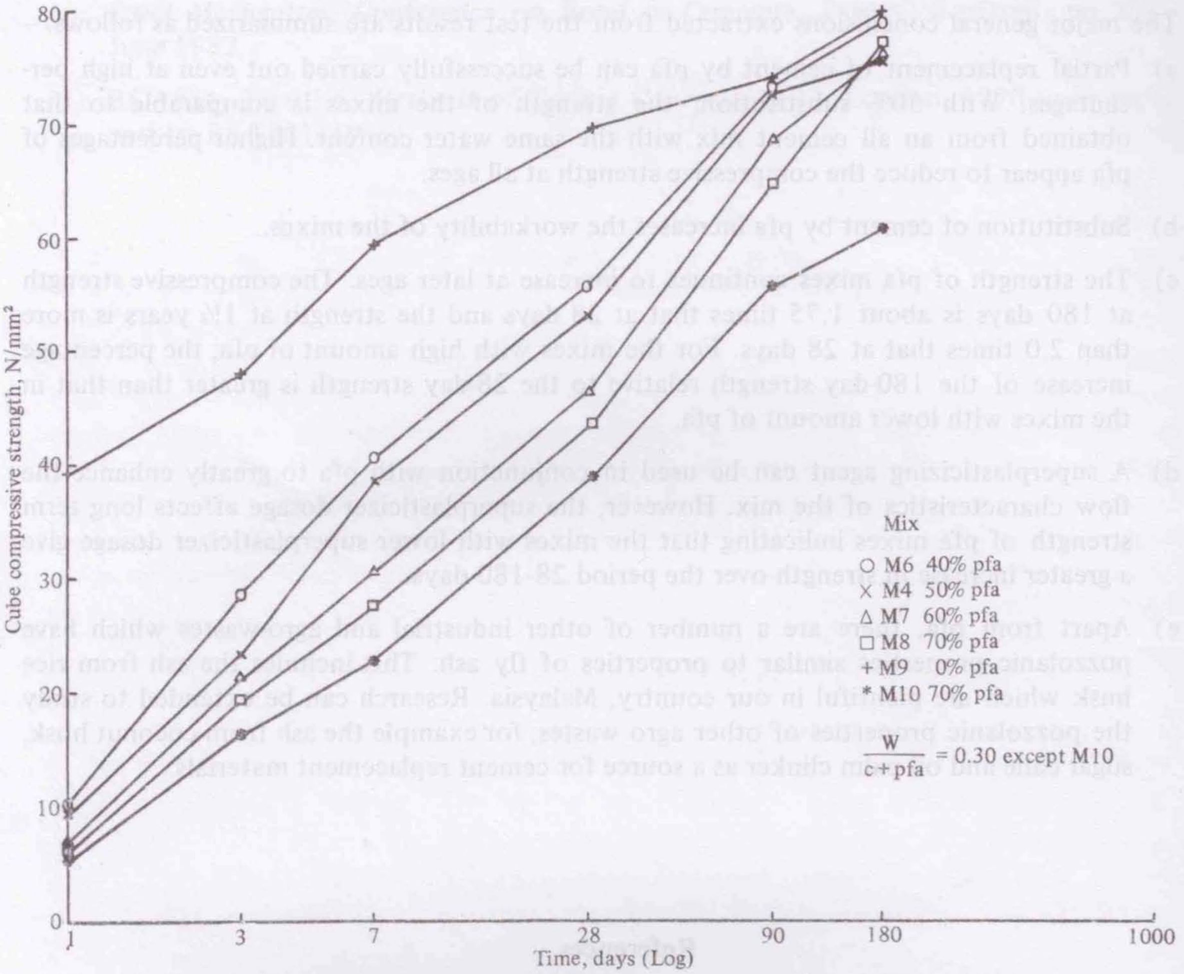

Figure 3 Compressive strength of series II specimens with time (normal weight mortar matrix)

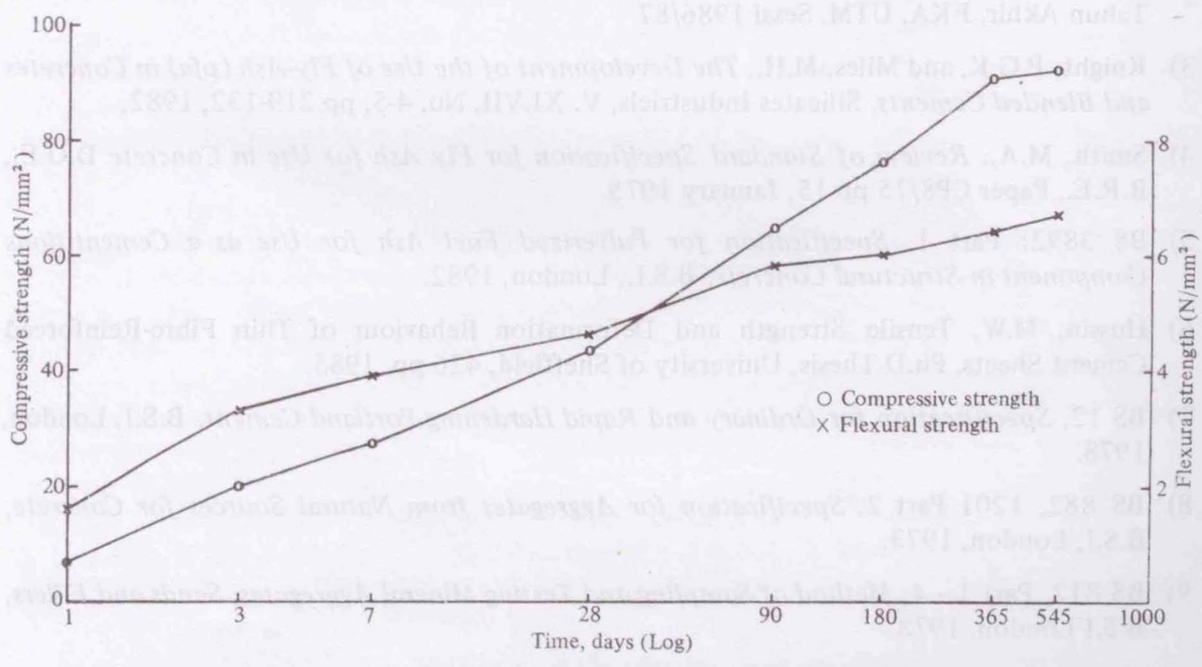

Figure 4 Compressive strength and flexural strength development of normal weight mortar matrix used

Conclusion and Suggestion

The major general conclusions extracted from the test results are summarized as follows:—

a) Partial replacement of cement by pfa can be successfully carried out even at high percentages. With 50% substitution, the strength of the mixes is comparable to that obtained from an all cement mix with the same water content. Higher percentages of pfa appear to reduce the compressive strength at all ages.

b) Substitution of cement by pfa increases the workability of the mixes.

c) The strength of pfa mixes continues to increase at later ages. The compressive strength at 180 days is about 1.75 times that at 28 days and the strength at 1½ years is more than 2.0 times that at 28 days. For the mixes with high amount of pfa, the percentage increase of the 180-day strength relative to the 28-day strength is greater than that in the mixes with lower amount of pfa.

d) A superplasticizing agent can be used in conjunction with pfa to greatly enhance the flow characteristics of the mix. However, the superplasticizer dosage affects long term strength of pfa mixes indicating that the mixes with lower superplasticizer dosage give a greater increase in strength over the period 28-180 days.

e) Apart from pfa, there are a number of other industrial and agro-wastes which have pozzolanic properties similar to properties of fly ash. This includes the ash from rice husk which are plentiful in our country, Malaysia. Research can be extended to study the pozzolanic properties of other agro wastes, for example the ash from coconut husk, sugar cane and oil palm clinker as a source for cement replacement materials.

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