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Influence of fly ash characteristics on compressive strength of mortar

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ABSTRACT

Thesis : Influence of Fly Ash Characteristics on Compressive Strength of Mortar.

Poorna R. Ratnaweera, Master of Science in Civil Engineering, 1991

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Fly ash-cement mortar, constituting of fly ash, cement and sand, vary in strength characteristics from conventional cement sand mortar. Out of many parameters effecting the compressive strength characteristics of fly ash-cement mortar, four were investigated in this study. They are particle size and its distribution, weathering of fly ash, moisture content & water/cementitious ratio and mix proportioning.

Class F fly ashes from three different sources were used in this study. The particle size distribution and moisture content of fly ashes were investigated by standard ASTM methods. The unconfined compressive strength of mortar was obtained by testing 2"x2"x2" test cubes conforming to the ASTM standard testing procedures.

The results of the tests indicated that there is a direct relationship between particle size distribution and compressive strength of mortar. The finest particles, of diameters 0-10 micron are the most influential on strength development.

The water/cementitious ratio should be clearly defined as the ratio of weight of water to the weight of cement and total fly ash content of the mix. The optimum water content for the maximum compressive strength depend on the fly ash content in the paste.

The results show very clearly that weathering of fly ash brings about some physico-chemical changes in the fly ash rheology.

Neither cement content nor fly ash content alone but, rather the combination of these two parameters determine the compressive strength of a mortar mix.

INFLUENCE OF FLY ASH CHARACTERISTICS ON COMPRESSIVE STRENGTH OF MORTAR

by
Poorna R. Ratnaweera

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To my parents

And all parents who spare no pains

to see their children in the path of education

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I INTRODUCTION

1.1 GENERAL

Over the past few decades Fly Ash has emerged as a construction material in its own rights. The recognition that fly ash exhibits pozzolanic properties had originally lead to its use as a pozzolana for concrete. But with the passage of time fly ash has proved to be much more than a simple pozzolana. It is now identified as a compound which when used as a concrete constituent could not only replace considerable percentages of cement but also impart numerous beneficial effects on fresh and hardened concrete.

ACI 116R defines fly ash as "the finely divided residue resulting from the combustion of ground or powdered coal which is transported from the firebox through the flue gases" [1]. Although it was originally identified as an artificial pozzolana fly ash is now used as a part of the composite that forms the concrete mass, used as a substitute for binder and/or the aggregates of concrete. Regardless of what it substitutes for in concrete fly ash is known to affect all aspects of concrete properties [2].

Incorporation of fly ash in concrete improves workability and thereby reduces the water requirement with respect to the conventional concretes. This is most beneficial where concrete is pumped in to place. Among numerous other beneficial effects are reduced bleeding, reduced segregation, reduced permeability, increased plasticity, lowered heat of hydration, and increased setting time [2]. However the use of fly ash in concrete has its drawbacks such as high variability, low air entrainment and low early strength development. When incorporated in concrete in large proportions its known to change the color of hardened concrete.

At present the construction industry utilizes fly ash in two distinct ways, as a raw material for cement and as a constituent material for concrete. However, still it is only an insignificant percentage of the yearly production of fly ash that is being used effectively. Today the necessity to use fly ash is not only because of the economic and technical gains it entails but because of the impact it makes on the environment. Most utility companies today are faced with the problem of disposal of fly ash in compliance with the environmental regulations. The shortages of cement felt concurrently and the natural interest to cut down the cost of concrete adds to the drive to find better ways of utilizing fly ash in concretes.

Utilization of fly ash in concrete is hampered mainly by the lack of understanding we have of this material. The variability of fly ash also invites pessimistic attitudes towards use of fly ash in concrete. Although research has been going on since the beginning of the last half a century we have not yet achieved a complete and detailed knowledge of fly ash. Research on fly ash hitherto has taken us deeper in to a maze and the physical and chemical characteristics that govern its behavior are only beginning to be understood.

As a pozzolana fly ash basically reacts with lime to produce the Calcium-Silicate-Hydrates which is known as the C-S-H gel [3]. During the hydration Portland cement produces a surfeit of lime that is released to the pore spaces. Excessive lime weakens the concrete mass by making it more vulnerable to acid, carbon dioxide and sulfate attacks. Fly ash due to its fineness gets in the pore spaces and combines with this lime to produce C-S-H, not unlike the hydrates of cement. This process stabilizes the concrete, reduces permeability and increases resistance to chemical attacks.

All cement particles in the paste of mortars or concrete do not essentially take part in hydration. The hydration usually starts from the finest cement particles [3]. The hydrated cement envelopes unreacted cement particles and continues to grow from within. However this reduces the rate of hydration continuously that even after a long time appreciable amounts of unhydrated cement may remain in the paste. When fly ash is encorporated in the paste, these particles act as nuclei for the hydration reaction, thus generating more hydrated products than otherwise.

The hydration reaction of fly ash is known to be essentially the same as that of Portland cement [2,4]. The morphology of fly ash hydrates is suggested to be more denser than that of cement [5]. The reaction of fly ash is largely dependent upon the break down and dissolution of the glassy structure by hydroxide ions and heat mobilized by the hydration of the Portland cement fraction. Reaction of fly ash continues to consume calcium hydroxide to produce additional C-S-H gel as long as calcium hydroxide is present in the pore spaces [6]. This continuous reaction results in continuous strength development beyond 28 days. Fly ash concretes are known to show considerable strength gains at ages as late as 3 years [7]. Thus the 28 day compressive strength cannot be accepted as a good indicator of the strength capacity of fly ash concrete.

In the process of hydration fly ashes passes through an inert period in the early stages which results in low early strength development. This is looked upon as one of the major drawbacks encountered in the use of fly ash concrete. However this reduces the early heat evolution which is very desirable for mass concreting. It must be noted that where fly ash is added to the conventional concrete mixes without a reduction in cement portion the heat of hydration is observed to increase [8].

A complete knowledge of the principles of fly ash reaction will enable the identification of primary factors which influence these reactions. Thus a more reliable criterion to judge on the suitability of a particular fly ash type could be developed. Although past research has helped to establish many parameters that may effect the fly ash concrete behavior, a more detailed knowledge is needed before fly ash could be used in structural concrete with confidence.

1.2 LITERATURE REVIEW

Researchers take two distinct approaches in evaluating fly ash characteristics; direct assessment of material properties and evaluation of properties of fly ash in concrete or mortar mixes. Attempts are made to find relations between the physical and chemical properties of fly ash with its behavior in concrete.

In the earliest studies conducted the chemical analysis of fly ash has been given prominence. The researchers have sought to relate the performance of fly ash with the composition of chemical oxides but with little success [2]. Although a definite relation between chemical composition and fly ash behavior has not been positively established the general consensus seems to be that.

The present ASTM classification of fly ash, C 618 classifies fly ash in to two groups as Class C and Class F. Class F is defined as ash produced by burning Anthracite or bituminous coal while ash from sub-bituminous coal or lignite is defined to be in Class C. Class C fly ash has a CaO contents higher than 10% and the sum of the oxides SiO_2, Al_2O_3 and Fe_2O_3 is required to be a minimum of 70%. As for the Class F fly ash the CaO content is less than 10 % and the sum of the above mentioned oxides is to be a minimum of 50% [2].

Studies conducted so far has revealed that chemical composition alone is not the governing criterion for the behavior of fly ash [9]. The mix proportioning, moisture content, ratio of water to cementitious material, particle size and its distribution, method of curing, type of cement used, glassy and crystalline phases of fly ash structure and pH value have also been observed to affect fly ash behavior in fresh and hardened concrete [9,10].

Many researchers have observed that there is a direct increase in strength with the increase of fineness [9]. Research carried out by Ukita et al [11] show very clearly that as the percentage of finer particles ranging from diameters of 1 - 20 microns increases, the corresponding strength gain is notable. Similar results have been observed by Giergiczny and Werynska [12] in their experiments conducted with fly ash fractions separated depending on the particle size. Particles separated in to fractions of diameters as small as 0-5 microns have been used in these tests. In the cases where researchers have concluded that particle size does not have any notable effect on fly ash concrete strength, it is seen that they have not paid attention to the particles finer than 45 microns [10,13].

Pozzolanic activity of fly ash is found to increase with the increase of specific surface area [14]. Since specific surface area is directly proportional to the fineness of fly ash particles it could be argued that this results indicate a relationship between the fineness and the compressive strength of fly ash concrete.

The ASTM classification uses the retention on ASTM no. 325 sieve (opening size 45 microns) as a measuring stick for fineness and this seem to have set limits to investigations in this direction. However this specification tends to improve the fly ash quality by reducing the L.O.I. (loss of ignition) content since the unburnt carbon present in fly ash composes a larger part of the coarser particles [3]. The fineness and sphericity of fly ash particles are known to increase workability and thereby reduce the water requirement [2,10,15,]. Reductions in water requirement as much as 7% have been observed [16]. Reduced water content in concrete brings about increased compressive strengths automatically. Attempts have been made to relate the water cementitious ratio to the compressive strength [17]. However in most of the studies conducted on the water requirement moisture content of the fly ash has not been considered. Author feels that this is an important factor that should not be overlooked as the moisture content has shown marked effects in the tests carried out in this research.

Apart from the quality of fly ash and cement, mix proportioning is claimed to be the most important single factor influencing the properties of fly ash concrete.

Proportioning of fly ash concrete with aim of achieving higher strengths and/or enhancing desired properties has naturally been a major point of interest. Since fly ash essentially depends on cement for its hydration process with careful proportioning of cement and fly ash optimum results could be achieved.

The proportioning techniques seem to treat fly ash as a substitute material in all cases. Fly ash is not known to be introduced as a seperate component material. Three basic methods of mix proportioning have been developed over the years [18,19].

1. Partial replacement of cement.
2. Addition of fly ash as fine aggregate.
3. Modified partial replacement.

The first approach requires a direct replacement of cement by fly ash on a one to one basis and is not known to yield strengths comparable to the corresponding conventional concretes. The addition method requires addition of fly ash directly to the conventional mixes and higher compressive strengths have been obtained. The technique of modified partial replacement requires either cement or fine aggregate and to be replaced with fly ash and further addition of fly ash as in the second method. Each method has been found to yield concretes of different qualities [19].

Weathering of fly ash in long term storage should draw the attention of researchers. The usual way of storage of fly ash until it is either disposed of or utilized is to let it lie in a pond with water, open to weathering [20]. This process is known to make physical and chemical changes in the fly ash that is collected from the furnace in very dry conditions. Some chemicals in fly ash could dissolve in the water and cause changes in pH [21]. Studies carried out by Fraay et Al [22] show that at certain high acidic and basic pH ranges the glassy structure of fly ash could break down. Such changes could make a significant impact on fly ash qualities when used in concrete.

1.3 OBJECTIVES

Review of past work brings to light many parameters that could make effects on the behavior of fly ash in concrete. If a definite relationship could be established between these parameters and the properties of fresh and hardened fly ash concrete it would enable the use of fly ash in structural concrete with the same confidence as Portland cement.

In this research an attempt is made to investigate possible relations between the material properties and the properties of fly ash concrete.

The parameters selected for the investigation are

1. Particle size and its distribution
2. Weathering of fly ash
3. Moisture content and the water cementitious ratio
4. Mix proportioning

Particle size distribution of selected fly ash types are analyzed to find the range of the particle size distribution and the dominant fractions of particle size. Investigations are made to find a relationship between the dominant particle sizes and the compressive strength of fly ash-cement mortars at various ages up to 90 days.

Attention is given to the weathering of fly ash under storage conditions and the possible physical and chemical changes in fly ash this could entail. The effects of weathering of fly ash on the compressive strength of fly ash cement mortar are investigated.

The moisture content and the optimum water cementitious ratio are interrelated and each of the two parameters are investigated for their effects on the compressive strength of mortar mixes. Fly ash at different stages of age and storage posses different moisture contents [21]. This could lead to different water requirements for the mortar mixes incorporating the same fly ash.

The variations of the compressive strength with age, for 20 mortar mixes, all of different mix proportions is also investigated. An attempt is made to find optimum mix proportions to cater for desired strength capacities.

II EXPERIMENTAL PROGRAM

Experiments were set up with the objective of investigating the influence of selected parameters on the unconfined compressive strength of fly ash-cement mortar. All tests were performed in compliance with the ASTM standards and specifications.

Class F fly ashes from three different sources viz, Deep Hollow, Hudson, and PSE&G, were used in this program. The latter was obtained in both dry and weathered states. Simulating the usual storage conditions a "weathered" Hudson fly ash was produced in the laboratory using the Hudson dry fly ash.

PSE&G fly ash samples used in the tests were selected from two different consignments of fly ash. At the precipitators of the furnace and also in the storage pond depending on the location where its picked up fly ash will have different gradation curves. These two different samples will be referred to as Batch 1 and

Batch 2 PSE&G fly ash and is treated as two different fly ashes. Weathered fly ash of Batch 2 were collected in a very damp state and air dried before use.

2.1 INVESTIGATION OF MATERIAL PROPERTIES

2.1.1 PARTICLE SIZE DISTRIBUTION

Analysis of the particle size distribution of fly ash was carried out by wet sieving the fly ash fraction retained on ASTM no.200 sieve (opening size 75 microns) and hydrometer analysis of the fraction passing ASTM no. 200 sieve.

2.1.1.1 SPECIFICATIONS

The experiments were conducted in compliance with the ASTM specification for grain size analysis D 422- 63.

Applicable ASTM specifications:

- D 421 - Practice for dry preparation of soil samples for particle size analysis and determination of soil constants.
- E 11 - Specifications for wire-cloth sieves for testing purposes.
- E 100 - Specifications for ASTM hydrometer.

2.1.1.2 MATERIAL

Each of the fly ashes used in the research, Deep Hollow, Hudson & PSE&G were tested for the particle size distribution. Weathered and dry fly ashes of the same source and the PSE&G fly ashes from the Batch 1 and Batch 2 were tested and treated as different fly ashes.

Dry fly ashes from Deep Hollow, Hudson and PSE&G were obtained in dry form. PSE&G weathered fly ash of Batch 1 was also obtained in a dry form but the weathered fly ash of Batch 2 was made available in very damp lumps as it was picked up from the storage pond. Hudson weathered fly ash was a lab produced variation obtained by closely simulating the conditions of the storage pond. It was soaked in water for three months with water changed every fortnight regularly. These two wet forms of fly ashes were air dried and passed through ASTM No 200 sieve (opening size 75 microns). No heavy grinding was done for any one of the fly ashes.

The dispersing agent used for the hydrometer analysis was Sodium Hexametaphosphate ($NaPO_3$).

2.1.2 MOISTURE CONTENT TEST

Each category of fly ash used in the research was tested for moisture content before use. These fly ash samples were stored in dry conditions at a constant temperature of approximately 25^{o} C.

The "water content" that is determined in this test is the free water on the surface and that absorbed by the particles. Although samples of both dry and weathered fly ash appear dry and there was no surface moisture high variations of moisture contents were observed in the results. This is suggestive of absorbed water within the particles.

2.1.2.1. SPECIFICATION

Tests were conducted in compliance with the specifications of ASTM D 2216 - 80.

2.1.2.2 MATERIAL

Samples of wet weight about 25 grams were used for the moisture content determination. Fly ash from each of the three sources in dry and weathered conditions and the PSE&G fly ashes of Batch 1 and Batch 2 were tested separately.

2.2 UNCONFINED COMPRESSIVE STRENGTH OF FLY ASH-CEMENT MORTAR

This series of tests were conducted to investigate the influence of the selected parameters on the compressive strength of concrete.

In fly ash concrete the water cement ratio as defined in conventional concretes is modified, to include fly ash that is incorporated in the mortar as a part of the binder which, in conventional concrete consists of cement alone.[17] Thus the definition of water cement ratio is replaced with the definition "water cementitious ratio" which is the ratio of water to the total cement and fly ash content that makes up the binder, by weight. It must be noted that fly ash incorporated in the fine aggregate component is not included in this.

water cementitious ratio = wt. of water/wt. of binder (cement + fly ash)

Mortar specimens were cast, cured and tested for the compressive strength at the ages of 1, 3, 7, 14, 28, 56 and 90 days.

2.2.1 SPECIFICATIONS

The entire test program was conducted conforming to the ASTM standards and specifications.

Applicable ASTM specifications:

C 230 - Specifications for Flow Table for use in tests of Hydraulic cement.

C 305 - Mechanical mixing of Hydraulic cement pastes and mortars of plastic consistency

C 349 - Test for compressive strength of Hydraulic cement mortars

C 670 - Practise for preparing precision statements for test methods for construction materials

C 778 - Specifications for standard sand

E 11 - Specifications for wire cloth sieves for testing purposes

2.2.2 MATERIAL

Cement: throughout the experiment the same type of hydraulic cement Portland Cement Type I was used.

Fly Ash: Fly ash from three different sources in dry and weathered conditions were used. PSE&G fly ash of batch 1 and batch 2 were treated as two different ash types. Hudson weathered fly ash was a lab produced variation.

All weathered fly ashes were passed through ASTM No. 50 sieve (opening size 150 microns).

Sand — Regular river sand conforming to the ASTM specification C 778-80a 3.1 was used throughout the test program except for the first test series. In the first test series a graded 20-30 standard sand, Ottawa sand was used in place of regular sand.

2.2.3 FABRICATION OF SPECIMEN

Fabrication of test specimens was carried out conforming to the relevant ASTM specifications.

A mechanical mixer was used for mixing the mortar. In the process of mixing, regardless of what it substitute for in the mix, fly ash was added together with cement and mixed with water. The entire batch of test cubes for a particular mix were cast in one day.

Standard 2"x2"x2"test cubes were cast and cured in lime saturated water until the date of test. Specimen were air dried for about 6 hours prior to testing.

2.2.4 TEST PROCEDURE AND SET UP

An MTS closed loop servo controlled model 810 testing machine was used for the unconfined compression test. This testing machine is a computerized version and the peak compressive load is read off the digital scale directly.

The machine was set to control the stroke i.e, the rate of the loading crosshead movement, at .05 inch per minute.

2.2.5 MIX PROPORTIONING

Mortar constitutes of two components, binder and the fine aggregate. Binder is the cementitious component which could consist of a mixture of cement and fly ash or cement alone. The fine aggregate component is either sand or a mixture of sand and fly ash. This identification is very important because in the different mix proportioning techniques used, fly ash could be incorporated in any one or both of the two components. But when defining water cementitious ratio only the fly ash in the binder is included in the cementitious component.

Three different mix proportioning methods have been used in this test series.

1. Partial replacement of cement with fly ash where fly ash is incorporated in the binder or the cementitious component.
2. Addition of fly ash where fly ash is added to the fine aggregate component.
3. Modified partial replacement methods,
    a) partial replacement of sand with fly ash and addition of fly ash to the cementitious component.
    b) partial replacement of cement and further addition of fly ash as a part of the fine aggregate.

Since the incorporation of fly ash changes the water requirement of a mortar mix, initially the water added to each mix was kept at a constant. The changes associated with the change of water cementitious ratio were verified later, with tests carried out for optimum water cementitious ratio.

2.2.5.1 TEST SERIES 1

Objective of this test series was to investigate the variation of strength with the various fly ash types used with regards to the particle size distribution. The mix proportioning technique adopted was partial replacement of cement by fly ash.

Five different fly ash types were used in this test series. Namely Deep Hollow dry fly ash, Hudson dry and weathered fly ashes, and PSE&G dry and weathered fly ashes of batch 1.

Conforming to the ASTM specifications C 778-80a, 3.2 Ottawa sand was used as the fine aggregate for the mortar mixes.

2.2.5.2 TEST SERIES 2

Test series 2 investigates the variation of strength with the different proportioning techniques. PSE&G dry and weathered fly ash from batch 2 were used in this test series. Regular river sand conforming to the ASTM specifications C 778-80a 3.1 was used as the fine aggregate.

For the ease of comparison of the batching techniques the material proportions are given in parts of equal weights for one batch.

2.2.5.3 TEST SERIES 3

Influence of the water cementitious ratio on the compressive strength of fly ash cement mortar mixes was investigated in the test series 3.

Two mortar mixes were selected from the test series 2 so as to represent low and high fly ash content mixes. Both dry and weathered fly ash mixes of these two mortars were used in this experiment. The water cementitious ratio was varied to obtain a complete optimization curve.

PSE&G dry and weathered fly ash of batch 2 and natural river sand conforming to ASTM specifications C 778-80a 3.1 were used in this test.

For the ease of comparison material proportions are given in equal parts of weight per batch.

III EXPERIMENTAL RESULTS AND DISCUSSION

3.1 EXPERIMENTAL RESULTS

Tabulated results of the tests conducted are given in Appendix C. The graphs developed from the test results are given in Appendix D.

3.1.1 PARTICLE SIZE DISTRIBUTION

The complete particle size distribution curves were obtained by combining the results of wet sieve analysis for the part retained on ASTM standard sieve no. 200 and hydrometer analysis for the fly ash passing this sieve. The distribution curves for the fly ash types used in this experimental program are given in Appendix D.

The conventional graph for the particle size distribution, where cumulative percentage of particles finer is plotted against the diameter in log scale, does not show any significant difference between the dry and weathered fly ash of the same source nor between different fly ash types. But the graphs developed from this, giving the percentage of particle sizes against the diameter, show that there are dominant particle size ranges for each fly ash type.

These dominant particle size ranges include a major portion of the material in very small ranges of sizes compared to the complete range of the particle sizes. About 55% - 70% of material could lie in the range 0 - 20 microns which is only about 3% of the total range of diameters which extends from 1 micron to about 600 microns. In general bulk of the material lies within the range of very fine particle sizes.

Table 3.1 Percentages of fly ash retained on ASTM no. 200 and 325 sieves.

fly ash type	percentage by wt. retained on sieves	
	on ASTM 200 (75 microns)	on ASTM 325 (45 microns)
Deep Hollow	18.50%	24.75%
Hudson dry	17.00%	17.58%
Hudson soaked	14.00%	14.19%
PSE&G batch 1		
dry	7.00%	21.65%
weathered	9.99%	15.07%
PSE&G batch 2		
dry	10.28%	15.68%
weathered	5.30%	8.35%

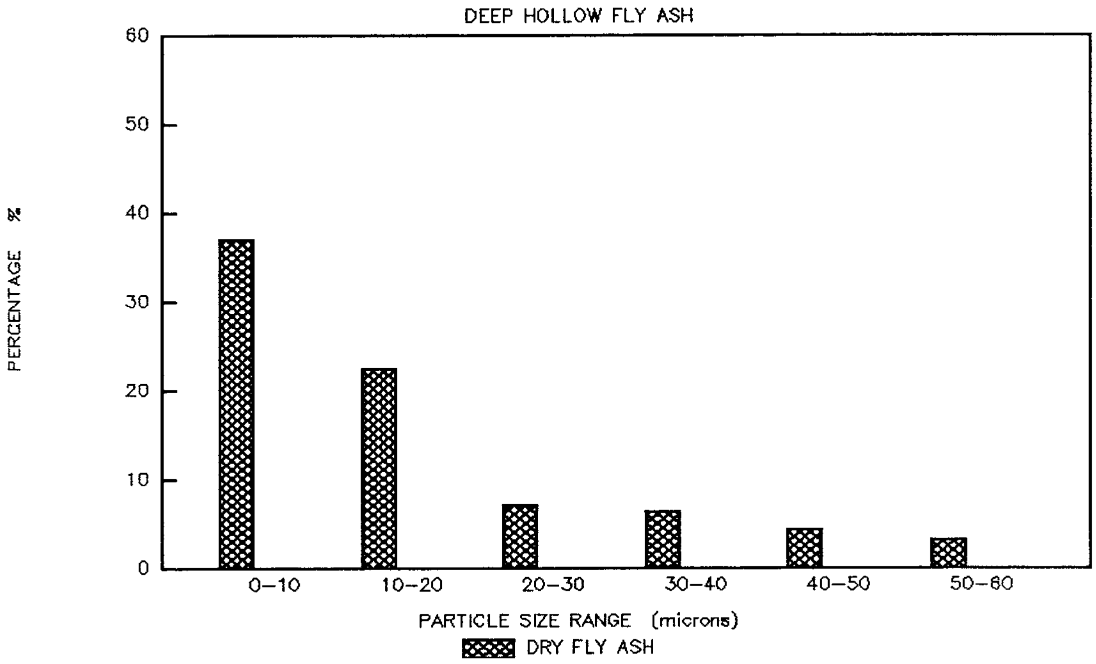

Fig. 3.1 Dominant particle size ranges of Deep Hollow fly ash.

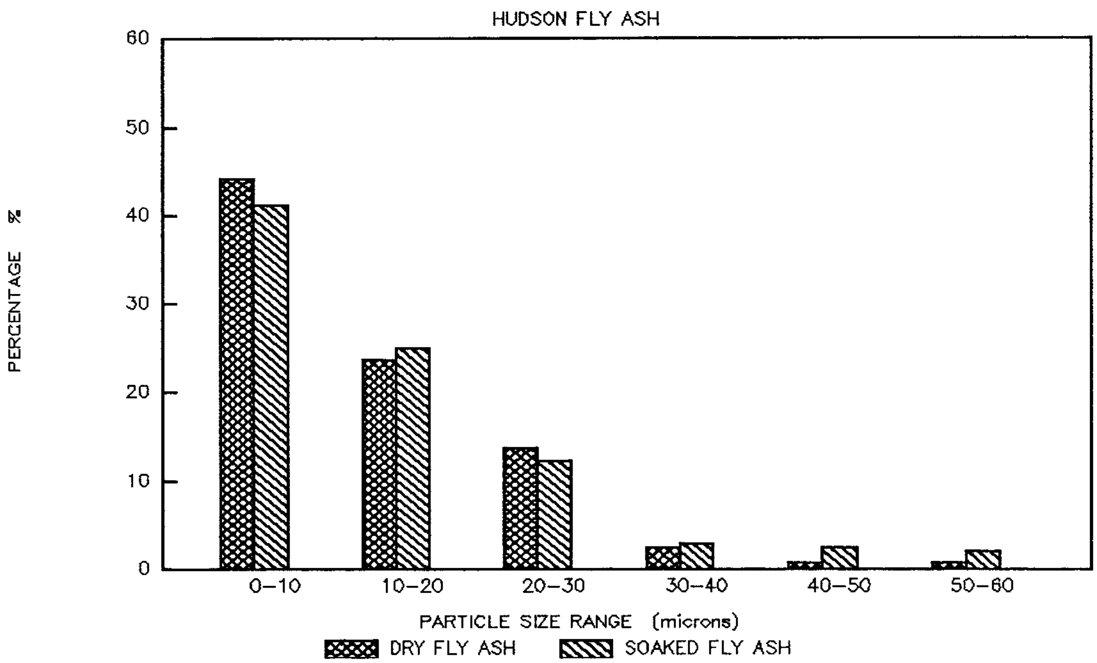

Fig. 3.2 Dominant particle size ranges of Hudson fly ash.

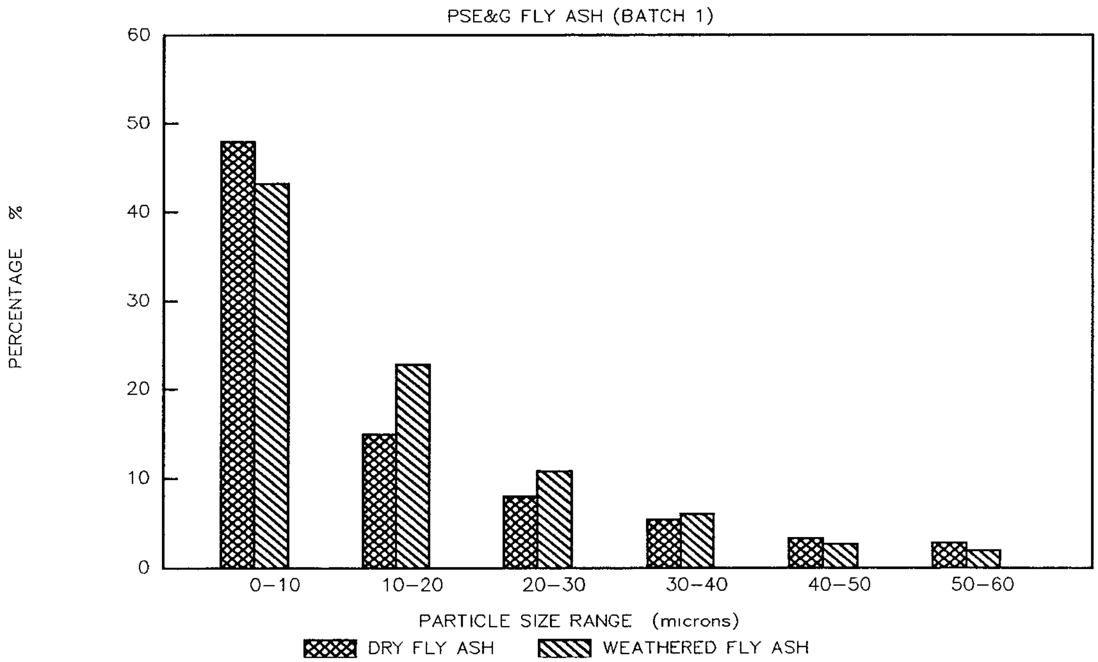

Fig. 3.3 Dominant particle size ranges of PSE&G fly ash (batch 1).

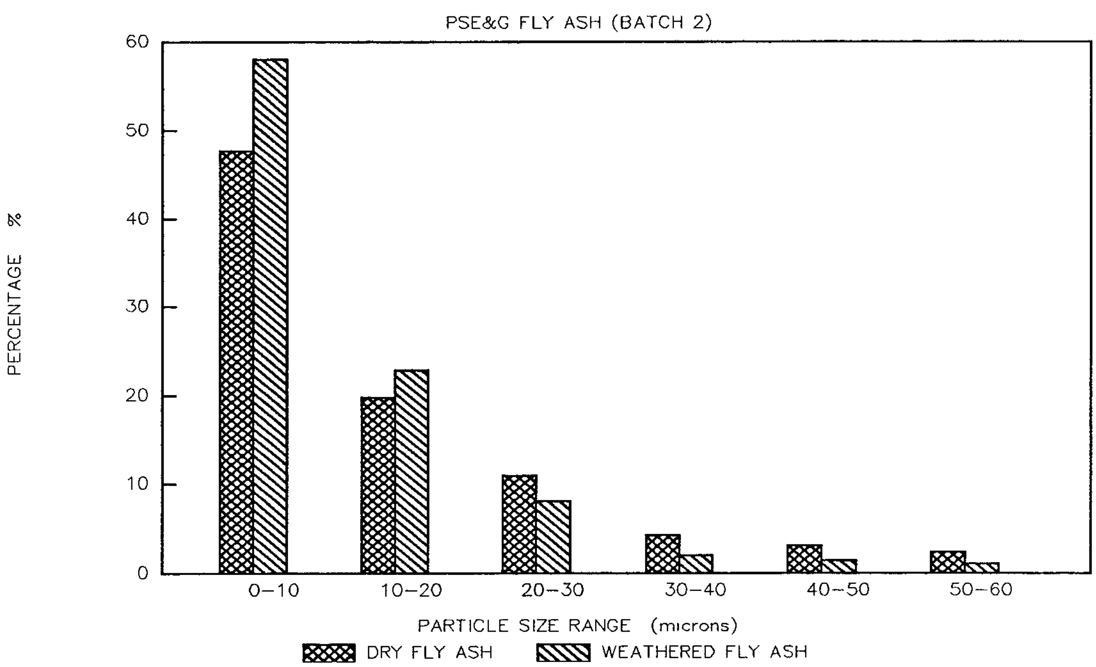

Fig. 3.4 Dominant particle size ranges of PSE&G fly ash (batch 2).

The percentages of material passing through ASTM no. 200 and no. 325 sieves (opening size 75 microns and 45 microns respectively) are close and variation of these percentages between different fly ash types is not very significant.

3.1.2 MOISTURE CONTENT

Moisture contents of the fly ashes and cement were found to be very close and also very small. Dry fly ashes have as little moisture as 0.21 % by dry weight. However the moisture content of PSE&G weathered fly ash of batch 2, which was air dried in the laboratory about a month before use was about 3 times more than the moisture content of the other fly ashes used. Hudson weathered fly ash which was lab produced also showed a higher moisture content.

Although the tests proved otherwise there were no visible differences between the fly ashes as regards to their moisture contents. All samples used in the test program were dry to the touch, far from being damp.

Tabulated results of the moisture content test are given in Appendix C.

3.1.3 COMPRESSIVE STRENGTH DEVELOPMENT

3.1.3.1 COMPRESSIVE STRENGTH DEVELOPMENT OF MORTAR WITH FLY ASH FROM VARIOUS SOURCES.

The results of the test series 1 show that the compressive strength development vary with the type of fly ash incorporated in the mortar mix. The rate of strength gain and the compressive strength vary from one mortar to the other. The tabulated results for test series 1 is given in Appendix C.

The difference in compressive strength can be observed through out the test. It is more prominent after 28 days than the early ages up to about 14 days. The rate of strength development of fly ash mortars, at early ages fall very much below that of conventional cement sand mortars. In general all fly ash mortars irrespective of the fly ash type used, show low early rates of strength gain. Beyond 14 days the rate of strength gain increases and unlike in conventional mortars does not diminish with age but keeps steady even up to 180 days age.

It is interesting to note that weathered fly ash mortars show lower strengths than their dry fly ash counterparts. The same could be said about the early compressive strength development rates.

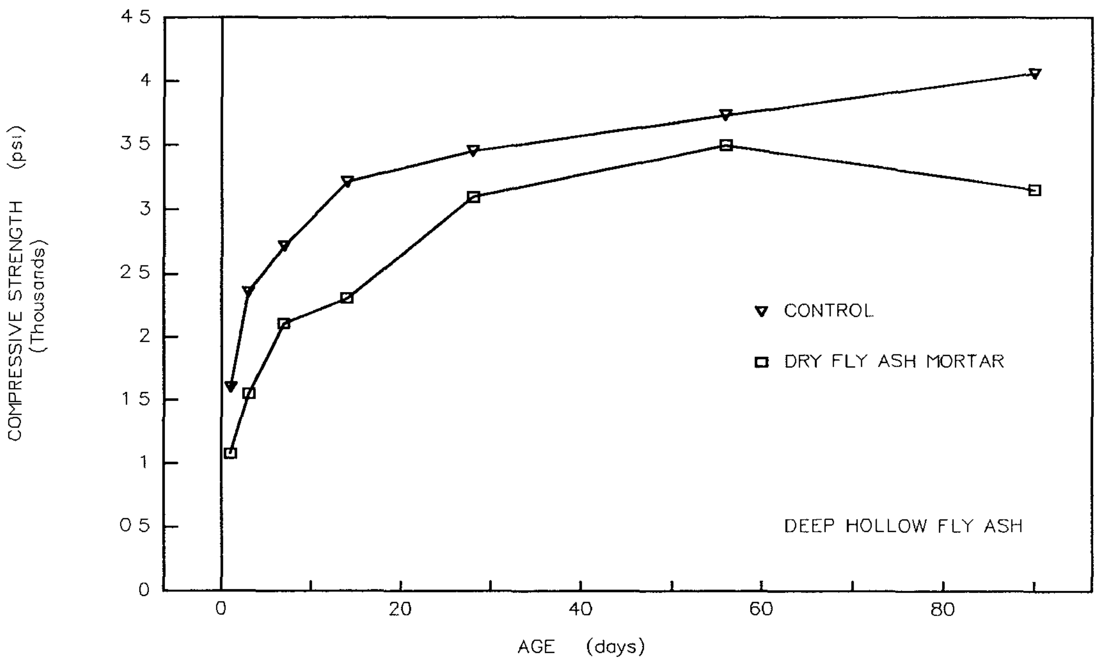

Fig. 3.5 Compressive strength development of Deep Hollow fly ash mortar

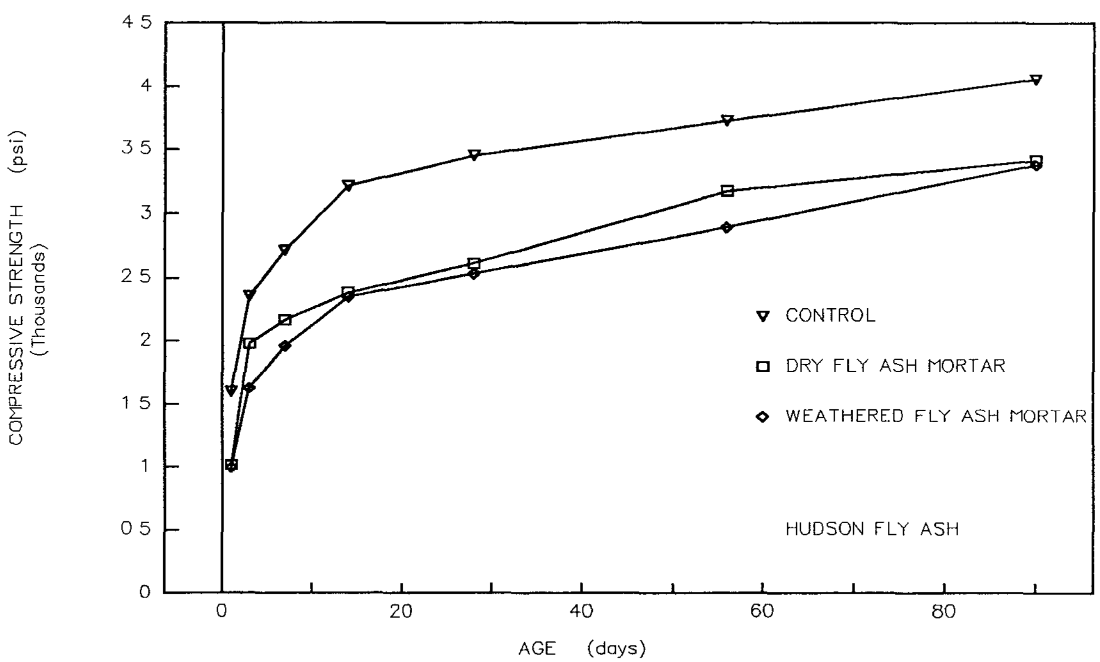

Fig. 3.6 Compressive strength development of Hudson fly ash mortar

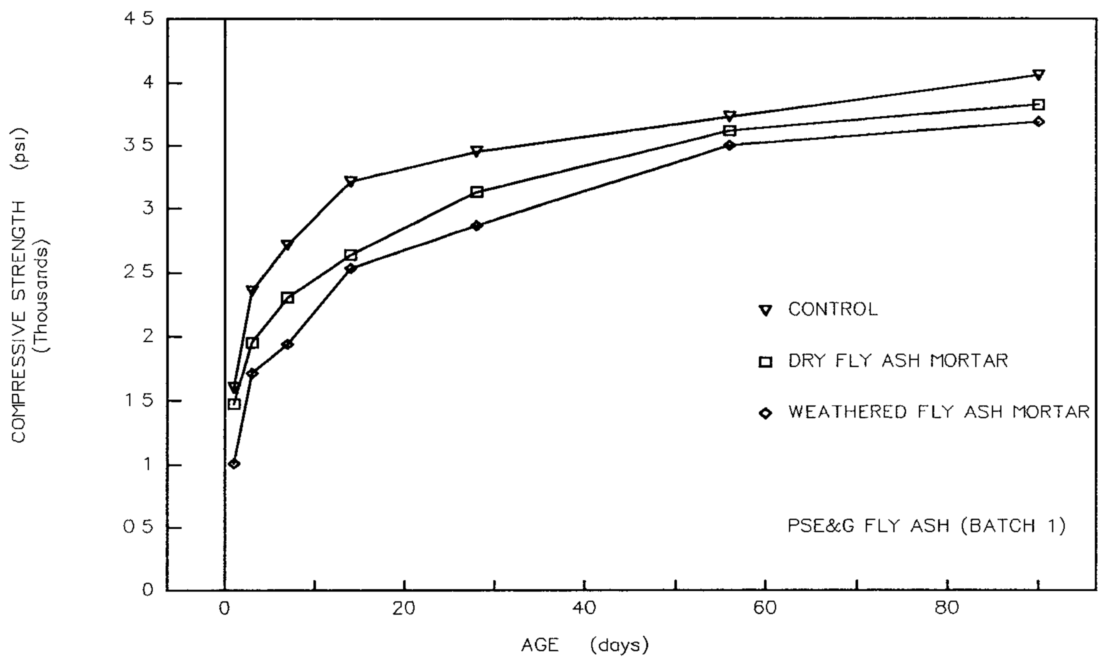

Fig. 3.7 Compressive strength development of PSE&G (batch 1) fly ash mortar

3.1.3.2 COMPRESSIVE STRENGTH DEVELOPMENT WITH THE VARIATION OF MIX PROPORTIONS

The proportioning techniques adopted give a wide variety of mortar mixes, each with different proportions in cement fly ash and sand by weight. It is quite evident from the results that relative proportioning of the constituent material has a direct and more significant effect on compressive strength of fly ash mortars than any other parameters discussed. Tabulated results of the tests 2A, 2B, 2C and 2D are given in Appendix C.

Incorporating the same type of fly ash in the mortar a wide range of strengths can be achieved with different mix proportioning techniques. At the age of 90 days the compressive strengths of different mortar mixes range from 5339 psi to 10173 psi.

These results show that the cement content of the mix does not necessarily govern the compressive strength of a mortar. For the same content of cement by weight of the mix, different strengths result, depending on the proportioning of fly ash and sand with this amount of cement. The mix CBW20 of Test series 2D gives the highest strength of the whole series of tests but it has a lower cement content than many other mixes tested.

The mix proportioning also affects the rate of strength development at all stages of age. Many mortar mixes that show different early strength developments gain similar strength capacities by 28 days age and again the strengths of these mixes vary considerably at ages of 56 or 90 days.

3.1.3.3 COMPRESSIVE STRENGTH DEVELOPMENT WITH THE VARIATION OF WATER/CEMENTITIOUS RATIO

Two different mortar mixes representing mixes of low and high fly ash contents were selected for this test. Tabulated results of this test series are given in Appendix C.

The results showed that the optimum water cement ratio is different for dry and weathered fly ash mortars of similar mix proportions. The mix proportions of a mortar has a direct effect on the optimum water requirement. Cement rich mixes required a higher content of water per unit weight of mortar than leaner mortar mixes.

At low water contents cement and fly ash formed lumps and did not mix well with sand to make a homogeneous mix. The mortar mix took a crumb-like appearence before it was compacted in to the moulds. The fractured faces of the test cubes showed dark spots indicating the cement-fly ash lumps.

At high water contents the mix turned out as a thick paste and was difficult to be compacted in to moulds. Fractured faces of theses test cubes did not show any dark spots as did the test cubes of the drier mixes.

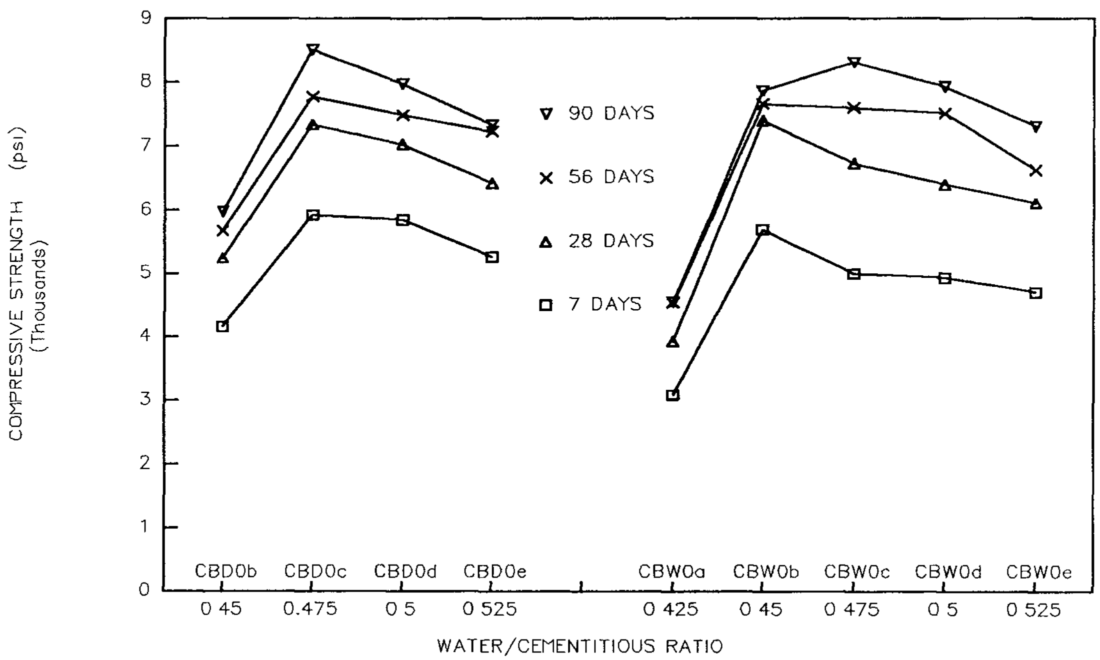

Fig. 3.8 Variation of compressive strength with water cementitious ratio for mortar mix CBD0

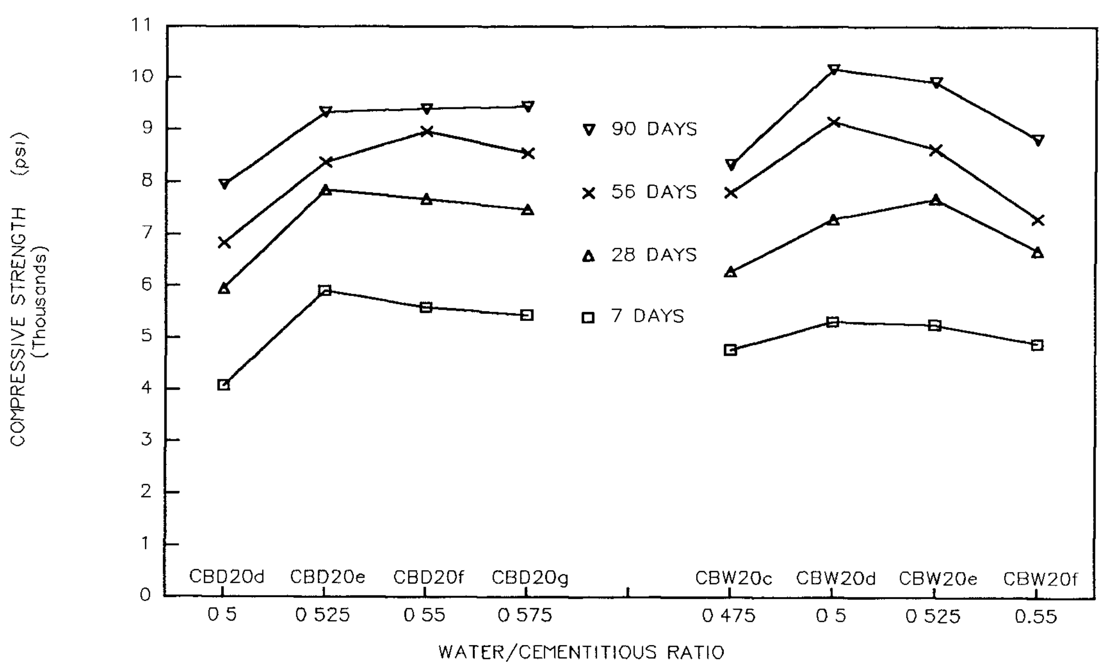

Fig. 3.9 Variation of compressive strength with water cement ratio for mortar mix CBD0

3.2 INFLUENCE OF SELECTED PARAMETERS ON THE UNCONFINED COMPRESSIVE STRENGTH OF MORTAR

3.2.1 INFLUENCE OF THE PARTICLE SIZE DISTRIBUTION

The graphs presented in 3.1.1 and Appendix D show that bulk of the fly ash particles lie within a relatively small range of very fine diameters. More than 60% of fly ash particles are concentrated in the region of 0-20 microns which is only 3% of the total range of particle size distribution.

Fly ashes of different sources show different distribution patterns within the region of 0 - 20 microns. Fig. 3.1, 3.2, 3.3, show the particle size distribution in this range for different fly ash types. These distribution charts are developed from the particle size distribution curves given in Appendix D.

The percentage of particles passing through the ASTM standard sieves no. 200 and no. 325 of opening sizes 75 and 45 microns respectively, are not representative of the actual distribution pattern of the particles since bulk of the material lie within diameters much finer than these.

The results of test series 1, the variations in the compressive strength of the fly ash-cement mortars of the same mix proportions but incorporating different fly ash types, can be explained with relation to the particle size distribution of these fly ashes.

Compressive strengths plotted against percentage of particles passing sieves no. 200 and no. 325 do not show any relationship between the strength and the fineness of the particles. This conforms with the observations of the past researchers.

However as the finer diameters are considered the strength and particle size distribution gradually fall in to a more definite pattern. Figures 3.10, 3.11, and 3.12 show the compressive strengths at ages 1, 7, 14, 28, 56, and 90 days plotted against the percentages of particles finer than 20, 10 and 5 microns, in each fly ash type.

Even with the percentage of particles finer than 20 micron size, a definite relationship between the compressive strength and the percentage of particles cannot be established. The regression lines for this graph, (fig. 3.13) take negative slopes or lie parallel to the *x* axis. The particle size distribution of fly ashes vary considerably even within 20 microns diameter. PSE&G weathered fly ash has a higher percentage of particles finer than 5 microns than the Hudson dry fly ash. But of the particles finer than 10 microns, Hudson dry fly ash has a higher percentage than PSE&G weathered fly ash. Regression lines for the curves of compressive strength against percentage of particles finer than 10 and 5 microns, take positive slopes. For these, the compressive strength of fly ash mortar increases with the percentage of particles finer than 10 and 5 microns.

However the differences in strengths even at the age of 90 days are not too significant. This may be due to the fact that in the selected mix, fly ash composes only 15% of the cementitious component and the effect of fly ash at such small percentages cannot dominate over the effects of cement.

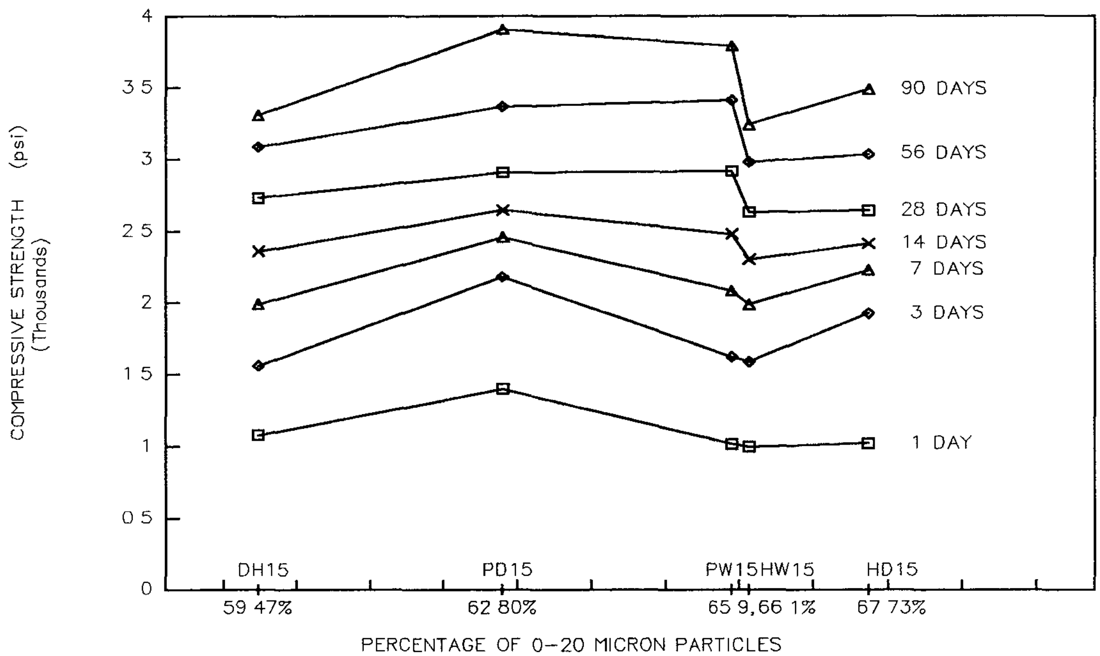

Fig. 3.10 Effect of 0-20 micron size particles on compressive strength

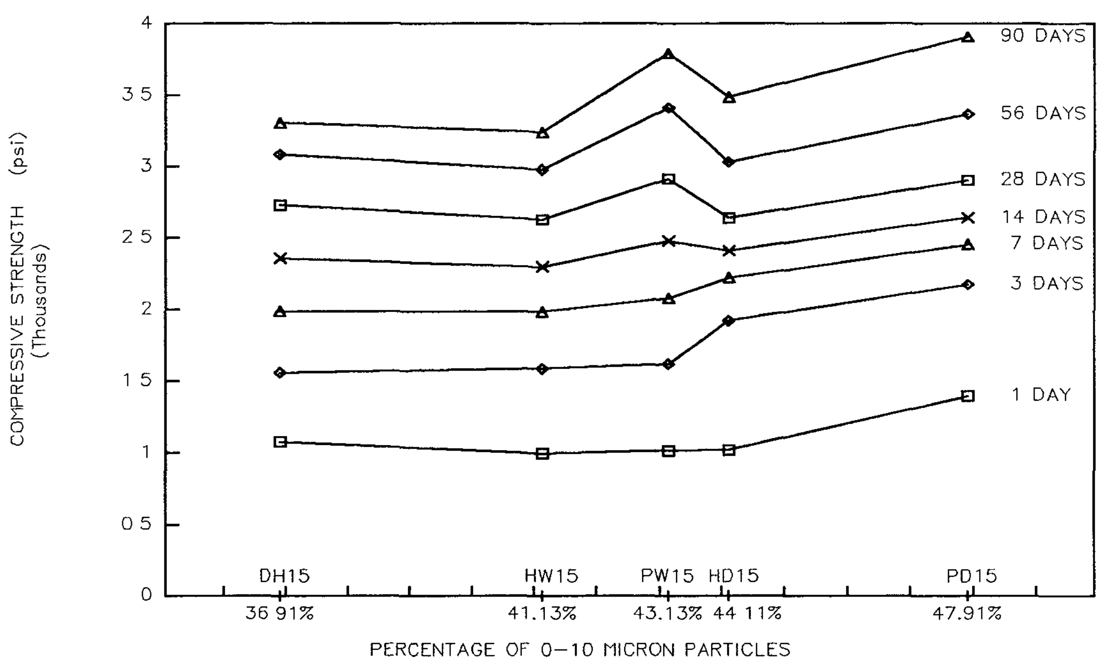

Fig. 3.11 Effect of 0-10 micron size particles on compressive strength

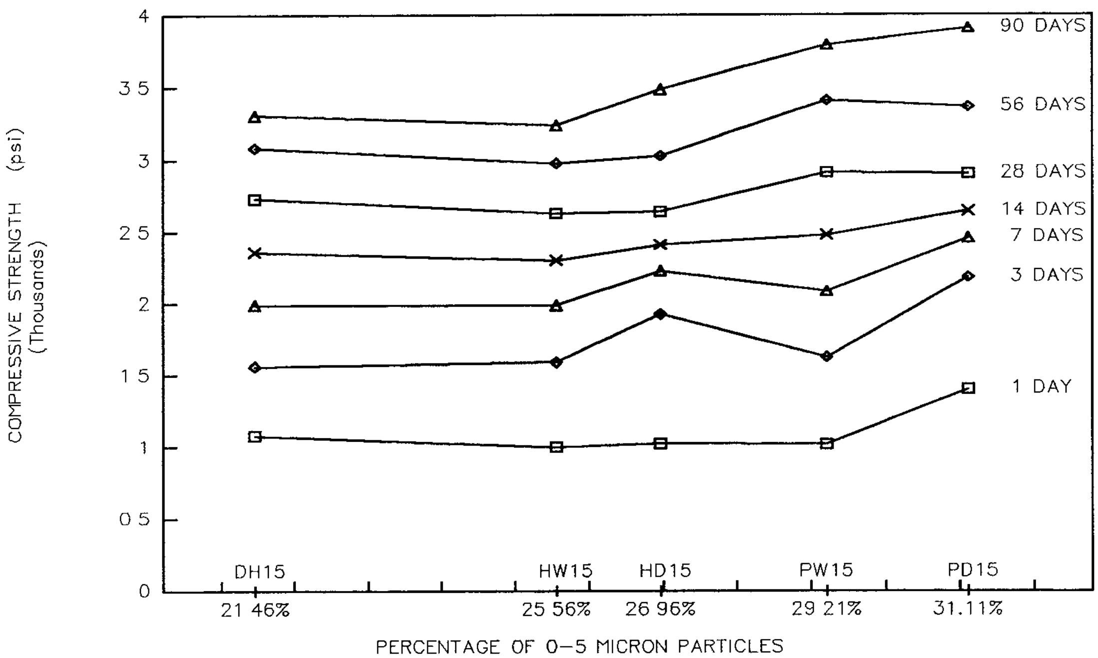

Fig. 3.12 Effect of 0-5 micron size particles on compressive strength

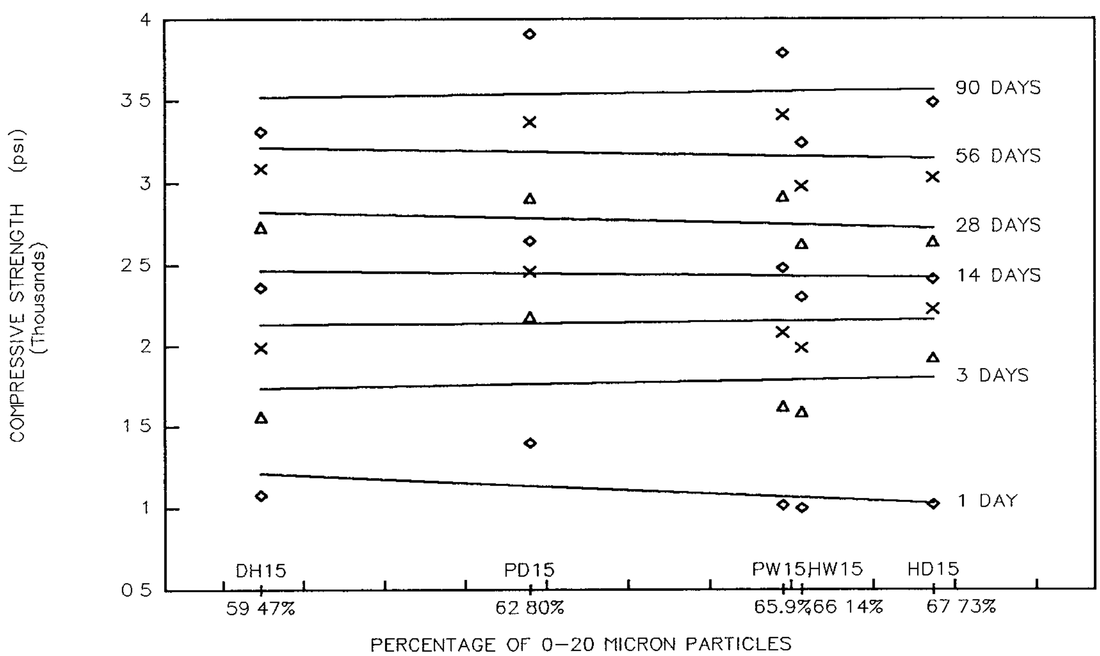

Fig. 3.13 Regression lines for the graph of compressive strength vs percentage of 0-20 micron size particles

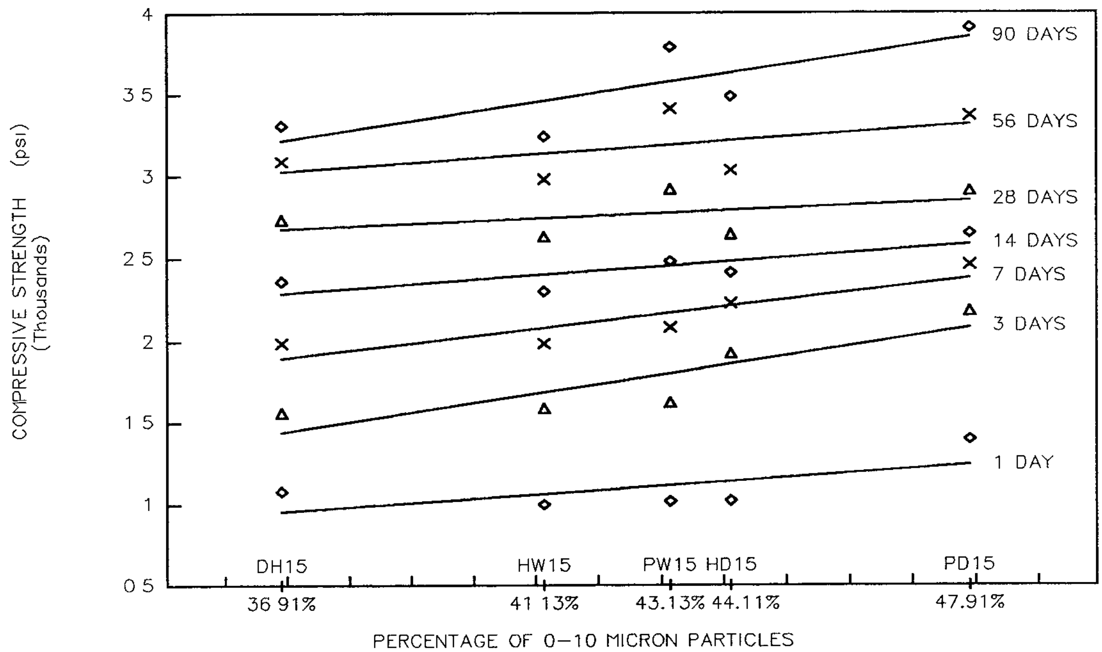

Fig. 3.14 Regression lines for the graph of compressive strength vs percentage of 0-10 micron size particles

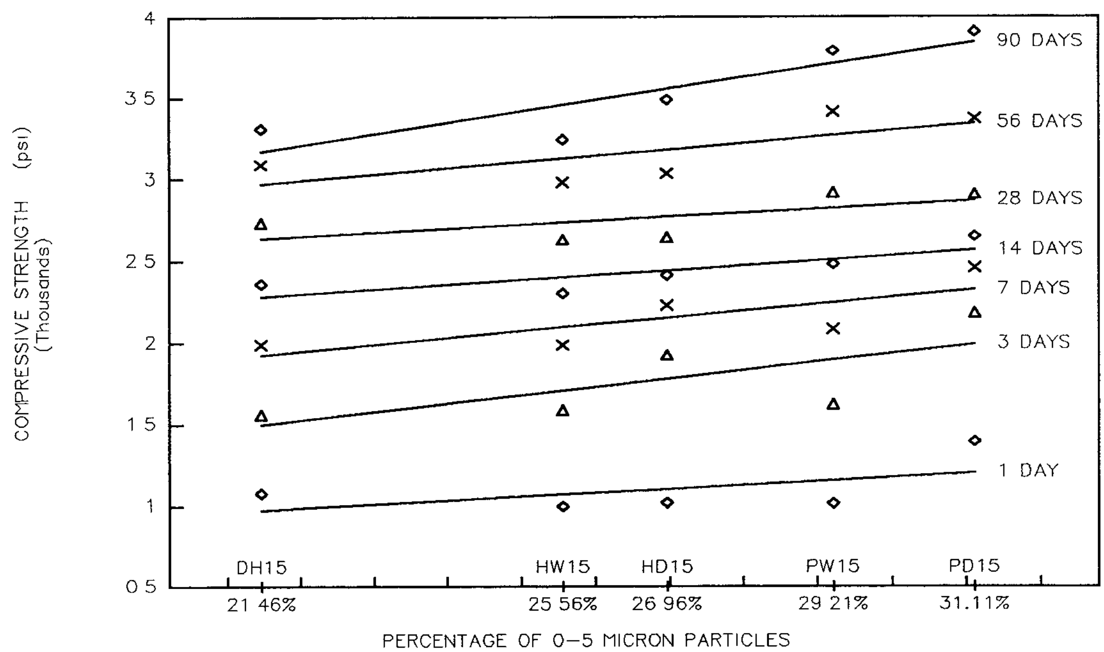

Fig. 3.15 Regression lines for the graph of compressive strength vs percentage of 0-5 micron size particles

The PSE&G fly ashes of batch 1 and batch 2 show different particle size distribution patterns.(figures D.7 and D.8) Depending on the location these samples are picked up from, at the precipitators of the furnace and at storage pond, the dry and weathered fly ash will have different particle size distributions. Dry fly ash of batch 1 has a higher percentage of finer particles than the weathered fly ash while the weathered fly ash of batch 2 has more finer particles than the dry fly ash.

It is interesting to note that the compressive strength development of PSE&G fly ash also changes trend with the change of particle size distribution. The weathered fly ashes show relatively lower strengths than the dry fly ashes as observed throughout the research. This strength drop between the dry and weathered fly ashes is very distinct in the PSE&G fly ashes of batch 1. However fly ashes of batch 2 do not show a notable difference in strength and at ages of 90 and later the strength are almost equal or weathered fly ash mortars show strengths slightly higher than the dry fly ash mortar strengths. (test series 2A, 2B, 2C & 2D)

The past research work confirms that the chemical composition of a fly ash type does not change with the fineness of the particles.[11] The chemical composition of the fly ash types used do not show any considerable variations either. Therefore these results points to increased reactivity of the paste due to the fineness of the fly ash incorporated in the mix. The difference of compressive strengths are more prominent when the fly ash content of the paste is more.

In the test series 3, two mortar mixes incorporating PSE&G fly ash of batch 2, selected from test series 2-D are tested for the optimum water cementitious ratio. The results of this test show that at optimum water contents, when water cementitious ratio effects are eliminated, still the same trend described above prevails. As the fly ash content in the mix increases the weathered fly ash mortars develop higher strengths contrary to the results obtained for mortars of batch 1.

It is the total surface area of the cementitious component that represent the material available for hydration.[3] Therefore the rate of hydration, as well as the percentage of cement that actually hydrates completely, depend on the fineness of the particles. However there are restrictions on the fineness of cement imposed by economic considerations such as high grinding costs and by other undesirable chemical and rheological changes it may entail. Finer cement deteriorates more rapidly on exposure to the atmosphere and makes paste more prone to shrinkage and cracking. Therefore by incorporating very fine fly ashes in the paste, hydration process could be enhanced without bringing about adverse effects.

3.2.2 INFLUENCE OF WEATHERING OF FLY ASH

It is quite evident from the results of the test series 1, 2 and 3 that weathering of fly ash brings about some changes which causes it to behave differently from dry fly ashes. Throughout the entire test program weathered fly ash mortars showed lower strengths than dry fly ashes regardless of the mix proportions.

The results of the test series 2D where for certain high fly ash mixes, weathered fly ash mortars show higher strengths when the corresponding dry fly ash mortars show sudden drops in strength, actually need to be corrected for water cementitious ratios. The dry fly ash mortars in question were too dry in mix and with increased water cementitious ratios gave high strengths falling in line with the general pattern of strength build up.

The chemical composition of the dry and weathered fly ashes show very little differences.(Appendix A) The calcium oxide content which is believed to effect reactivity is 1.65% for the dry fly ash and 1.70 % for the weathered. The difference in both silicon dioxide and aluminium oxide are only about 3%. In general it could be said that there is almost no chemical change associated with the process of weathering. However the chemical analysis does not indicate any changes in the structure of chemicals or reactive form.

The results of test series 2D show that the dry and weathered fly ash mortars reach same compressive strengths at late ages of 56 to 90 days. But at early ages up to about 28 days the weathered fly ash show lower strengths than dry fly ash. This trend is confirmed by the results of test series 3, where strengths can be compared at optimum water cementitious ratios, eliminating any effects of water content in the mix. The weathering process seems to cause some change in the fly ash that retards the early strength development.

In the light of this view, an observation made during the hydrometer analysis seems worthy of notice. The water in the sedimentation jar containing weathered fly ash was a very dark gray in color with a tint of brown while the dry fly ash jar took on a light gray tone. The ash settled at the bottom of the two jars were of the same light gray. This raises a question whether the fly ash is contaminated on the surface with some deleterious material in the process of weathering.

3.2.3 INFLUENCE OF MOISTURE CONTENT AND WATER CEMENTITIOUS RATIO.

The results of the moisture content tests reveal that, the fly ashes in general contain very little moisture. Dry fly ashes contain as little as 0.21% moisture while weathered fly ashes show moisture contents slightly higher than that. The PSE&G weathered fly ash of batch 2 show a moisture content of 0.65%, about three times that of dry fly ash which is 0.23%. The difference of absorbed moisture between the two fly ashes is about 0.41 grams per 100 grams of fly ash.

Moisture contents of the component materials invariably effect the water cementitious ratio of any mortar or concrete. Water content is vital to the strength development of the mix and should be carefully controlled. Too dry mixes would result in crumb-like nonhomogeneous mixes, making poor binders while too much water in the mix would hinder good compaction. Either way it would reduce the compressive strength of the hardened mortar.

When fly ash is incorporated in conventional cement sand mortar the definition of water cement ratio is extended to include fly ash and, a "water cementitious ratio" is used in its place. However in mix proportioning techniques, fly ash is used in mortars either as a part of the cementitious component or as a part of the fine aggregate, sand or both.

Table 3.2 Optimum Water Content for the Selected Mortar Mixes.

mortar mix	cementitious com.		fine aggregate		optimum water content
	cement	fly ash	fly ash	sand	
CBD0	425	75	0	1375	240.0
CBD20	425	75	100	1375	265.0
CBW0	425	75	0	1375	231.25
CBW20	425	75	100	1375	256.25

Note: material proportions given in equal parts of weight

In this test program fly ash in the cementitious component alone, has been considered for the calculation of the water requirement for the mix. The two selected mixes CBD0 and CBD20 have same cementitious component, comprising of cement and fly ash in ratio of 425:75 by weight but different fine aggregate components. Mortar mix CBD20 has fly ash in the fine aggregate in addition to sand whereas CBD0 contains no fly ash in fine aggregate.

Although the two mixes are of similar cementitious components, they yield different optimum water requirements. Similar results were obtained with the weathered fly ash mortars of same mix. CBD0 with a total material weight (per batch) of 1875 grams required 240 m.l. of water which amounts to 0.128 m.l. of water per unit weight. At this rate water requirement for CBD20 which contains 100 grams more fly ash, should have been 252.8 m.l. per batch (of total weight 1975 grams) but the actual water requirement was found to be 265 m.l. per batch. The additional 100 grams of fly ash in the fine aggregate component had demanded more water than would sand.

These results show that regardless of what it substitutes in mortar, fly ash makes a demand on water. In the light of these observations the different mix proportioning techniques, incorporating fly ash in different components seem to serve no purpose.

Both mixes exhibited noted differences in water requirement between dry fly ash mortar and weathered fly ash mortars. This difference was far more than the difference dictated by the variation in their moisture contents. The dry fly ash mortar required 8 m.l. more water per batch than its weathered counterpart while the difference due to variation in moisture content was only 0.73 m.l. per batch containing 175 grams of fly ash.

The results of this test explains the sudden drops in strength observed in dry fly ash mortars in the test series 2 D. At optimum water cementitious ratios this could be avoided and a general variation pattern could be obtained.

3.2.4 INFLUENCE OF MIX PROPORTIONING

Tests conducted in test series 2 investigates the basic mix proportioning techniques in use. It is evident from the results of these tests, that these proportioning methods serve only as a convenient basis for introducing a new material as a partial substitute for any of the constituent materials in conventional concrete or mortar. The compressive strength of the fly ash mortar do not show any relation to the corresponding conventional mortar. Nor is there any relation between different proportioning techniques. Thus it could be concluded that the proportioning method is not indicative of compressive strength a mix could develop.

Although the proportioning methods carefully define to which component in mortar and in what proportion fly ash is to be substituted this does not seem to have any strong basis either. Samples AD15 and ED15 have similar cementitious components comprising of cement and fly ash. But their fine aggregate components are different, AD15 having only regular river sand in its fine aggregate component while the other, ED15 has fly ash in the fine aggregate component replacing part of the river sand. The two mixes showed different strength development patterns and the 180 day strengths recorded were 9633 psi and 8131 psi for AD15 and ED15 respectively.

It is evident from these comparisons that it is the total amount of fly ash and the relative proportion of cement fly ash and sand that determines the strength development regardless of what fly ash is substituted for in the mortar.

The same holds true for the optimum water requirement, as discussed in article 3.2.3. When fly ash is incorporated in a mortar mix the water requirement invariably changes from the optimum water requirement of the corresponding conventional mix. With one to one replacement of cement by fly ash the water requirement will drop while with addition or one to one replacement of sand by fly ash, the water requirement will increase.

Whatever the proportioning technique is, the compressive strength of the mortar and the strength development pattern depend on the relative proportion of cement fly ash and sand. Thus the proportioning techniques in use seem to serve no purpose.

and in fact could be misleading. Fly ash concrete or mortar should be identified as distinctly as fibre reinforced concrete or polymer concrete and fly ash treated as a constituent material not a substitute.

Using different proportioning techniques 19 different mortar mixes have been obtained in test series 2. Since dry fly ash mortars of test series 2D showed sudden strength drops due to inadequate water, the weathered fly ash mortars were analyzed to find a relation between compressive strength and constituent material.

In the early stages of age before 28 days the compressive strength seem to increase linearly with the increase in cement content in the mix. However beyond 28 days, at 56 and 90 days a direct relation between the cement content and strength cannot be established. The highest compressive strengths appear to lie within the range of 18 - 24 percent of cement content.

A similar trend can be observed with the fly ash content or the fly ash/cement ratio and compressive strength. Up to 28 days the compressive strength seem to decrease linearly with the increase in fly ash/cement ratio. But beyond 28 days this pattern changes and the highest strengths build up within the small region 20-50 percent in the fly ash/cement ratio. At early ages below 28 days compressive strength decreases linearly with the increase of fly ash content. But this relation does not hold beyond the age of 28 days.

The ratio of binder to fine aggregate, where binder is defined as the total quantity of fly ash and cement in the mix and fine aggregate is sand, does not seem to have any relation with the compressive strength development of the mortar at any age.

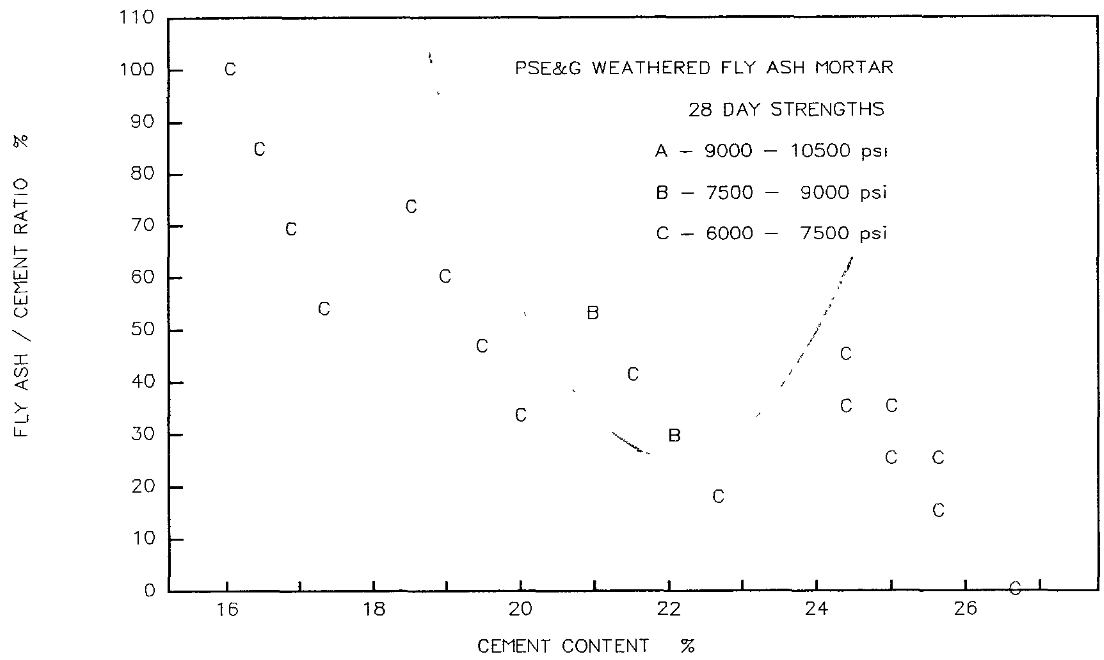

Fig. 3.16 Strength contours defined by the cement content and the fly ash/cement ratio at the age of 28 days.

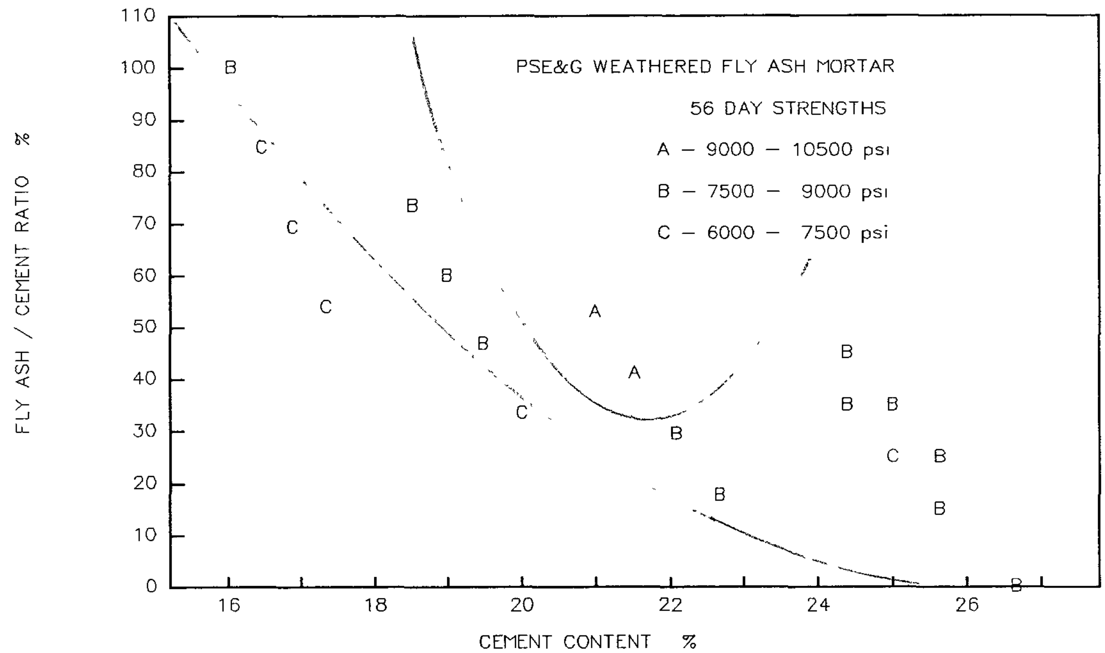

Fig. 3.17 Strength contours defined by the cement content and the fly ash/cement ratio at the age of 56 days.

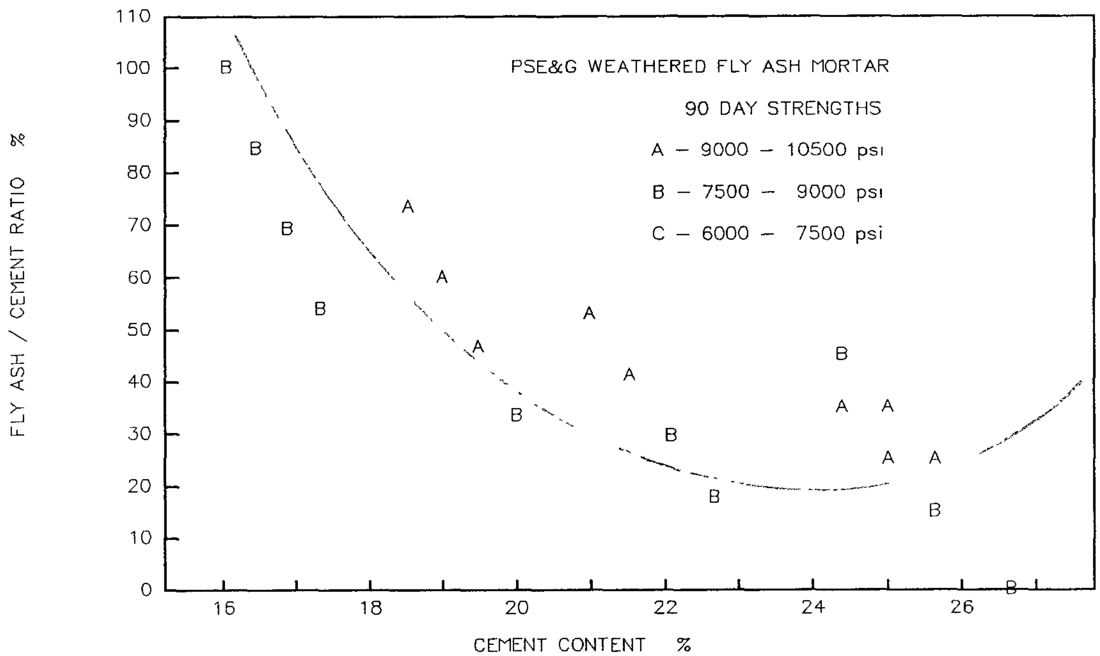

Fig. 3.18 Strength contours defined by the cement content and the fly ash/cement ratio at the age of 90 days.

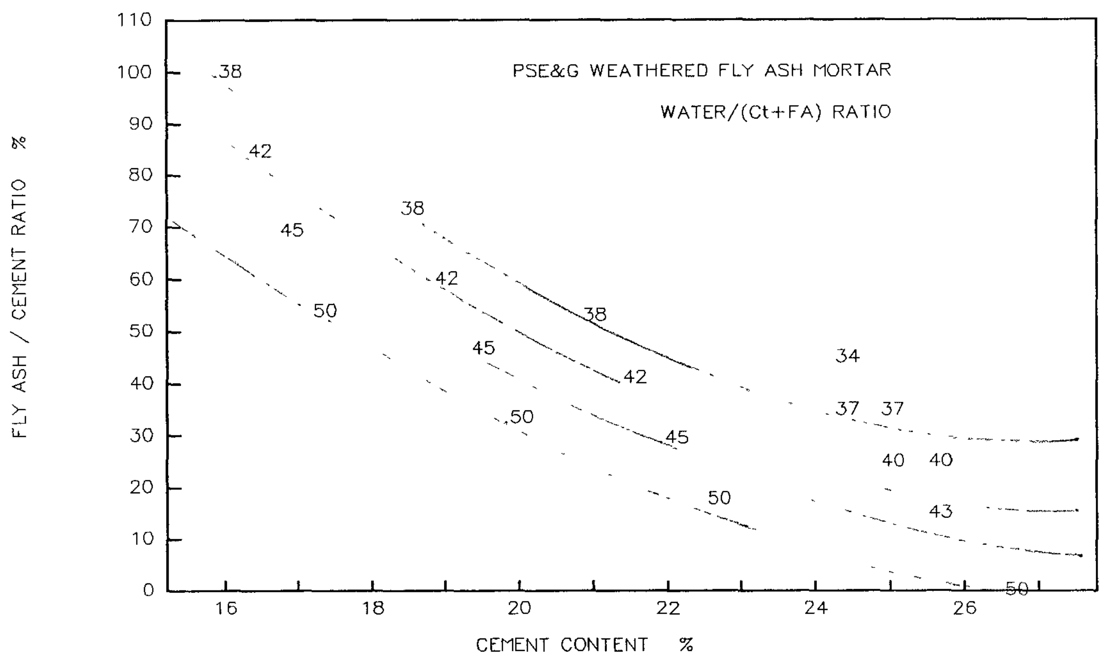

Fig. 3.19 Contours defined by the water/cementitious ratio of the mortar mixes.

The cement content in the mix nor the fly ash/cement ratio alone seem to govern the strength development pattern but, together they clearly define ranges of cement content and fly ash/cement ratio which would give specific compressive strengths ranges. Figures 3.16, 3.17, 3.18 show plots of strengths in the axes of cement content and fly ash/cement ratio. The distribution of the compressive strength ranges denoted by A, B and C seem to define contour patterns of strengths. The layout of the contour lines shift, but the basic pattern remains the same.

In the cases where data points do not seem to agree with this pattern, for an instance mix CBW20 at 28 days age which lies in the strength region B, (7500-9000 psi) but has a lower strength it is seen that these are stray points on the respective strength development curves. At 28 days age the strength recorded is 7304 psi but the regression curve made to this graph gives a value of 7725 psi. The same can be said about the other data points in figures 3.17 and 3.18 which do not fall in line with these contour pattern.

The water/cementitious ratio recorded in the same axes show that the strength contours are not dictated by the water/cementitious ratio. Figure 3.18 show the water/cementitious ratio contours of the mortar mixes. The water/cementitious ratio contours pass through all regions of strength. These contours could be developed to be used as mix design charts for fly ash cement mortar. The strengths should be replaced with those at the optimum water content so that the water/cementitious ratio effects are eliminated.

IV CONCLUSIONS

The results of the experiments conducted in this study lead to the following conclusions.

It is quite evident from the results of the tests conducted, that there is a direct relationship between particle size and its distribution and the compressive strength development of fly ash cement mortar.

The finest particles of diameters ranging from 0 to 10 microns, are the most influential in compressive strength development. An exact relationship between the two has not been established in this study but, the results are supportive of the view that the percentages of particles lying within the diameters of 0-5, and 5-10 microns, could be a governing factor in the compressive strength development of fly ash cement mortar.

Weathering of fly ash does bring about physico-chemical changes in the rheology of fly ash, that can not be easily overlooked. The early rate of compressive strength development is retarded due to weathering. Even at the age of 180 days the compressive strength of weathered fly ash mortar is lower than its dry fly ash counterpart. A further in depth study of the process of weathering and its effects is strongly urged in the view that most fly ash that is available in the market has undergone some weathering.

The fly ash should be tested for moisture content before use since two samples could have considerably different moisture contents without betraying it by the appearance or feel.

The water/cementitious ratio of fly ash-cement mortars should be clearly defined as the ratio of weight of water to the weight of cement and total quantity of fly ash in the mix.

The optimum water cementitious ratio for the maximum compressive strength is dependent upon the fly ash content of the paste. Water cementitious ratio is influenced by the fly ash characteristics and for any mortar mix using a particular fly ash type, the optimum ratio is a unique value that has to be established by a test.

The mix proportioning techniques in use, serve no other purpose than providing a convenient basis for introducing a new material in to the conventional cement sand mortar.

Fly ash should be identified as a constituent material of fly ash-cement mortar and not as a mere substitute. By them selves, neither the cement content nor the fly ash content of the mix can determine the compressive strength. But the combination of these two parameters can define the compressive strength capacity of a mortar mix.

To achieve maximum compressive strengths by the age of 28 days, the cement content of fly ash mortars should be within 20% to 23% and the fly ash/cement ratio should be within 30% to 60%.

APPENDIX A

CHEMICAL COMPOSITION OF FLY ASH

Table A.1 Chemical Composition of Fly ashes Used in the Test Program

Chemical Component	Composition in Percentage			
	Deep Hollow fly ash	Hudson fly ash	PSE&G dry fly ash	PSE&G weathered fly ash
Silicon Dioxide	50.95	50.64	53.57	50.15
Aluminum Oxide	29.30	27.19	26.70	29.11
Calcium Oxide	1.39	2.31	1.65	1.70
Magnesium Oxide	0.88	0.79	0.77	0.81
Iron Oxide	12.11	11.51	5.08	6.12
Sodium Oxide	0.28	0.29	0.30	0.51
Potassium Oxide	1.90	2.18	1.99	1.95
Sulfur Trioxide	0.53	0.64	0.70	1.10

APPENDIX B

MIX PROPORTIONS FOR THE MORTAR MIXES

Table B.1 Mix Proportions For Test Series 1

fly ash type	sample id.	C		S/C	W/C
		cement	fly ash		
Deep Hollow	DD15	85%	15%	2.75	0.5
Hudson dry	HD15	85%	15%	2.75	0.5
Hudson wet	HW15	85%	15%	2.75	0.5
PSE&G dry	PD15	85%	15%	2.75	0.5
PSE&G wet	PW15	85%	15%	2.75	0.5
Control	C	85%	15%	2.75	0.5

Notes:

1. C - cementitious material component
   S - fine aggregate (sand)
   W - water

2. dry - dry fly ash
   wet - weathered fly ash

Table B.2 Mix Proportions For Test Series 2 A

Partial Replacement of Cement by Fly Ash

sample id	cementitious mat.		fine aggregate		water	W/C
	cement	fly ash	sand	fly ash		
CTRL	500	-	1375	-	250	0.5
DRY FLY ASH MORTAR						
RD15	425	75	1375	-	250	0.5
RD25	375	125	1375	-	250	0.5
RD35	325	175	1375	-	250	0.5
WEATHERED FLY ASH MORTAR						
RW15	425	75	1375	-	250	0.5
RW25	375	125	1375	-	250	0.5
RW35	325	175	1375	-	250	0.5

Notes:

1. W/C - water cementitious ratio

2. material proportions given in equal parts of weight for one batch.

Table B.3 Mix Proportions For Test Series 2 B

Addition of fly ash

sample id	cementitious mat.		fine aggregate		water	W/C
	cement	fly ash	sand	fly ash		
CTRL	500	-	1375	-	250	0.5
DRY FLY ASH MORTAR						
AD15	500	-	1375	75	250	0.5
AD25	500	-	1375	125	250	0.5
AD35	500	-	1375	175	250	0.5
WEATHERED FLY ASH MORTAR						
AW15	500	-	1375	75	250	0.5
AW25	500	-	1375	125	250	0.5
AW35	500	-	1375	175	250	0.5

Notes:

1. W/C - water cementitious ratio

2. material proportions given in equal parts of weight for one batch.

Table B.4 Mix Proportions For Test Series 2 C

Modified Replacement Method 1

sample id	cementitious mat.		fine aggregate		water	W/C
	cement	fly ash	sand	fly ash		
CTRL	500	-	1375	-	250	0.5
DRY FLY ASH MORTAR						
AD15	500	75	1325	50	250	0.43
AD25	500	125	1325	50	250	0.40
AD35	500	175	1325	50	250	0.37
WEATHERED FLY ASH MORTAR						
AW15	500	75	1325	50	250	0.43
AW25	500	125	1325	50	250	0.40
AW35	500	175	1325	50	250	0.37

Notes:

1. W/C - water cementitious ratio

2. material proportions given in equal parts of weight for one batch.

Table B.5 Mix Proportions For Test Series 2 D
Modified Replacement Method 2

sample id	cementitious mat.		fine aggregate		water	W/C
	cement	fly ash	sand	fly ash		
CTRL	500	-	1375	-	250	0.5
DRY FLY ASH MORTAR						
CBD0	500	75	1375	-	250	0.5
CBD10	500	75	1375	50	250	0.5
CBD20	500	75	1375	100	250	0.5
CBD30	500	75	1375	150	250	0.5
CCD0	500	125	1375	-	250	0.5
CCD10	500	125	1375	50	250	0.5
CCD20	500	125	1375	100	250	0.5
CCD30	500	125	1375	150	250	0.5
CDD0	500	175	1375	-	250	0.5
CDD10	500	175	1375	50	250	0.5
CDD20	500	175	1375	100	250	0.5
CDD30	500	175	1375	150	250	0.5
WEATHERED FLY ASH MORTAR						
CBW0	500	75	1375	-	250	0.5
CBW10	500	75	1375	50	250	0.5
CBW20	500	75	1375	100	250	0.5
CBW30	500	75	1375	150	250	0.5
CCW0	500	125	1375	-	250	0.5
CCW10	500	125	1375	50	250	0.5
CCW20	500	125	1375	100	250	0.5
CCW30	500	125	1375	150	250	0.5
CDW0	500	175	1375	-	250	0.5
CDW10	500	175	1375	50	250	0.5
CDW20	500	175	1375	100	250	0.5
CDW30	500	175	1375	150	250	0.5

Notes:

1. W/C - water cementitious ratio
2. material proportions given in equal parts of weight for one batch.

Table B.6 Mix Proportions For Test Series 3

Test For Optimum Water Cementitious Ratio

sample id	cementitious mat		fine aggregate		water	W/C
	cement	fly ash	sand	flyash		
DRY FLY ASH MORTAR						
CBD0b	500	75	1375	-	225	0.45
CBD0c	500	75	1375	-	237.5	0.475
CBD0d	500	75	1375	-	250	0.5
CBD0e	500	75	1375	-	262.5	0.525
CBD20d	425	75	1375	100	250	0.5
CBD20e	500	75	1375	100	262.5	0.525
CBD20f	500	75	1375	100	275	0.550
CBD20g	500	75	1375	100	287.5	0.575
WEATHERD FLY ASH MORTAR						
CBW0a	500	75	1375	-	212.5	0.425
CBW0b	500	75	1375	-	225	0.45
CBW0c	500	75	1375	-	237.5	0.475
CBW0d	500	75	1375	-	250	0.5
CBW0e	500	75	1375	-	262.5	0.525
CBW20c	425	75	1375	100	237.5	0.475
CBW20d	500	75	1375	100	250	0.5
CBW20e	500	75	1375	100	262.5	0.525
CBW20f	500	75	1375	100	275	0.55

Notes:

1. W/C - water cementitious ratio
2. material proportions given in equal parts of weight for one batch.

APPENDIX C

EXPERIMENTAL RESULTS

Table C.1 Results of the Moisture Content Test

fly ash type	moisture content %
Deep Hollow dry	0.23
Hudson dry	0.21
Hudson soaked	0.36
PSE&G (batch 1) dry	0.21
weathered	0.21
PSE&G (batch 2) dry	0.23
weathered	0.65

Table C.2 Results of The Test Series 1

Sample id.	Compressive Strength (psi) at the age (days)						
	1	3	7	14	28	56	90
C	1601	2357	2715	3210	3450	3728	4058
DD15	1074	1548	2106	2310	3095	3497	3154
HD15	1013	1978	2169	2384	2613	3173	3416
HW15	992	1628	1958	2350	2533	2895	3381
PD15	1473	1954	2304	2637	3130	3615	3827
PW15	1008	1711	1939	2534	2866	3500	3689

Table C.3 Results of The Test Series 2 A

Sample id.	Compressive Strength (psi) at the age (days)							
	1	3	7	14	28	56	90	180
CTRL	2144	4303	5252	6109	6884	7320	7448	7965
DRY FLY ASH MORTAR								
RD15	1724	3811	4911	5357	6209	6380	6821	7703
RD25	1677	3545	4470	4779	5853	6430	6568	8323
RD35	1185	2944	3591	3998	5483	5604	6577	8066
WEATHERED FLY ASH MORTAR								
RW15	1847	3424	3893	4729	4968	5651	6667	8263
RW25	1230	3000	3702	4253	4623	5199	6230	7131
RW35	890	4303	5252	6109	6884	7320	7448	7965

Table C.4 Results of The Test Series 2 B

Sample id.	Compressive Strength (psi) at the age (days)							
	1	3	7	14	28	56	90	180
CTRL	2144	4303	5252	6109	6884	7320	7448	7965
DRY FLY ASH MORTAR								
AD15	2534	4560	5851	6579	7685	7829	8123	9633
AD25	2664	4736	5753	7254	7482	8664	8833	9542
AD35	2429	4450	5109	6220	6990	8130	8542	9226
WEATHERED FLY ASH MORTAR								
AW15	2312	4322	5306	6378	6909	8091	8428	9182
AW25	2512	4453	5024	5594	6985	7391	9054	9917
AW35	2344	4702	5076	6033	6886	8237	9513	10356

Table C.5 Results of The Test Series 2 C

Sample id.	Compressive Strength (psi) at the age (days)							
	1	3	7	14	28	56	90	180
CTRL	2144	4303	5252	6109	6884	7320	7448	7965
DRY FLY ASH MORTAR								
ED15	2684	5690	6636	7016	7079	8131	10386	11488
ED25	2533	4434	5769	6319	6386	7973	8628	9506
ED35	2889	4846	4838	5312	6647	7425	8142	9351
WEATHERED FLY ASH MORTAR								
EW15	2601	5704	5655	6508	6961	7865	9020	11348
EW25	2470	4445	5043	6351	6994	8679	9491	10903
EW35	2238	5412	5694	6526	7264	7686	8830	10517

Table C.6 Results of The Test Series 2 D

Sample id.	Compressive Strength (psi) at the age (days)						
	1	3	7	14	28	56	90
CTRL	2854	4678	5976	7057	7480	7712	8357
DRY FLY ASH MORTAR							
CBD0	2014	3880	5847	6176	7023	7479	7973
CBD10	2371	4146	5708	6635	7813	8233	9164
CBD20	1543	3229	4080	4857	5951	6836	7944
CBD30	1533	2797	3829	4374	4917	6037	6732
CCD0	1777	3605	4343	5262	6020	7233	7944
CCD10	2273	4193	4847	6211	7212	8446	9356
CCD20	2227	3889	4833	5876	7116	7917	8133
CCD30	1948	3395	4169	5360	6517	7596	7963
CDD0	1263	2803	4035	4833	5937	6823	7575
CDD10	1746	3421	4203	5200	6194	7030	7904
CDD20	1448	2656	4432	5254	6798	7496	8703
CDD30	1179	2372	3166	3823	4677	5446	5745
WEATHERED FLY ASH MORTAR							
CBW0	1723	3914	4931	5900	6404	7508	7930
CBW10	2117	4085	5479	6571	7848	8984	9269
CBW20	2181	4576	5328	6215	7304	9154	10173
CBW30	1938	4243	4959	6025	8036	9244	10102
CCW0	1677	3028	4598	5073	6038	7071	7955
CCW10	1948	3996	5238	5703	7255	7573	9153
CCW20	1848	3921	4964	6145	7310	7982	9466
CCW30	1933	3991	5111	6054	7197	8924	9613
CDW0	902	2604	3574	4542	6030	6413	7614
CDW10	1285	2878	3978	4739	6342	7409	7769
CDW20	1003	2798	4129	5333	6622	7412	7723
CDW30	1063	3135	4316	5574	6550	7787	8231

Table C.7 Results of The Test Series 3

Sample id.	Compressive Strength (psi) at the age (days)			
	1	28	56	90
DRY FLY ASH MORTAR				
CBD0b	4158	5252	5675	5975
CBD0c	5922	7334	7769	8503
CBD0d	5847	7023	7479	7973
CBD0e	5267	6421	7226	7332
CBD20d	4080	5951	6836	7944
CBD20e	5903	7853	8379	9329
CBD20f	5589	7680	8956	9396
CBD20g	5443	7478	8548	9443
WEATHERED FLY ASH MORTAR				
CBW0a	3081	3928	4535	4551
CBW0b	5698	7396	7656	7870
CBW0c	4993	6732	7598	8308
CBW0d	4931	6404	7508	7931
CBW20c	4781	6294	7816	8347
CBW20d	5328	7303	9154	10173
CBW20e	5268	7695	8632	9920
CBW20f	4902	6699	7325	8824

APPENDIX D

GRAPHS DEVELOPED FROM THE EXPERIMENTAL RESULTS

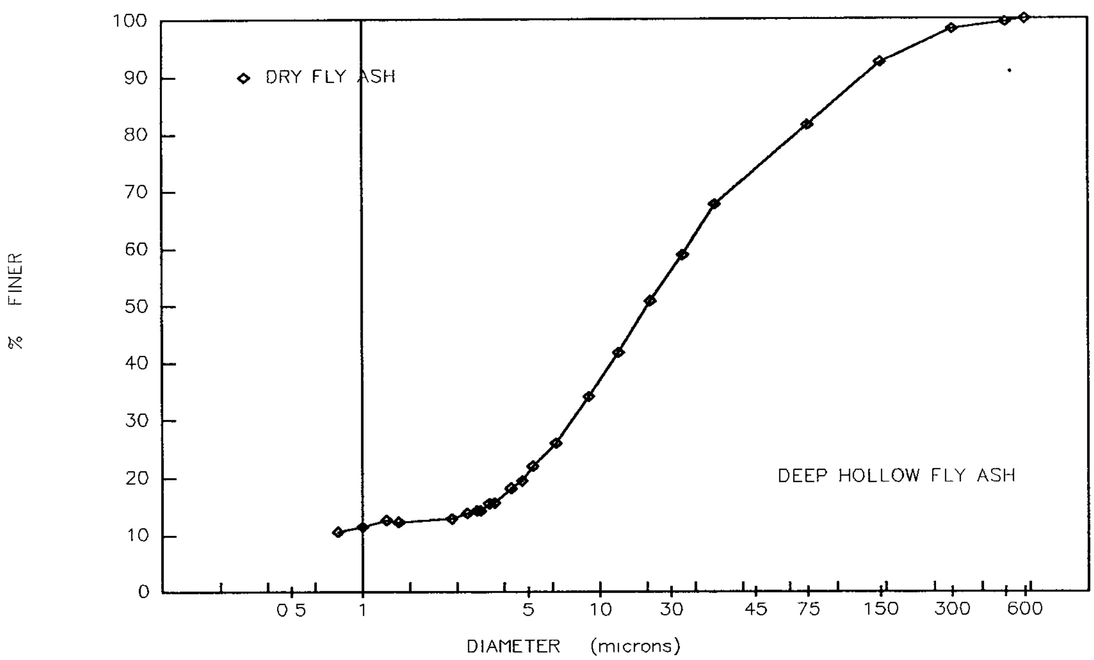

Fig. D.1 Particle size distribution of Deep Hollow fly ash.

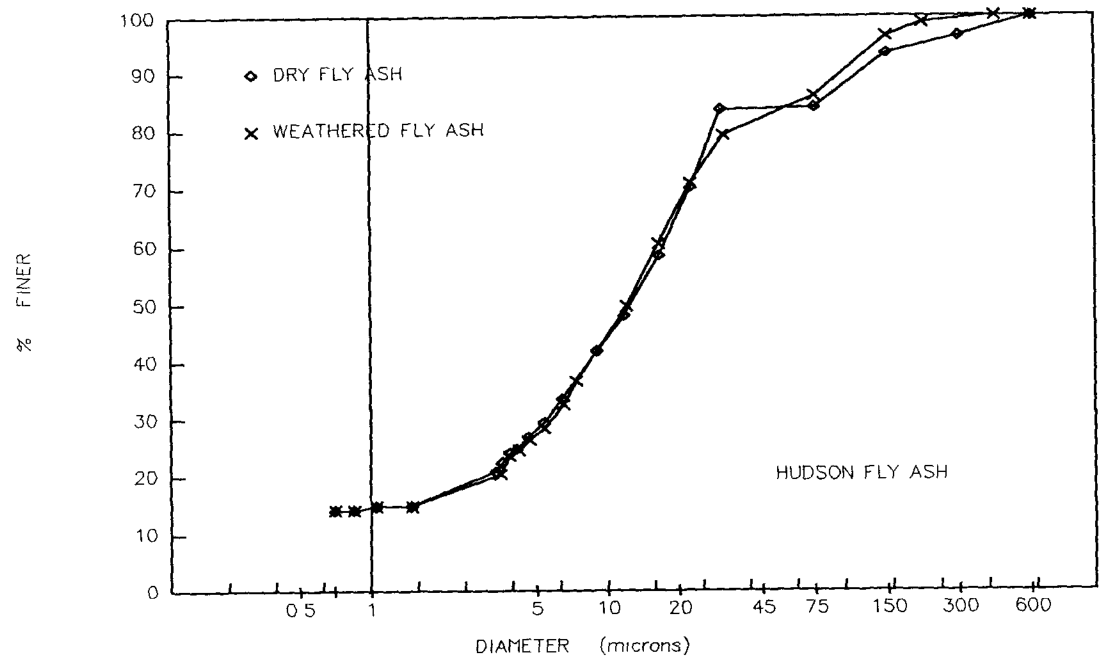

Fig. D.2 Particle size distribution of Hudson fly ash.

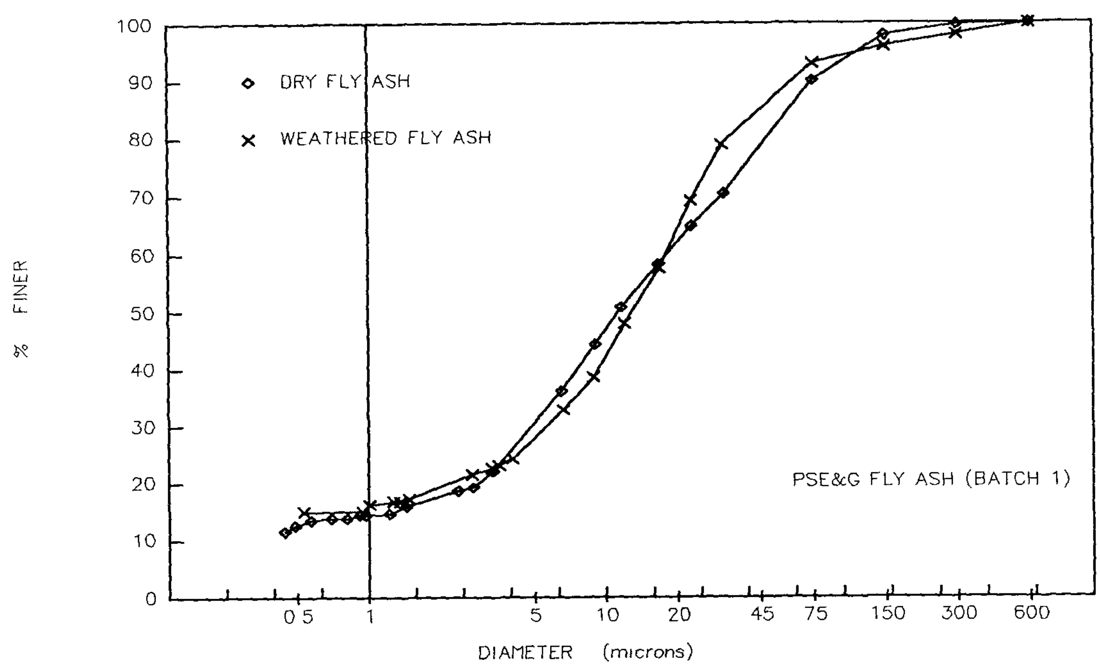

Fig. D.3 Particle size distribution of PSE&G fly ash (batch 1).

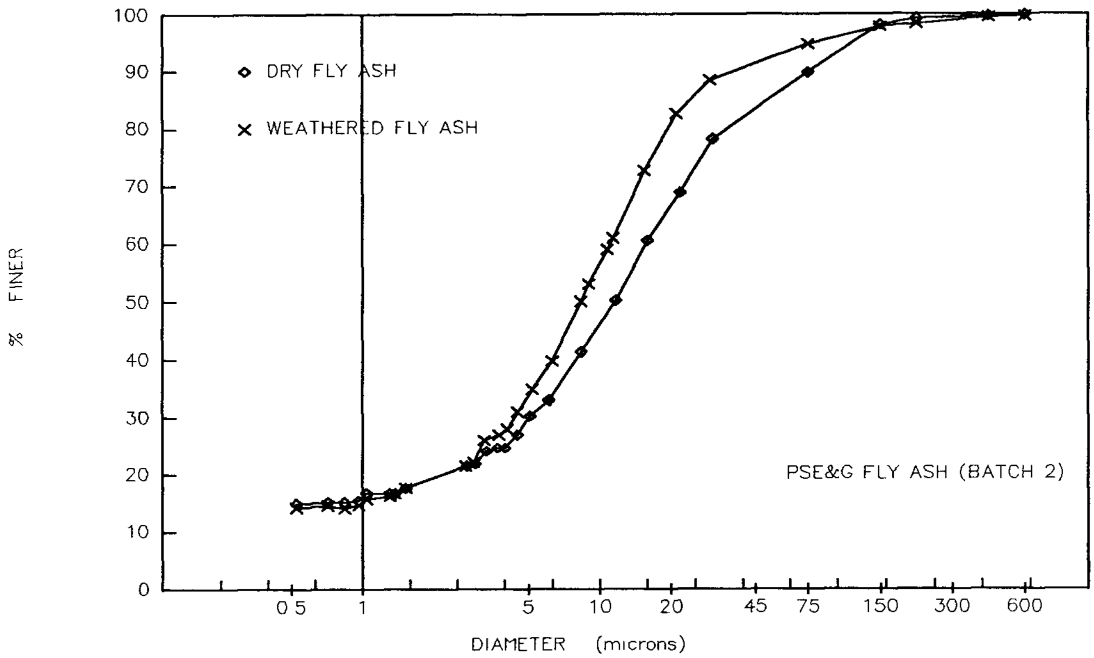

Fig. D.4 Particle size distribution of PSE&G fly ash (batch 2).

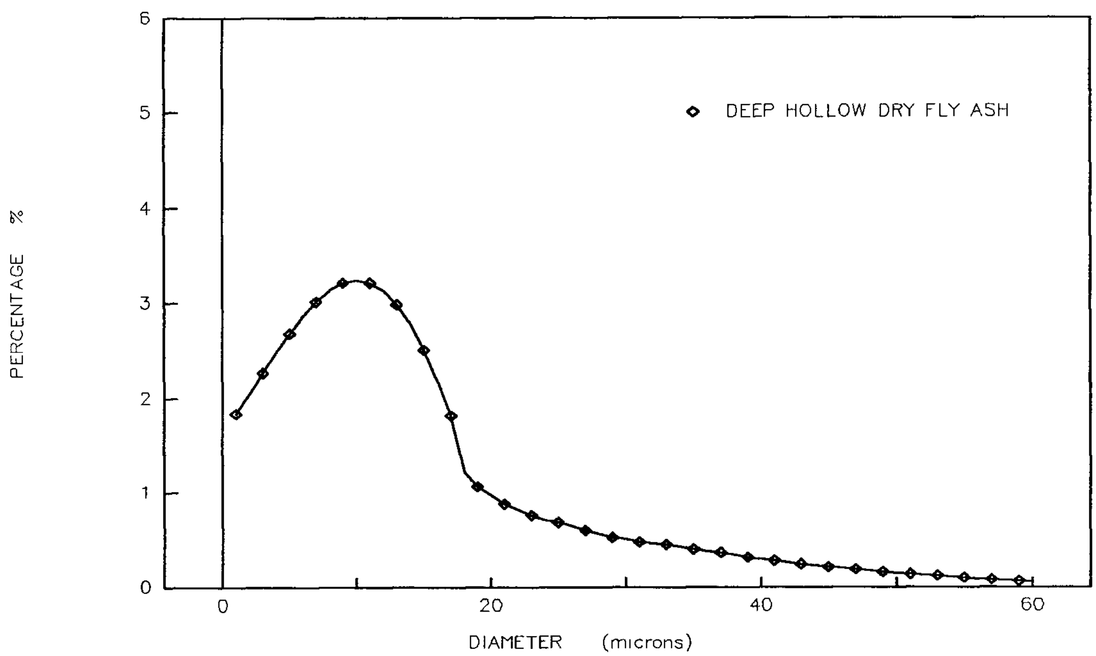

Fig. D.5 Percentage of particle sizes - Deep Hollow fly ash.

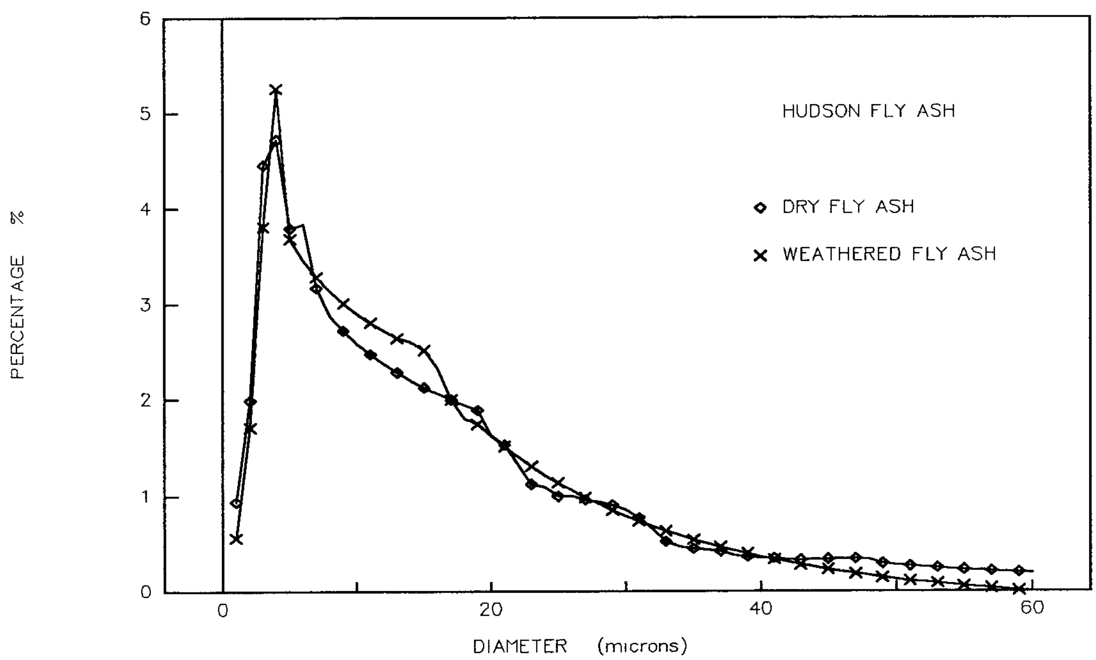

Fig. D.6 Percentage of particle sizes - Hudson fly ash.

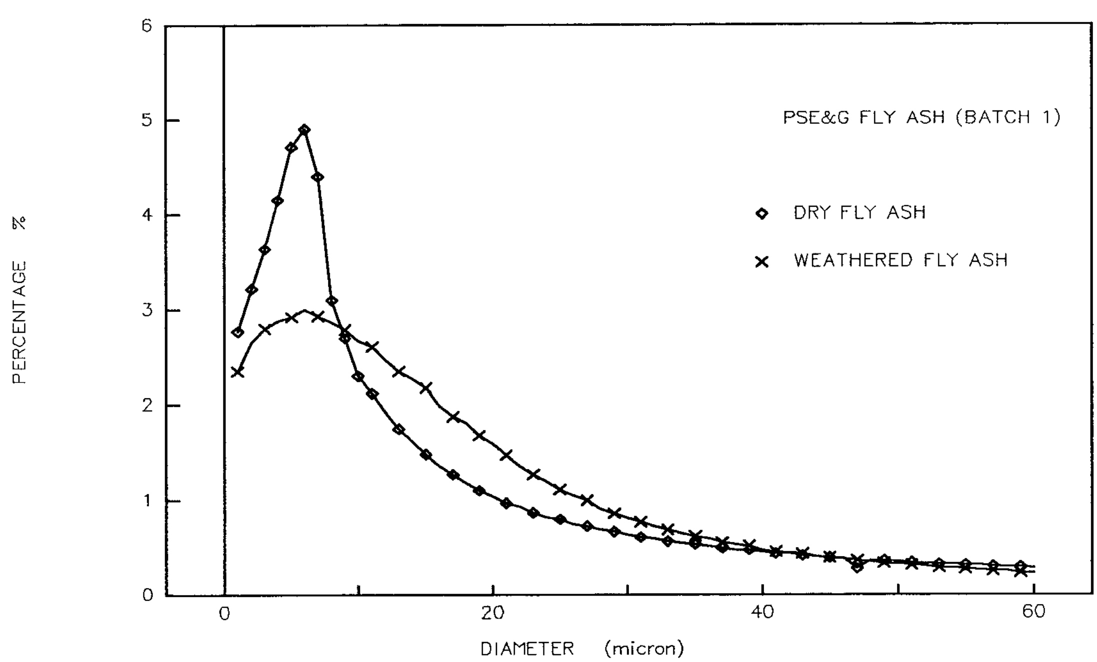

Fig. D.7 Percentage of particle sizes-PSE&G fly ash (batch 1).

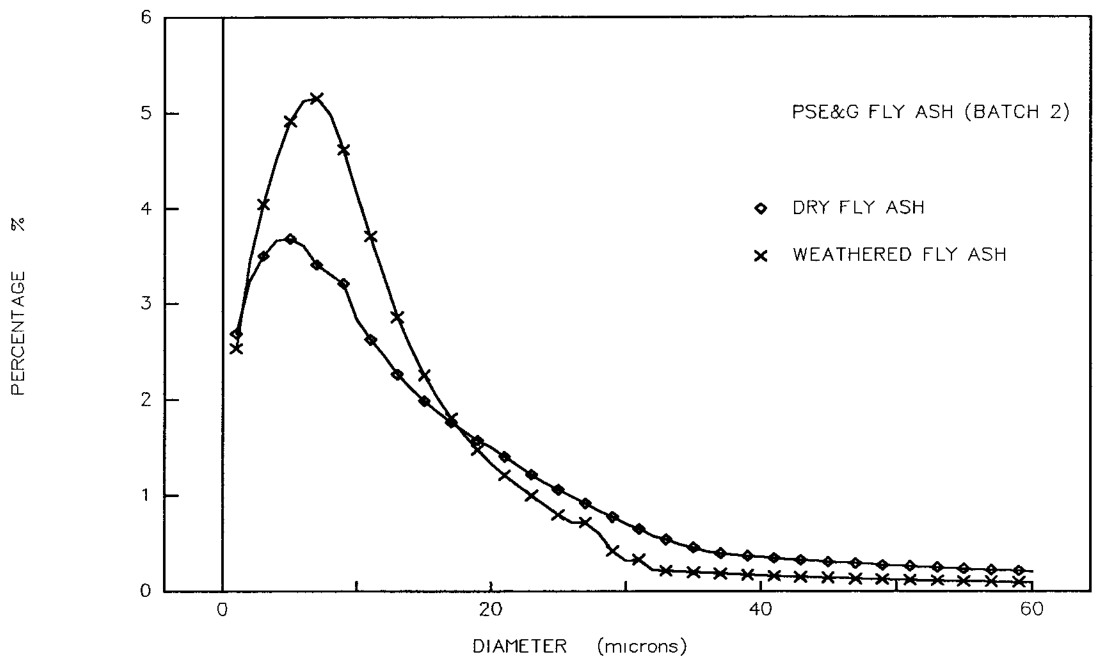

Fig. D.8 Percentage of particle sizes-PSE&G fly ash (batch 2).

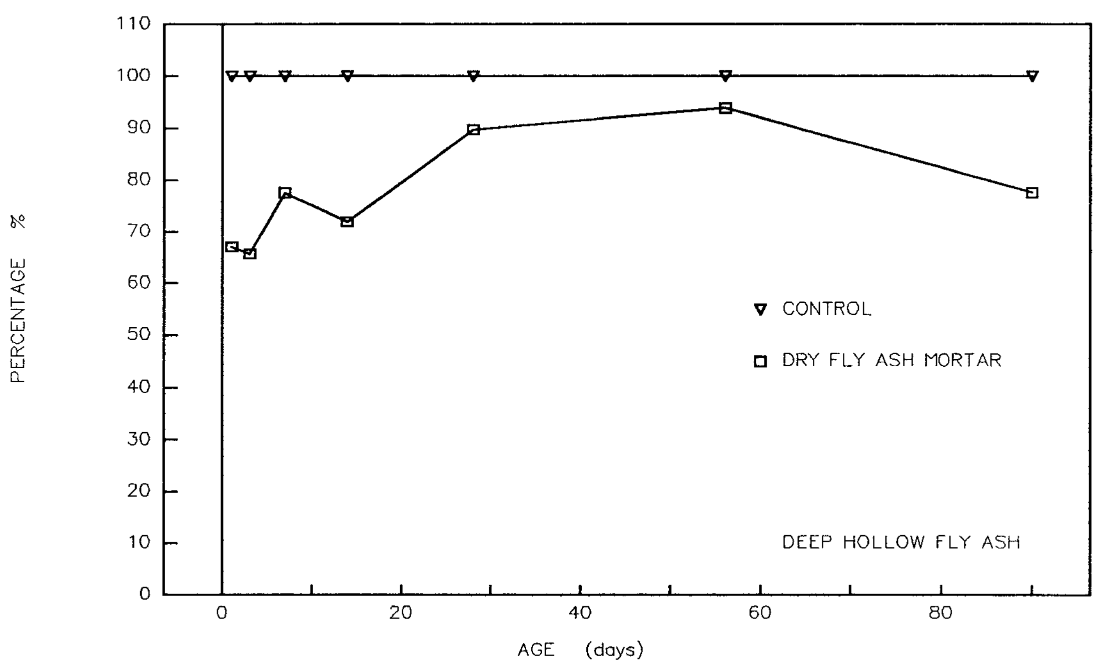

Fig. D.9 Compressive strength as a percentage of the control test strength. Deep Hollow fly ash mortar.

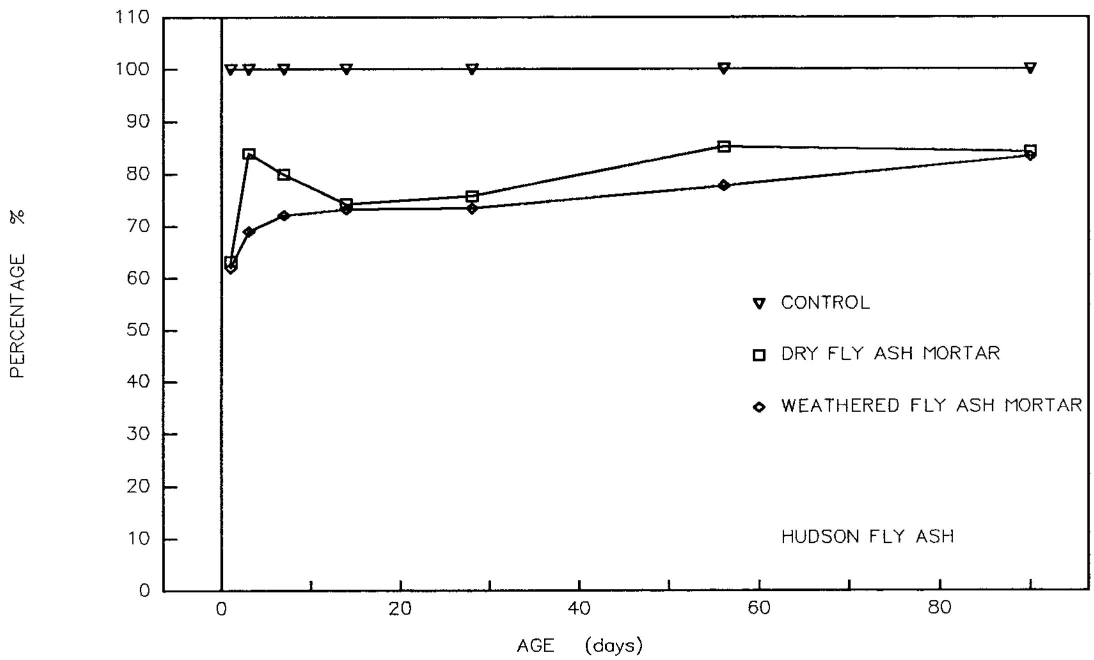

Fig. D.10 Compressive strength as a percentage of the control test strength. Hudson fly ash mortar.

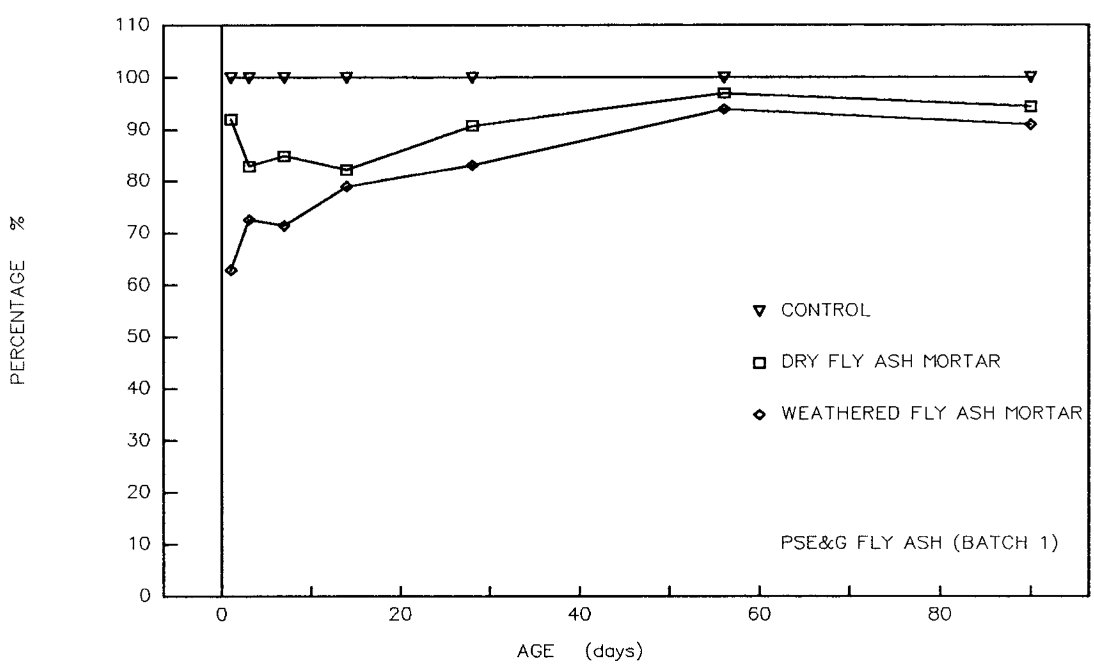

Fig. D.11 Compressive strength as a percentage of the control test strength. PSE&G fly ash mortar (batch 1).

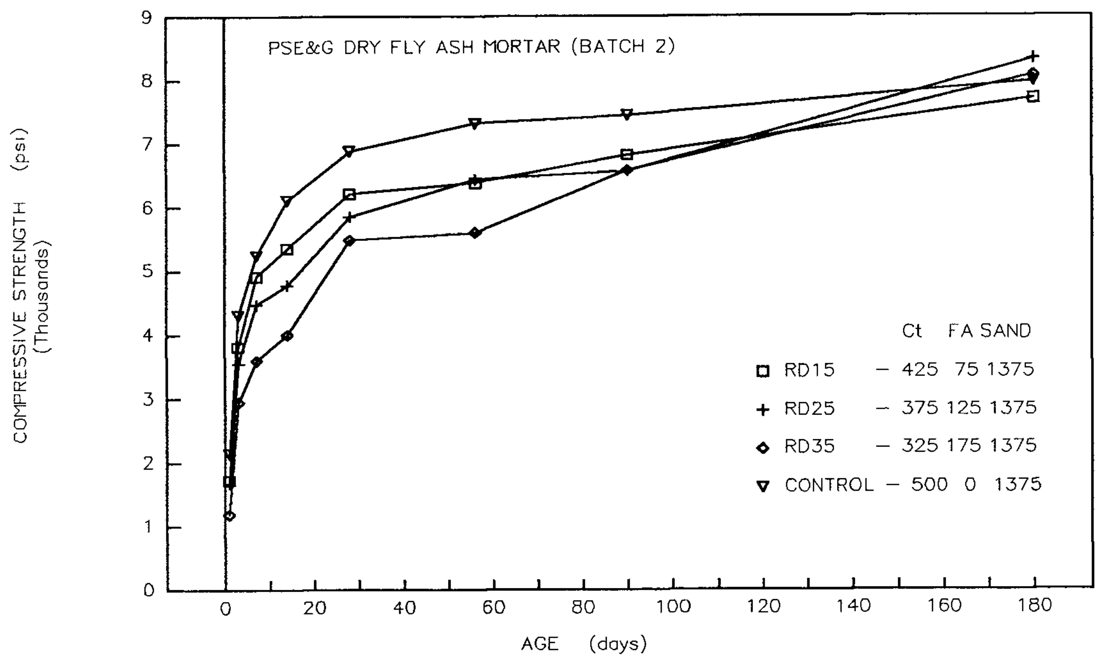

Fig. D.12 Compressive Strength of dry fly ash mortars. Test series 2 A

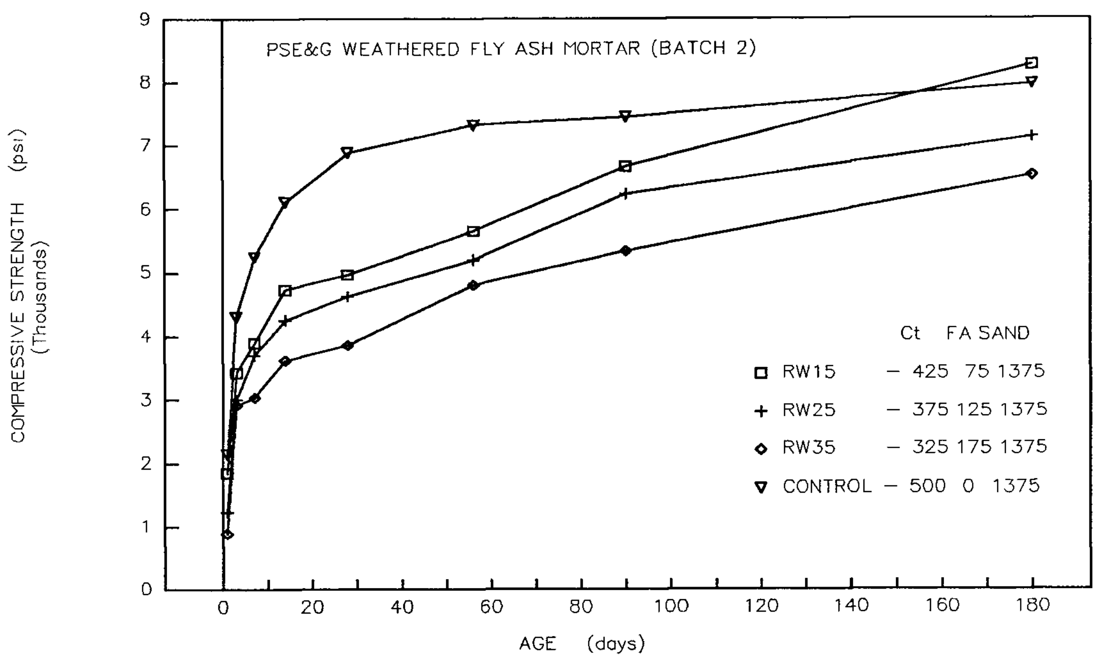

Fig. D.13 Compressive strength of weathered fly ash mortars. Test series 2 A

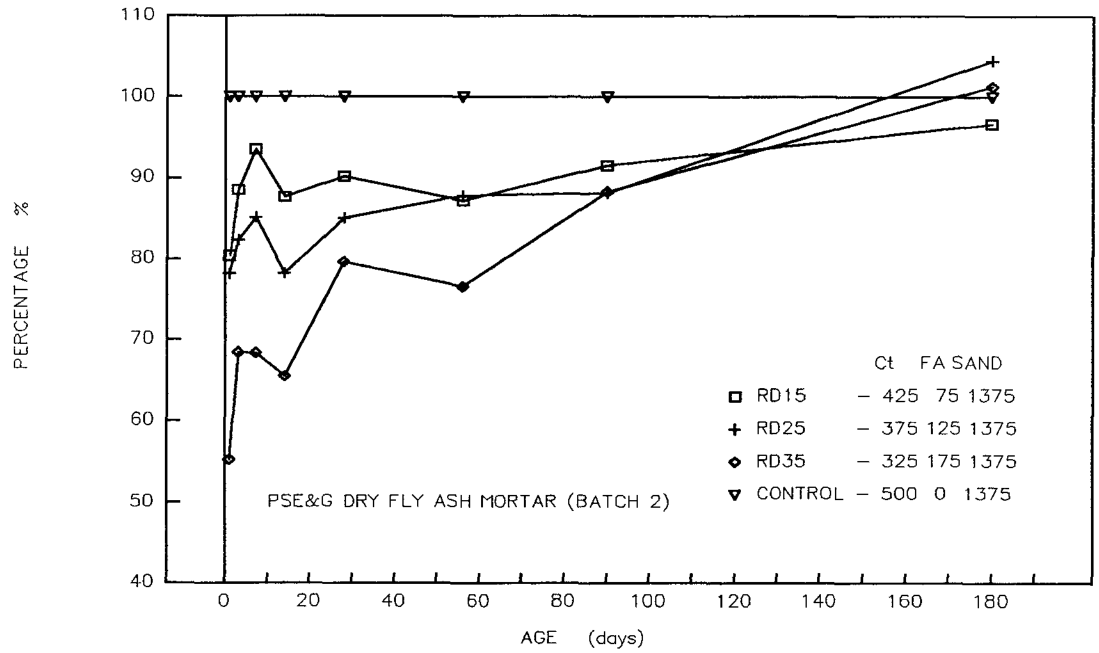

Fig. D.14 Compressive strength of dry fly ash mortars as a percentage of control test strength. Test series 2 A

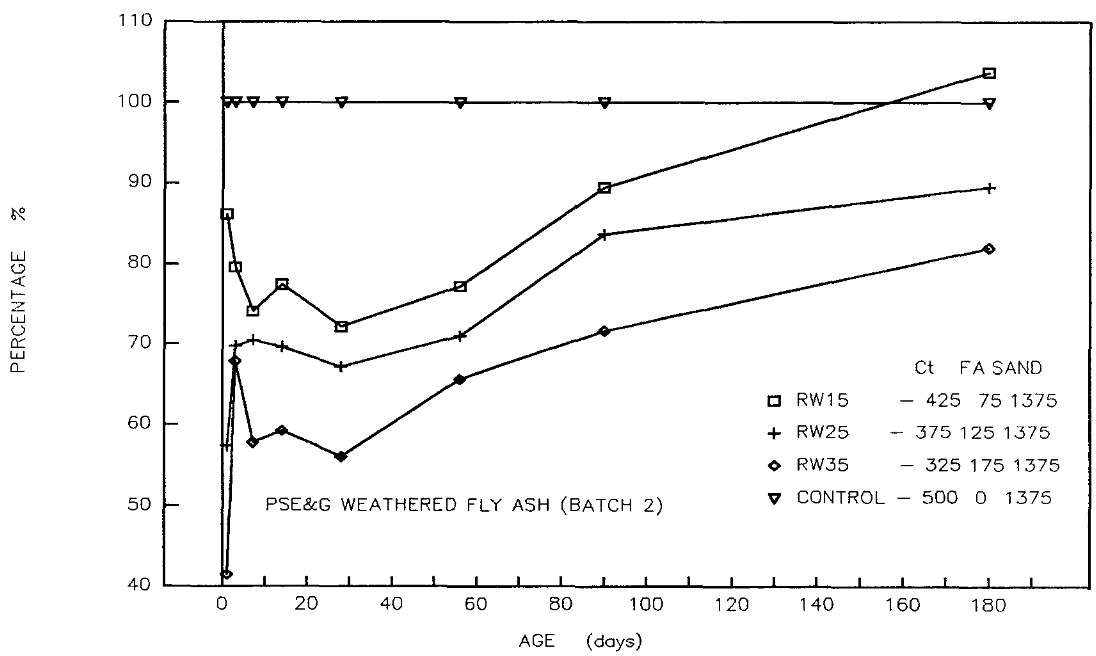

Fig. D.15 Compressive strength of weathered fly ash mortars as a percentage of control test strength. Test series 2 A

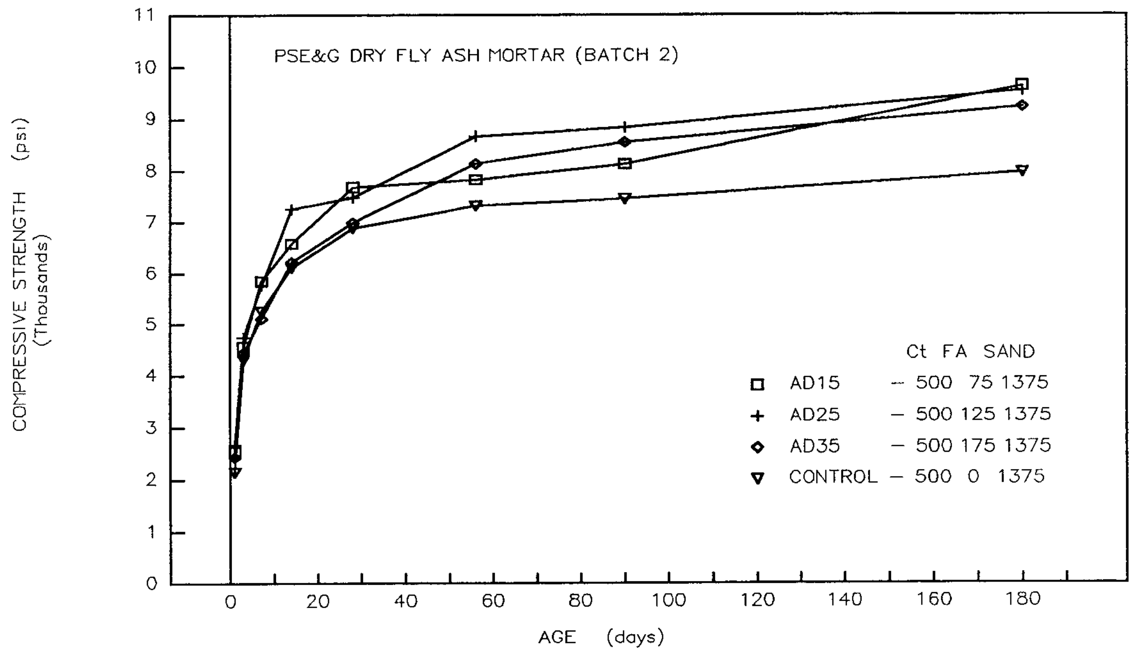

Fig. D.16 Compressive strength of dry fly ash mortars. Test series 2 B

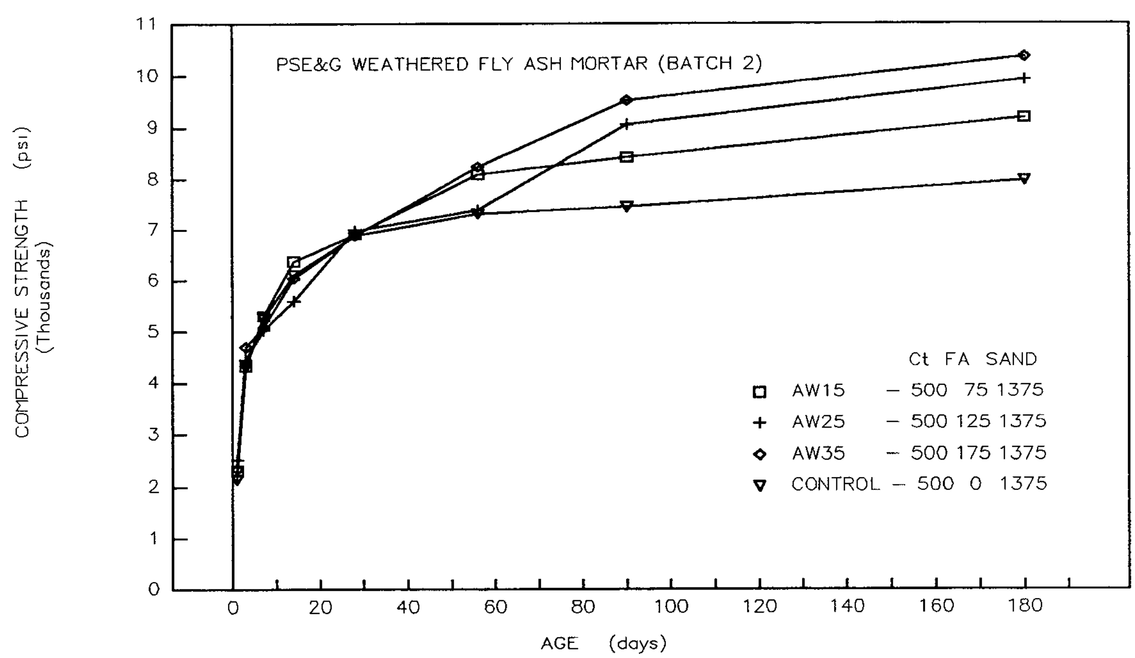

Fig. D.17 Compressive strength of weathered fly ash mortars. Test series 2 B

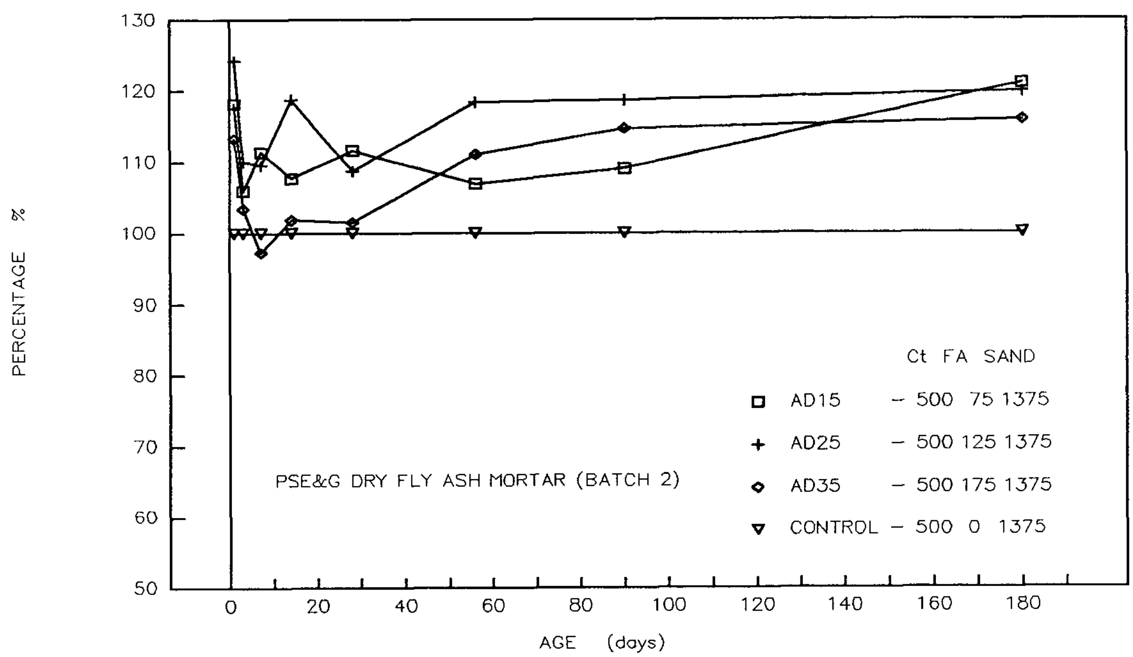

Fig. D.18 Compressive strength of dry fly ash mortars as a percentage of control test strength. Test series 2 B

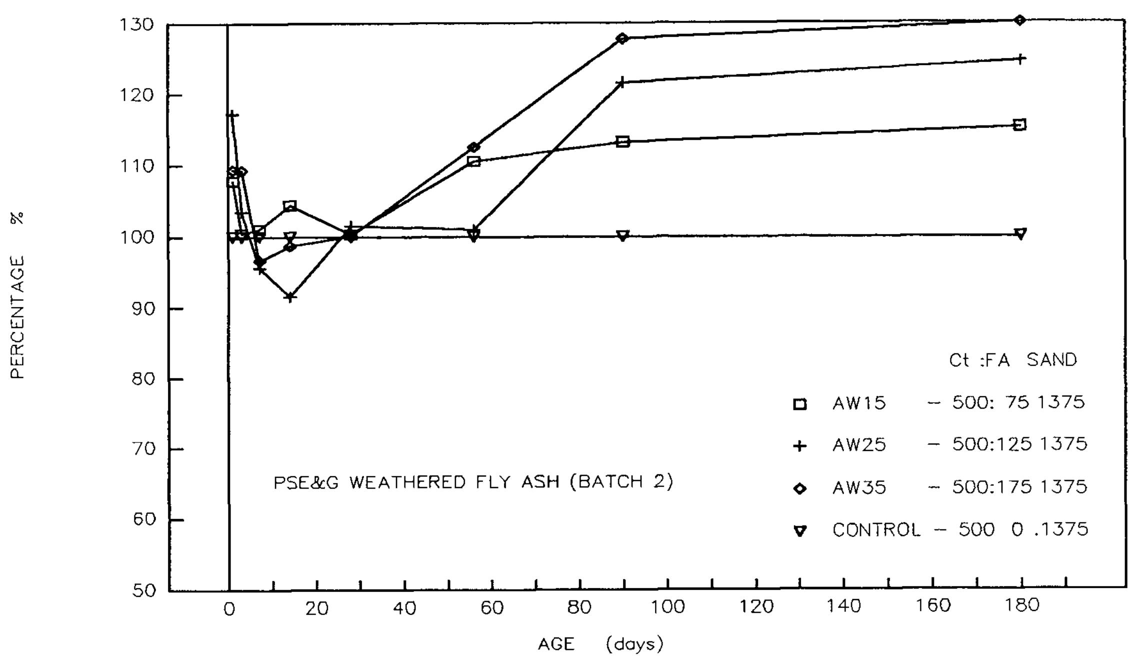

Fig. D.19 Compressive strength of weathered fly ash mortars as a percentage of control test strength. Test series 2 B

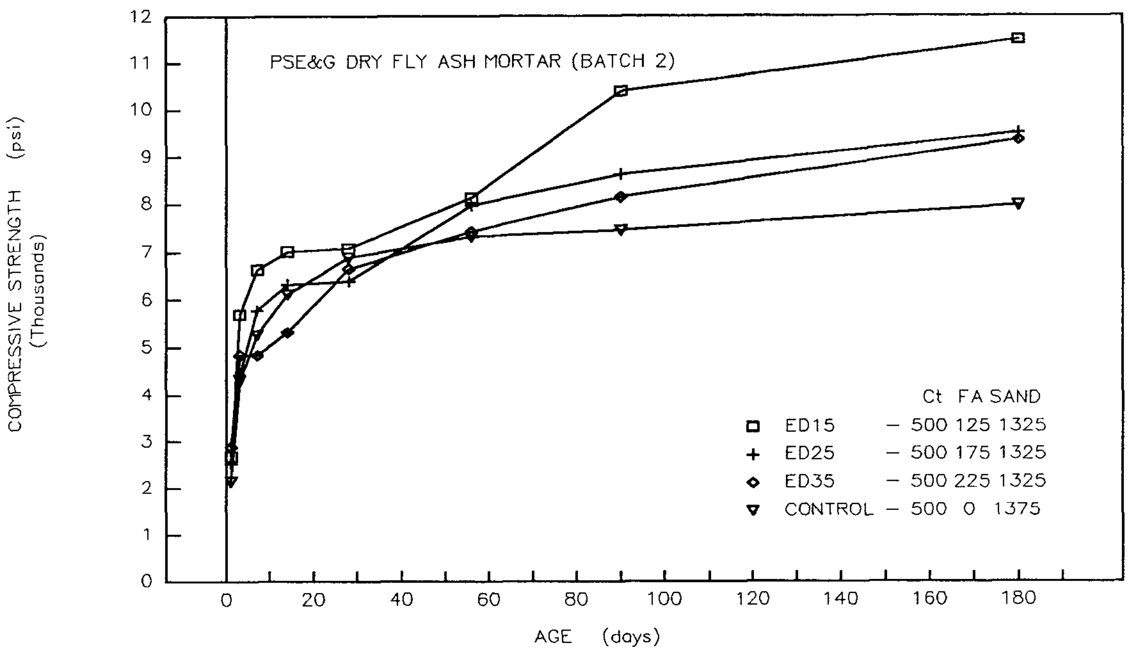

Fig. D.20 Compressive strength of dry fly ash mortars. Test series 2 C

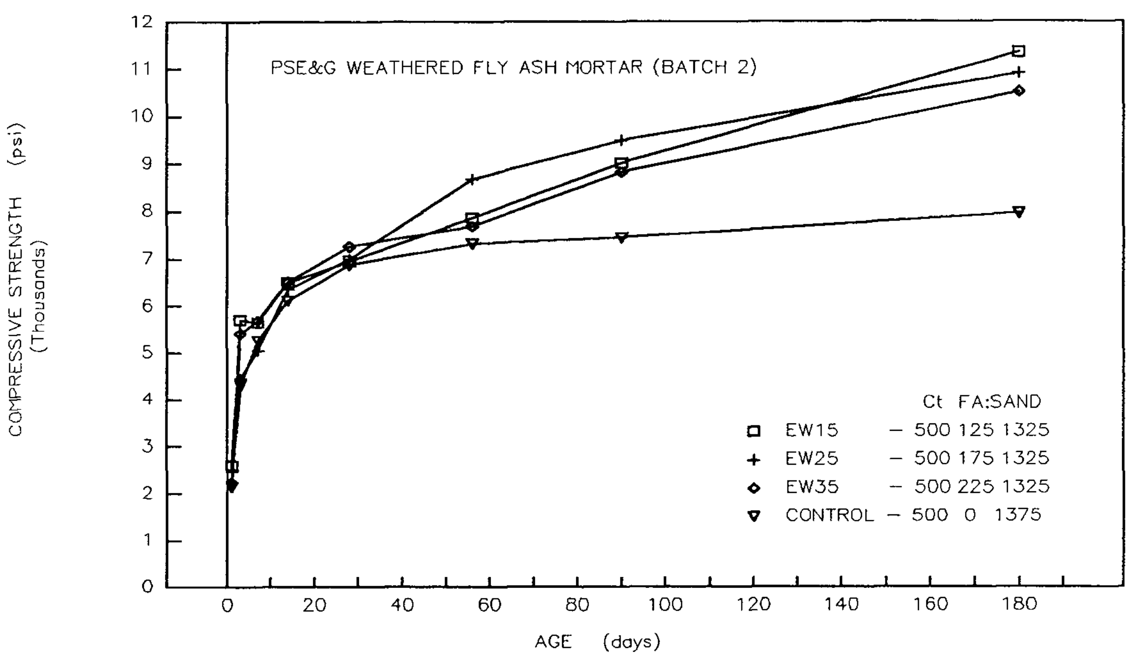

Fig. D.21 Compressive strength of weathered fly ash mortars. Test series 2 C

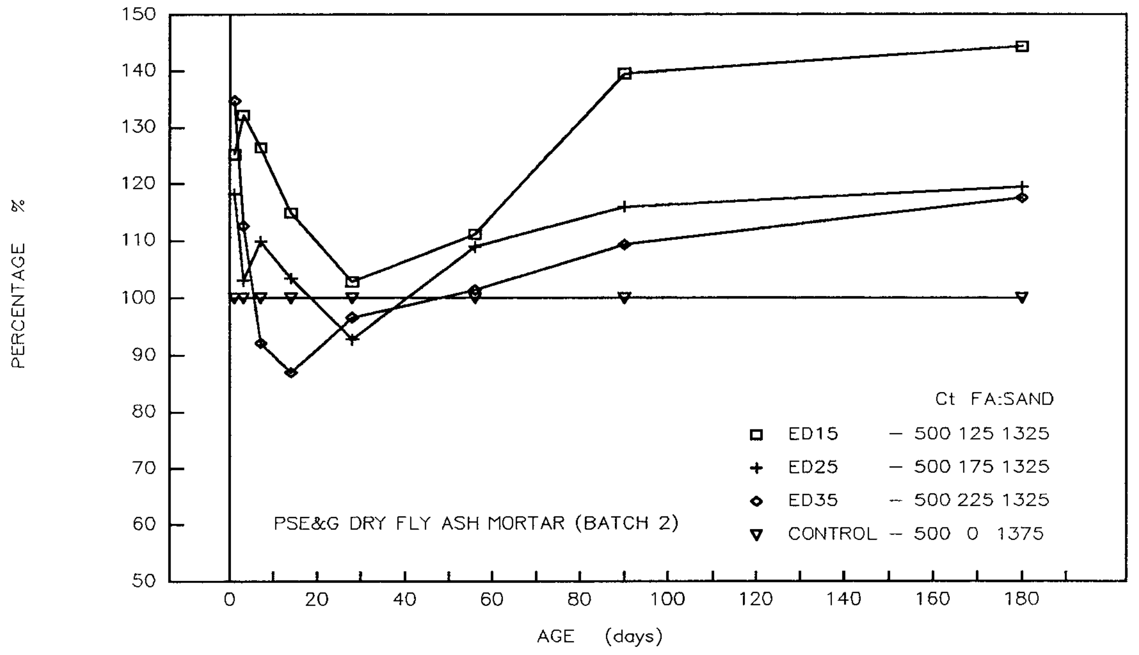

Fig. D.22 Compressive strength of dry fly ash mortars as a percentage of control test strength. Test series 2 C

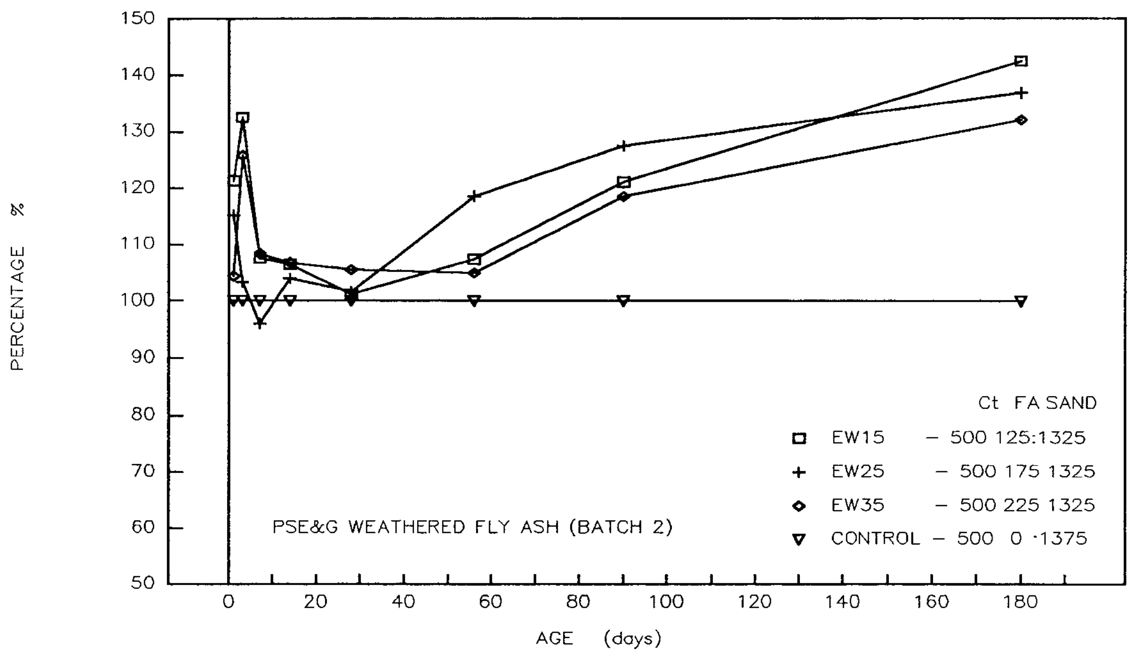

Fig. D.23 Compressive strength of weathered fly ash mortars as a percentage of control test strength. Test series 2 C

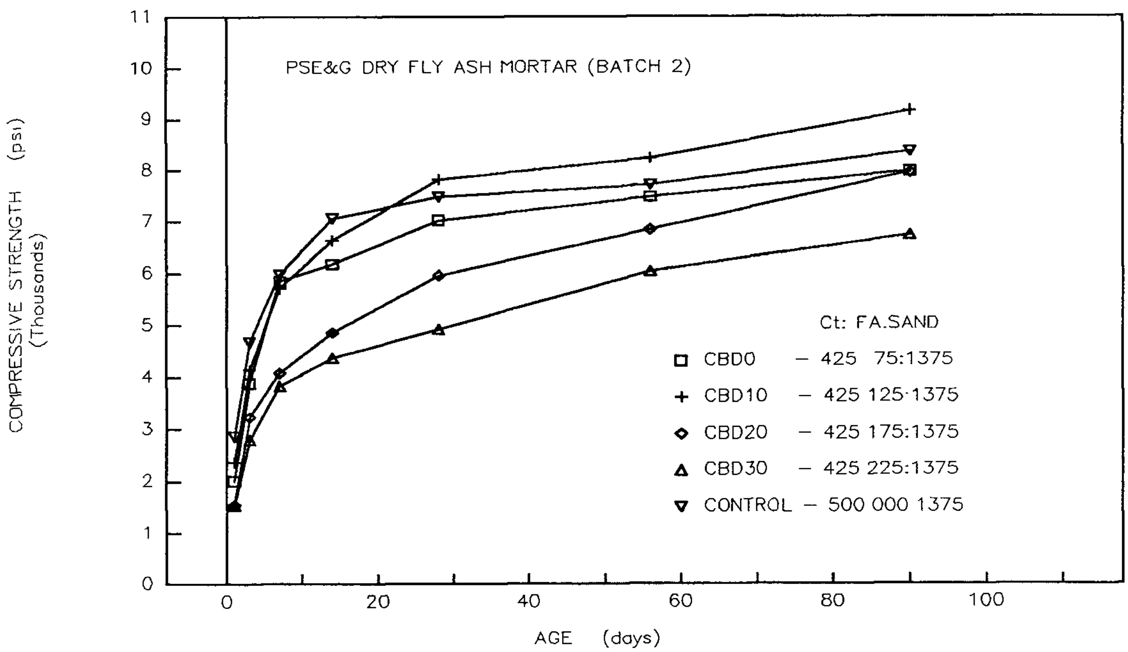

Fig. D.24 Compressive strength of dry fly ash mortars. Test series 2 D (i)

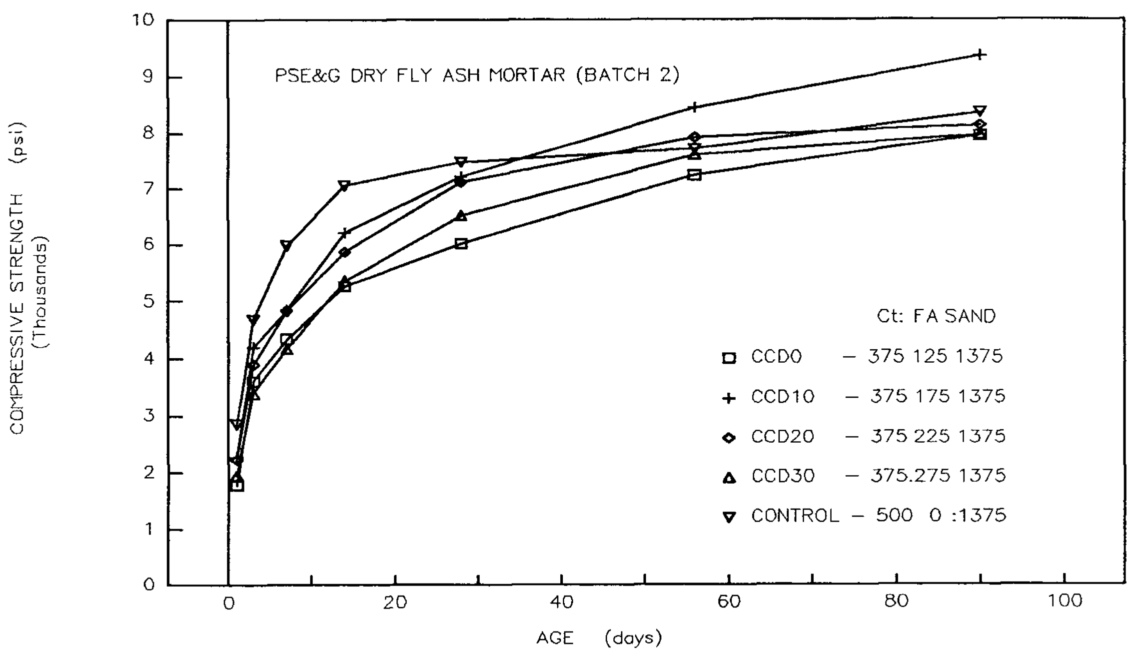

Fig. D.25 Compressive strength of dry fly ash mortars. Test series 2 D (ii)

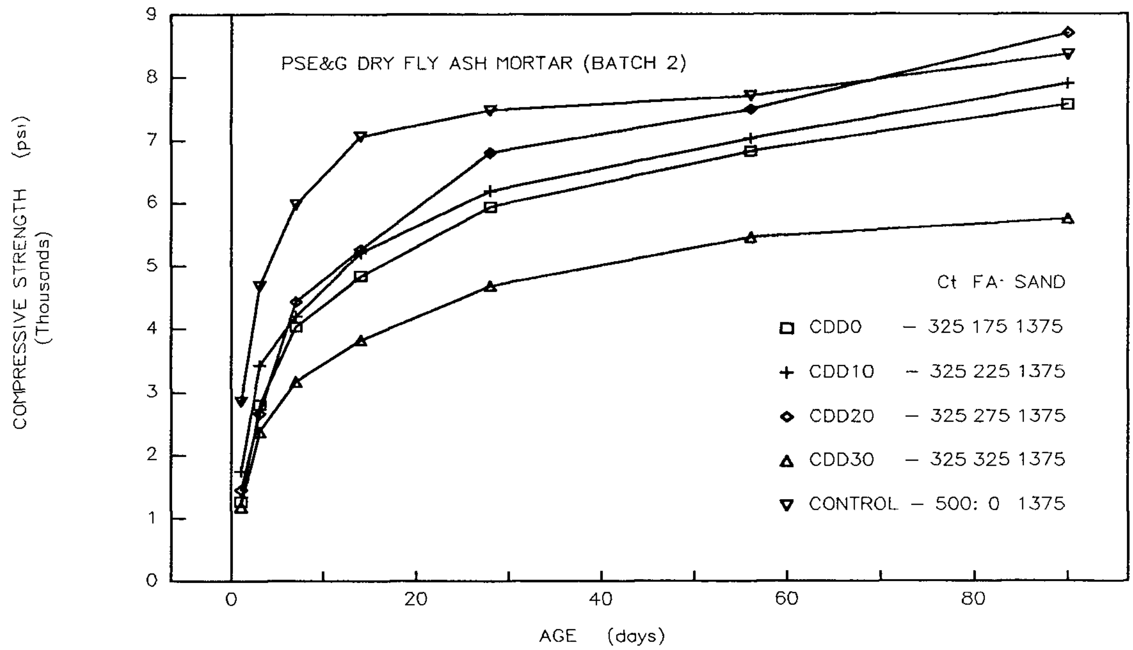

Fig. D.26 Compressive strength of dry fly ash mortars. Test series 2 D (iii)

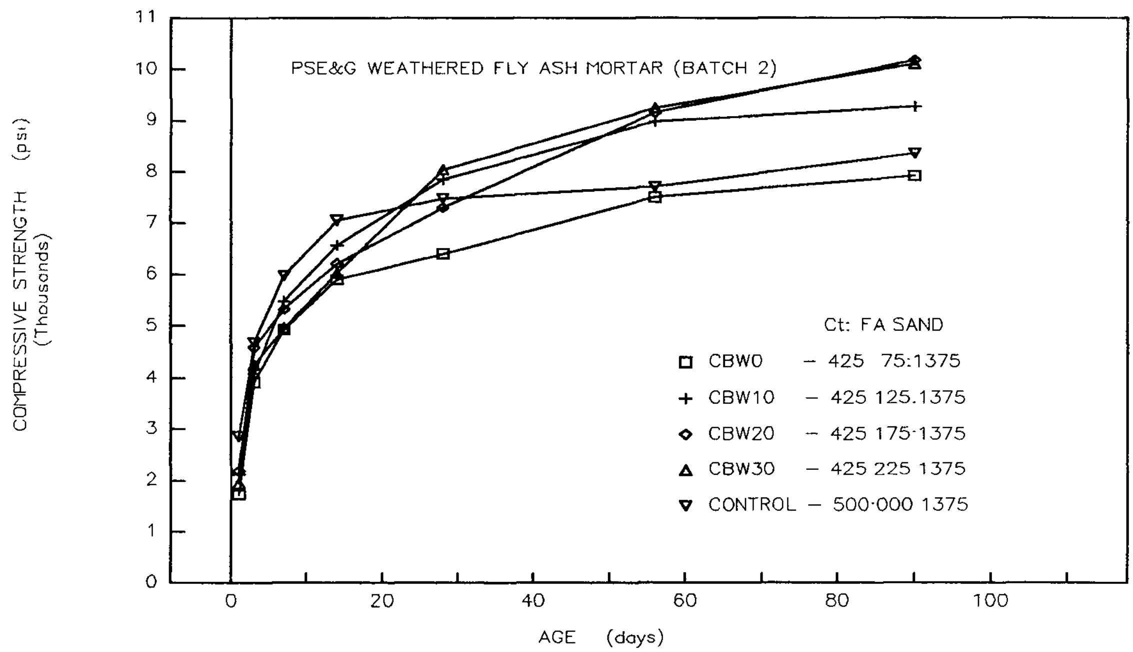

Fig. D.27 Compressive strength of weathered fly ash mortars. Test series 2 D (i)

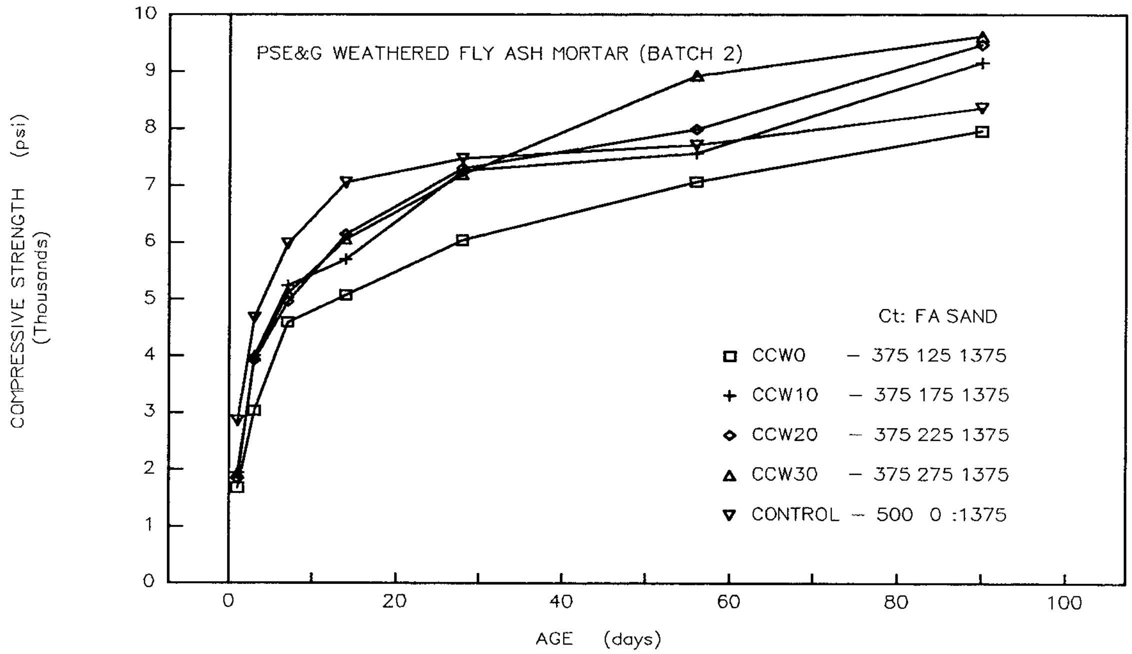

Fig. D.28 Compressive strength of weathered fly ash mortars. Test series 2 D (ii)

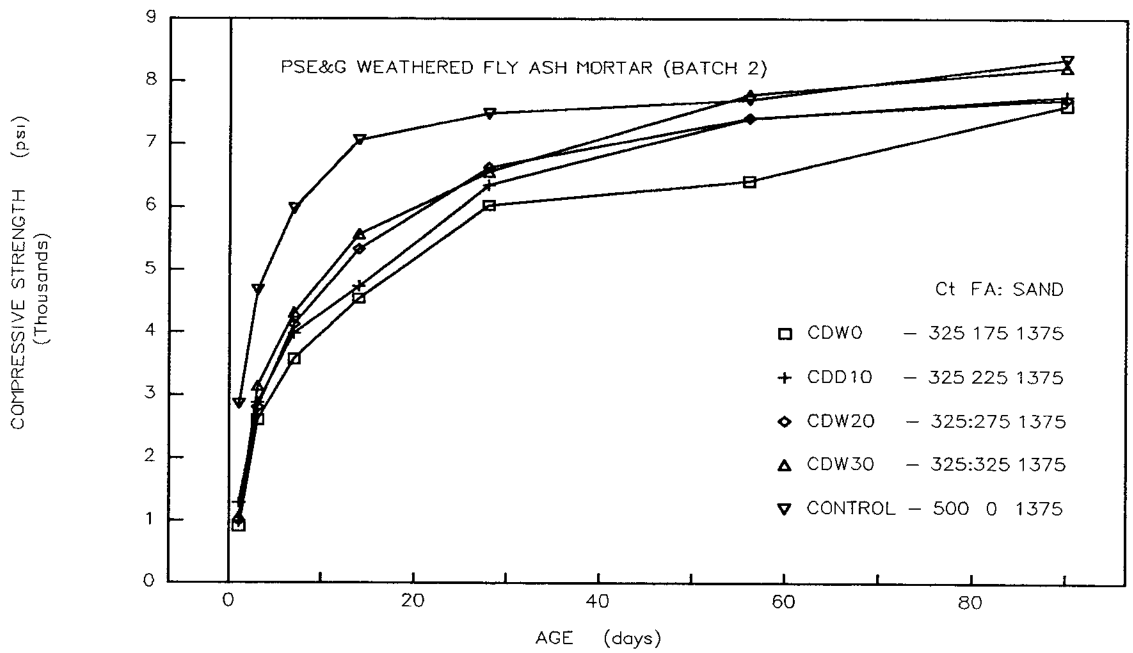

Fig. D.29 Compressive strength of weathered fly ash mortars.
Test series 2 D (iii)

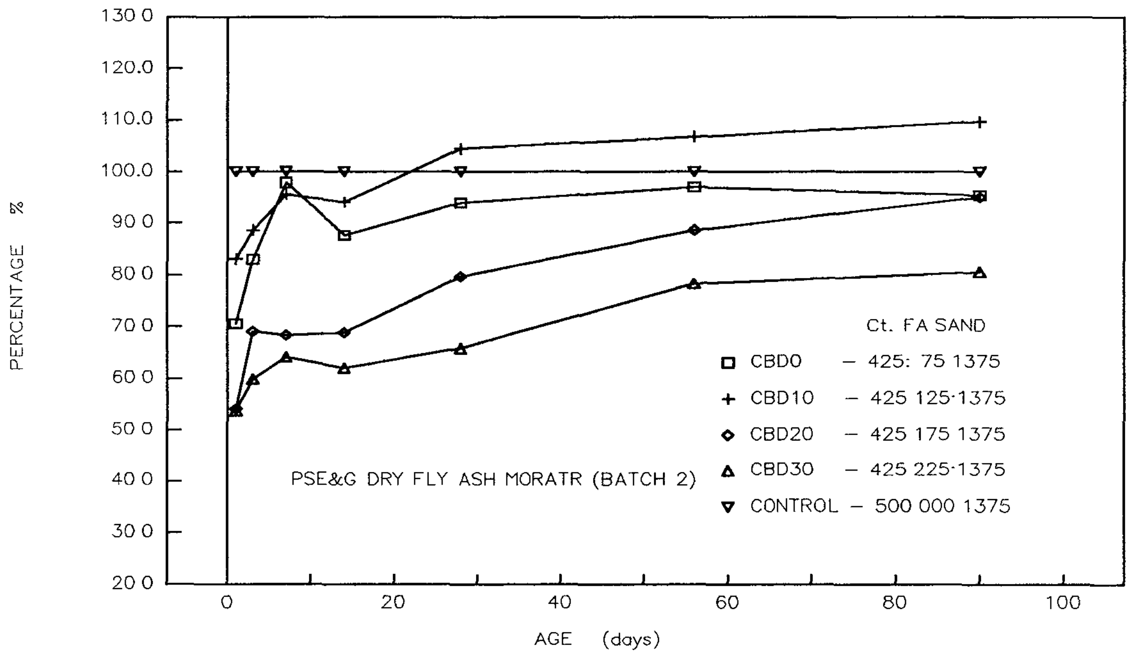

Fig. D.30 Compressive strength of dry fly ash mortars as a percentage of control test strength. Test series 2 D (i)

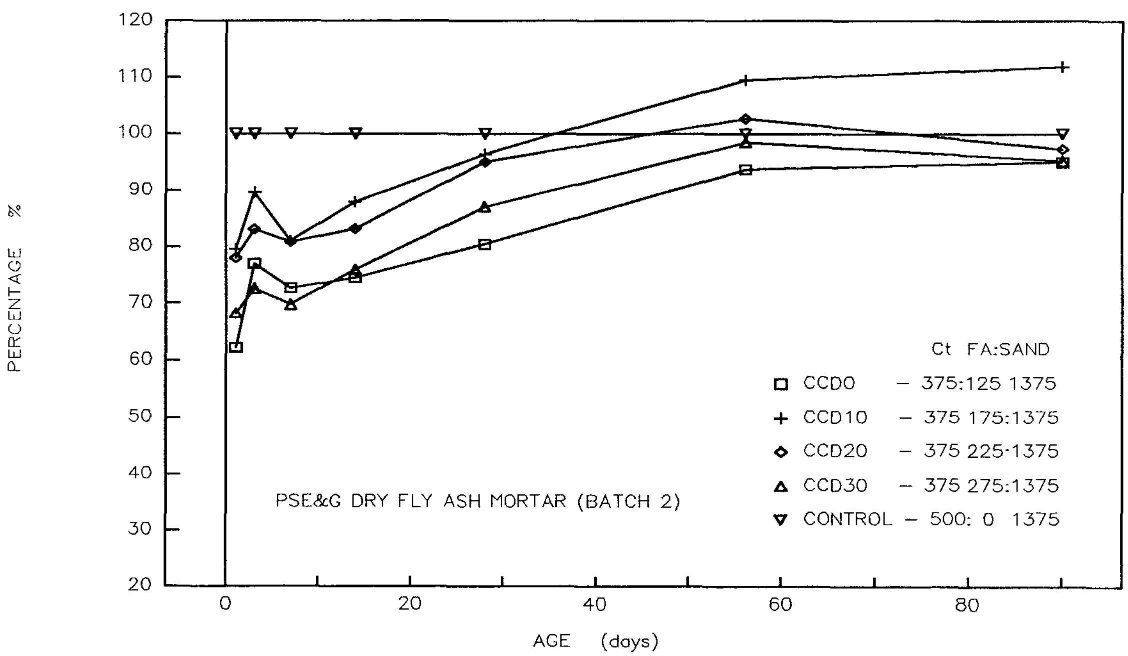

Fig. D.31 Compressive strength of dry fly ash mortars as a percentage of control test strength. Test series 2 D (ii)

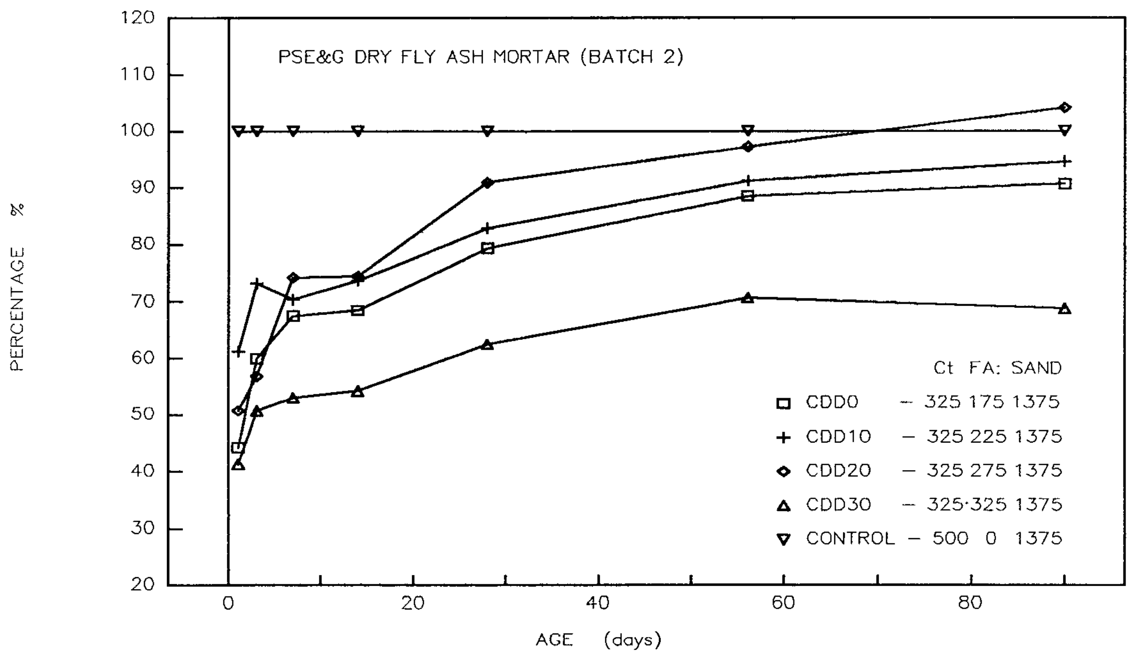

Fig. D.32 Compressive strength of dry fly ash mortars as a percentage of control test strength. Test series 2 D (iii)

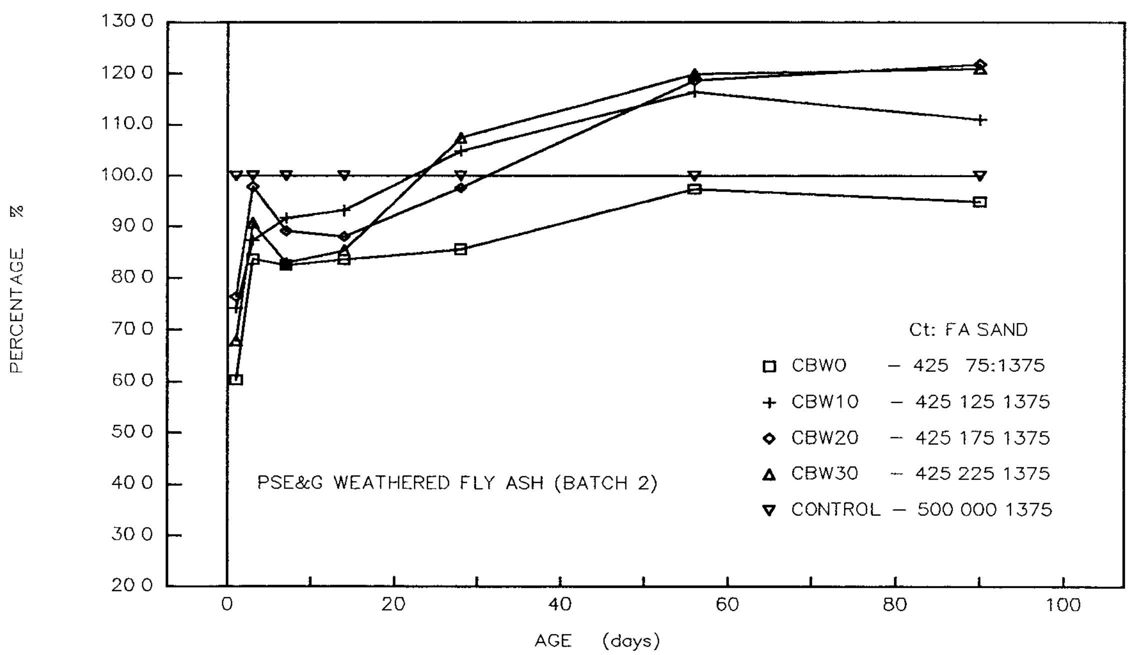

Fig. D.33 Compressive strength of weathered fly ash mortars as a percentage of control test strength. Test series 2 D (i)

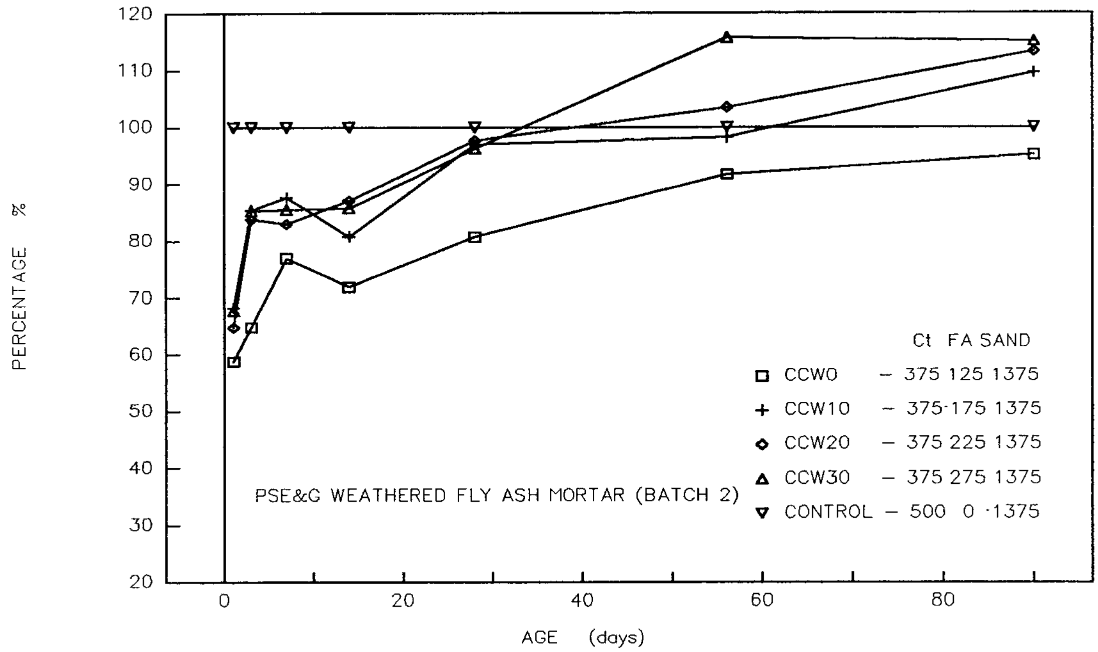

Fig. D.34 Compressive strength of weathered fly ash mortars as a percentage of control test strength. Test series 2 D (ii)

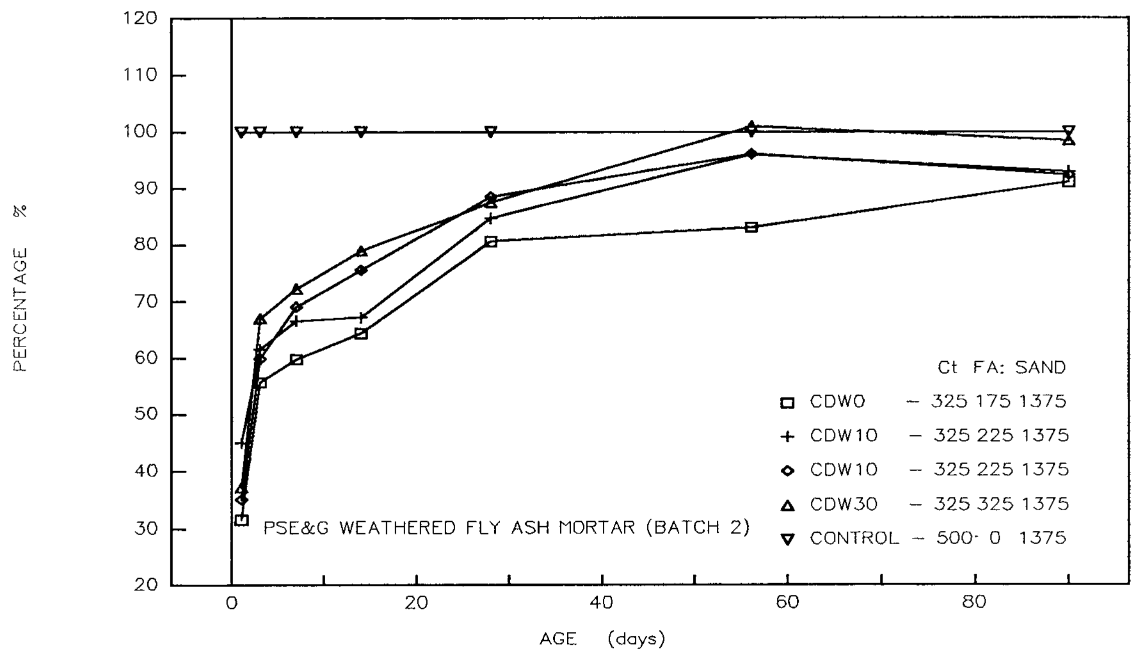

Fig. D.35 Compressive strength of weathered fly ash mortars as a percentage of control test strength. Test series 2 D (iii)

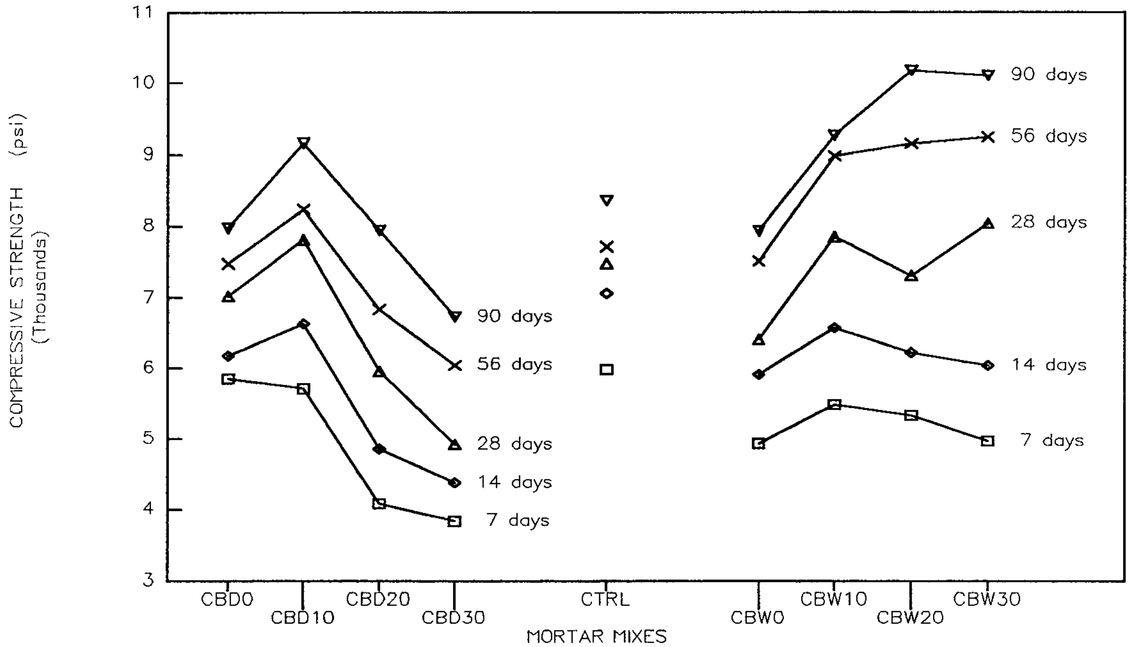

Fig. D.36 Compressive strength of dry and weathered fly ash mortars. Test series 2D (i)

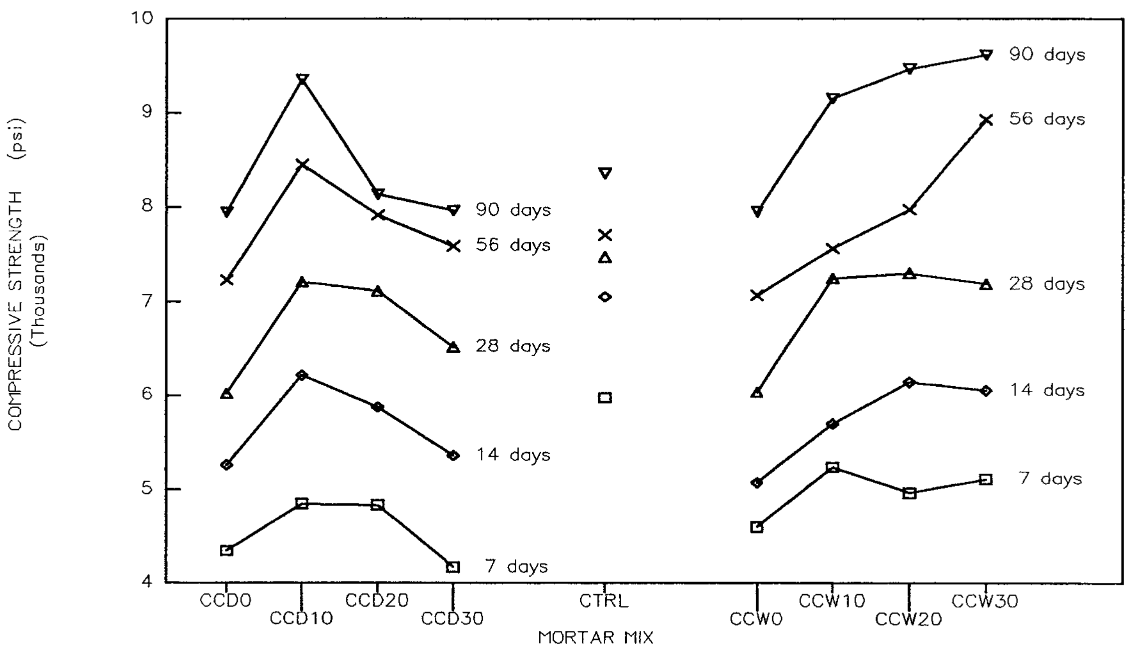

Fig. D.37 Compressive strength of dry and weathered fly ash mortars. Test series 2 D (ii)

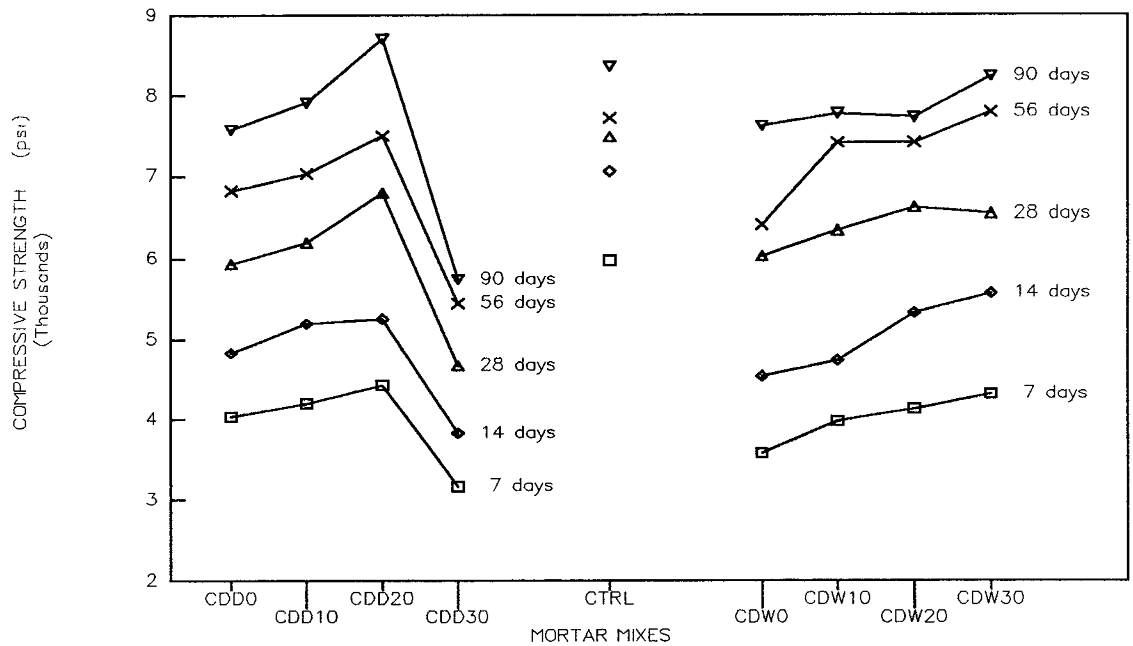

Fig. D.38 Compressive strength of dry and weathered fly ash mortars. Test series 2 D (iii)

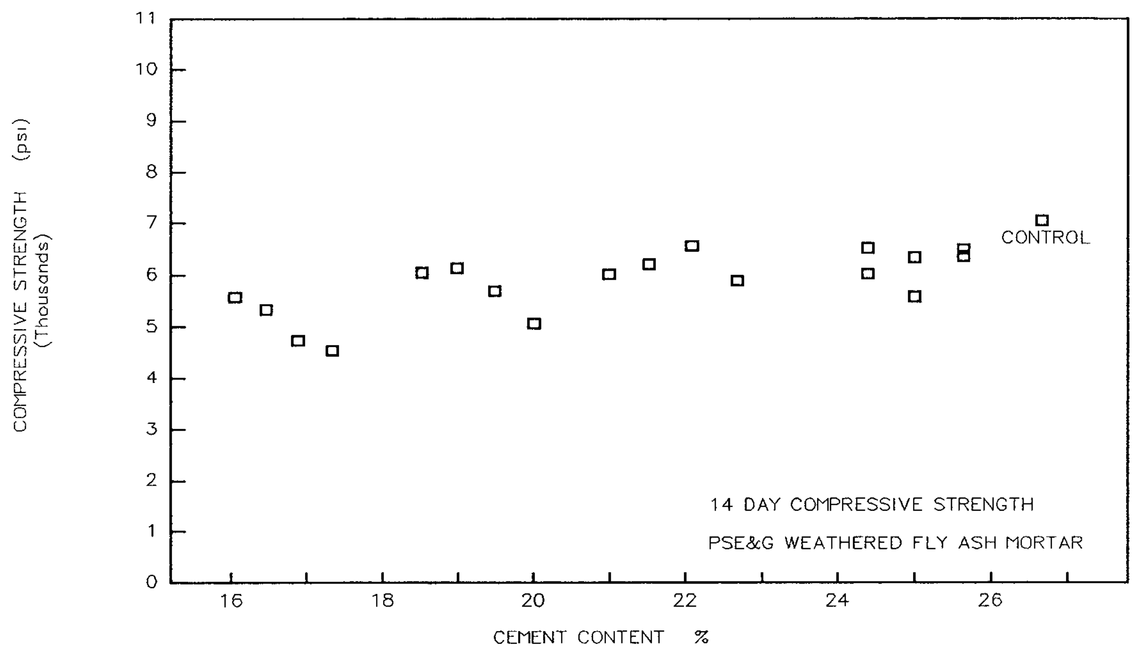

Fig. D.39 Compressive strength at 14 days age and cement content of the fly ash mortars.

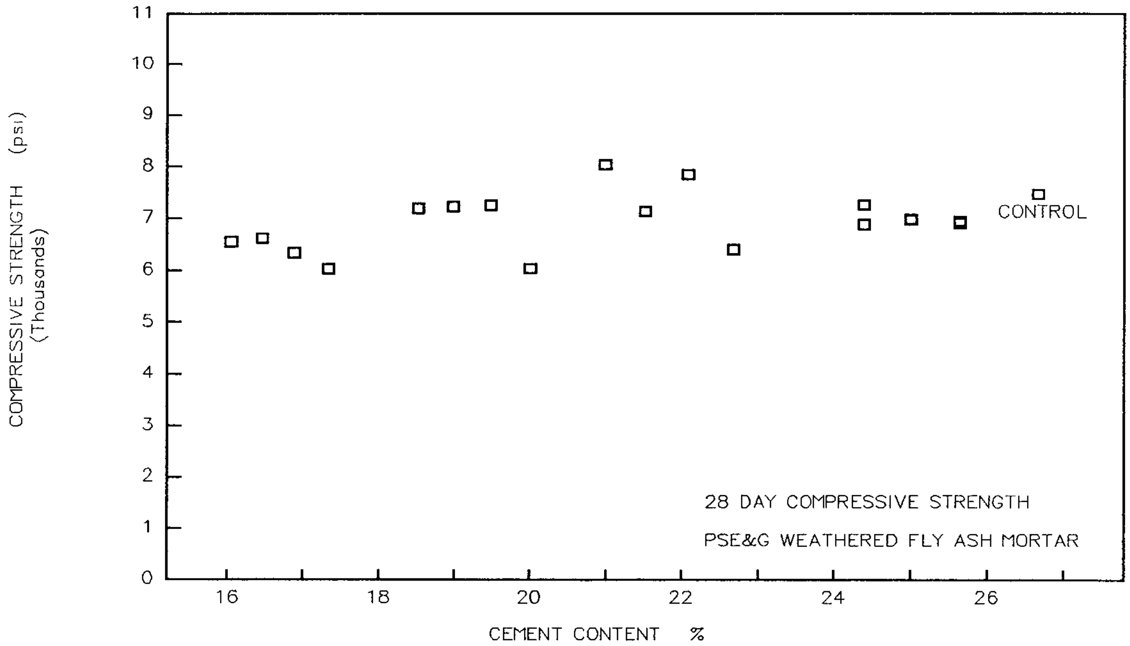

Fig. D.40 Compressive strength at 28 days age and cement content of the fly ash mortars.

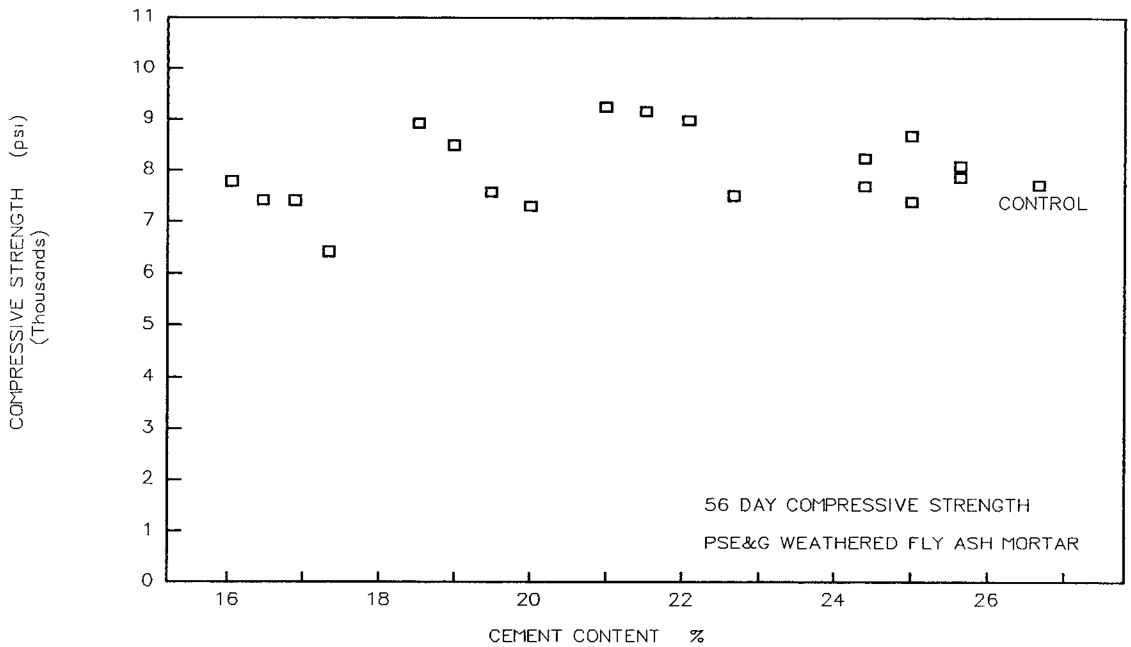

Fig. D.41 Compressive strength at 56 days age and cement content of the fly ash mortars.

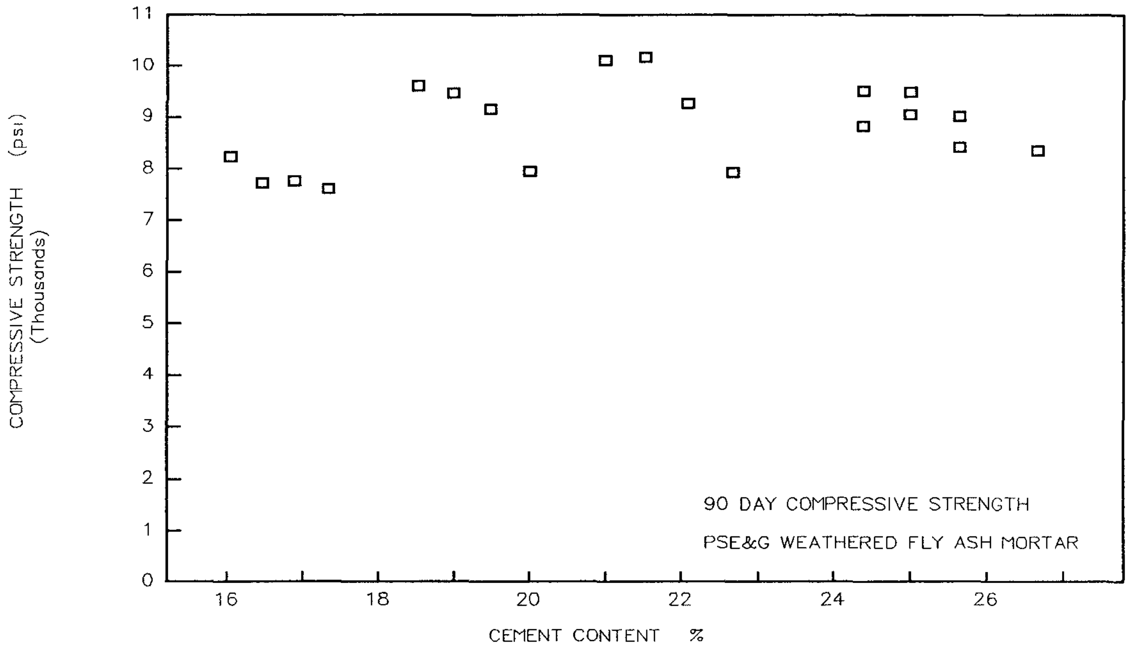

Fig. D.42 Compressive strength at 90 days age and cement content of the fly ash mortars.

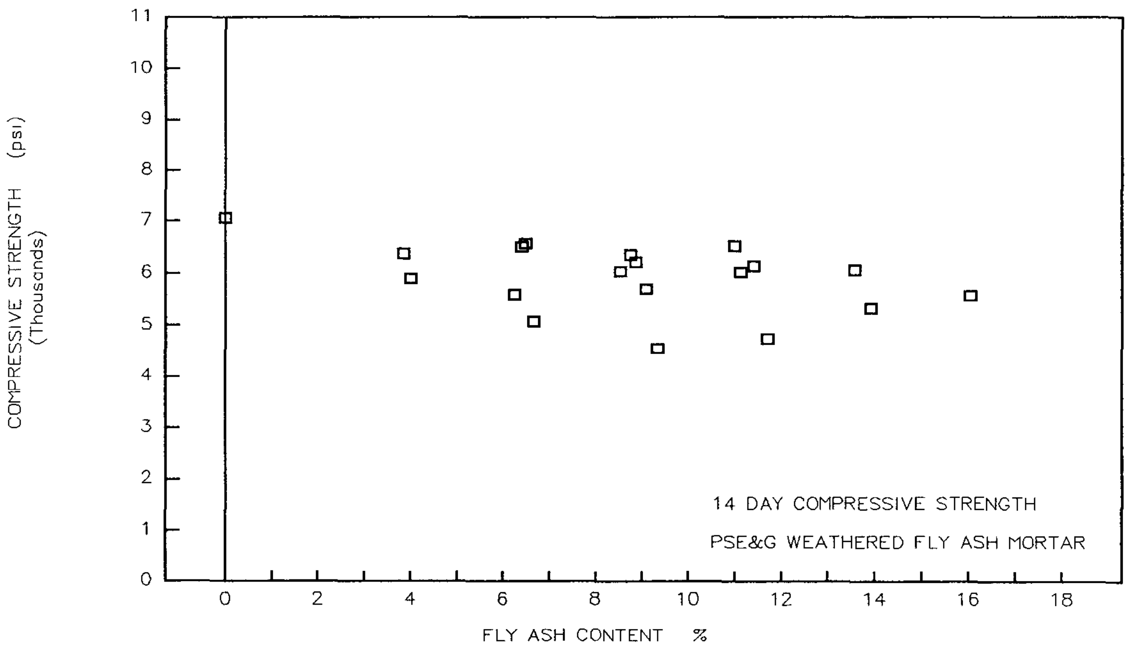

Fig. D.43 Compressive strength at 14 days age and fly ash content of the fly ash mortars.

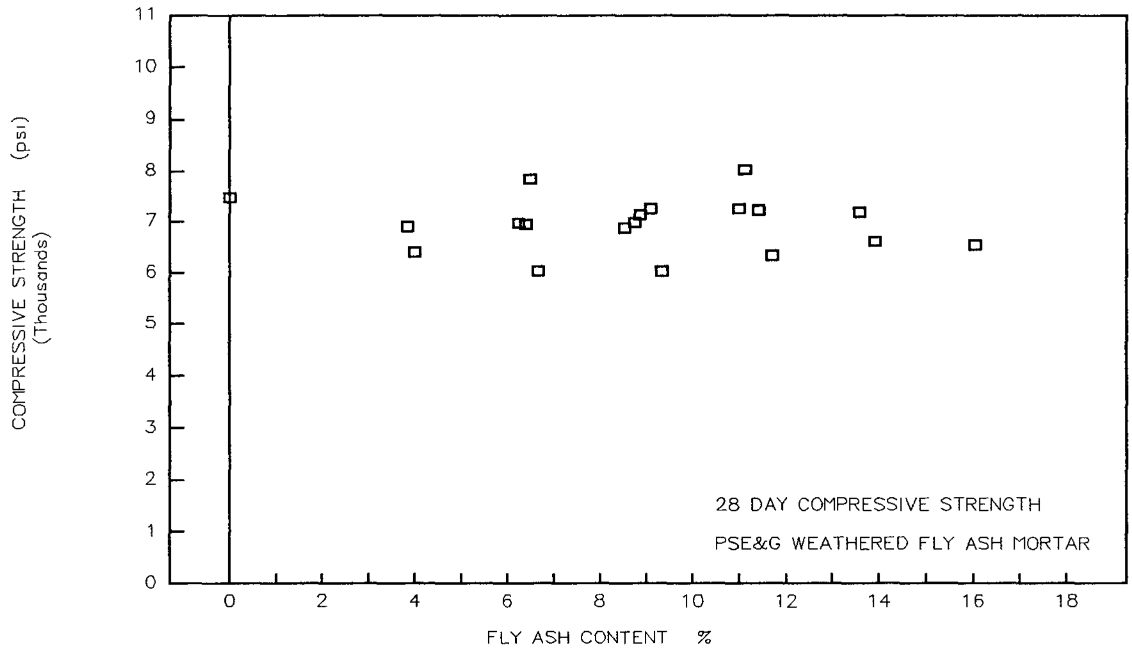

Fig. D.44 Compressive strength at 28 days age and fly ash content of the fly ash mortars.

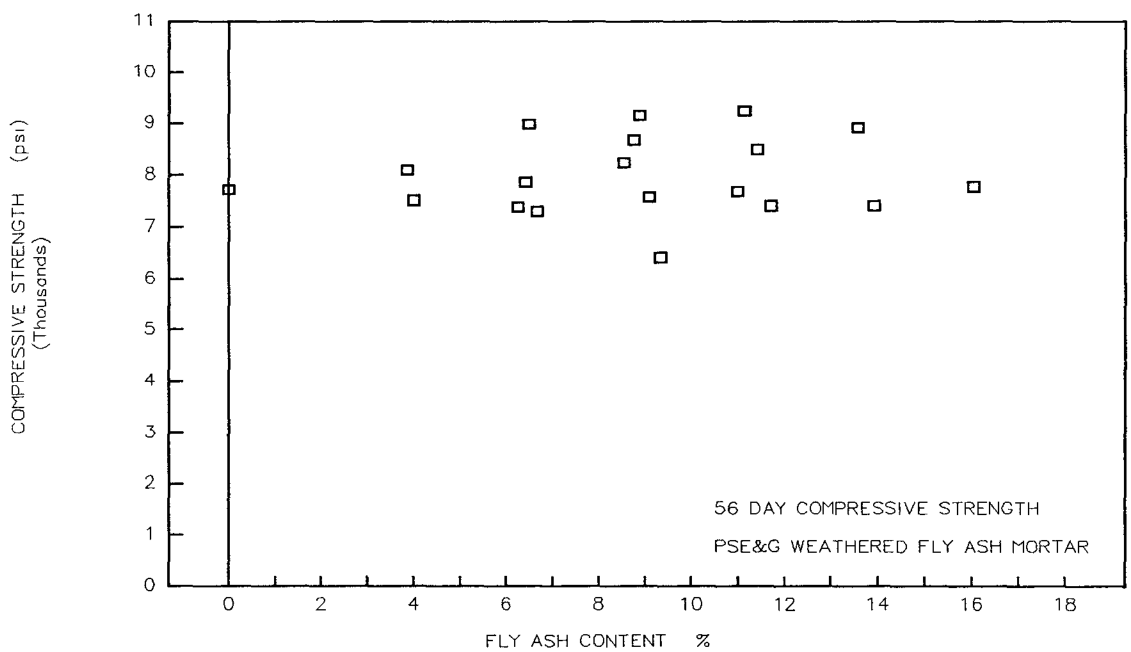

Fig. D.45 Compressive strength at 56 days age and fly ash content of the fly ash mortars.

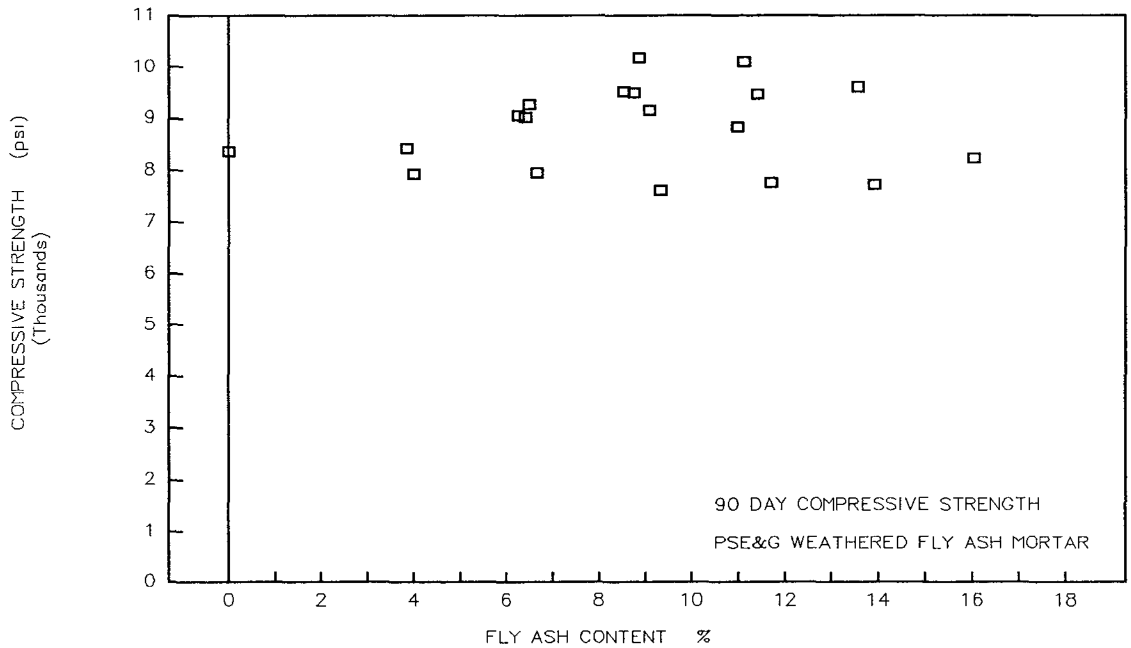

Fig. D.46 Compressive strength at 90 days age and fly ash content of the fly ash mortars.

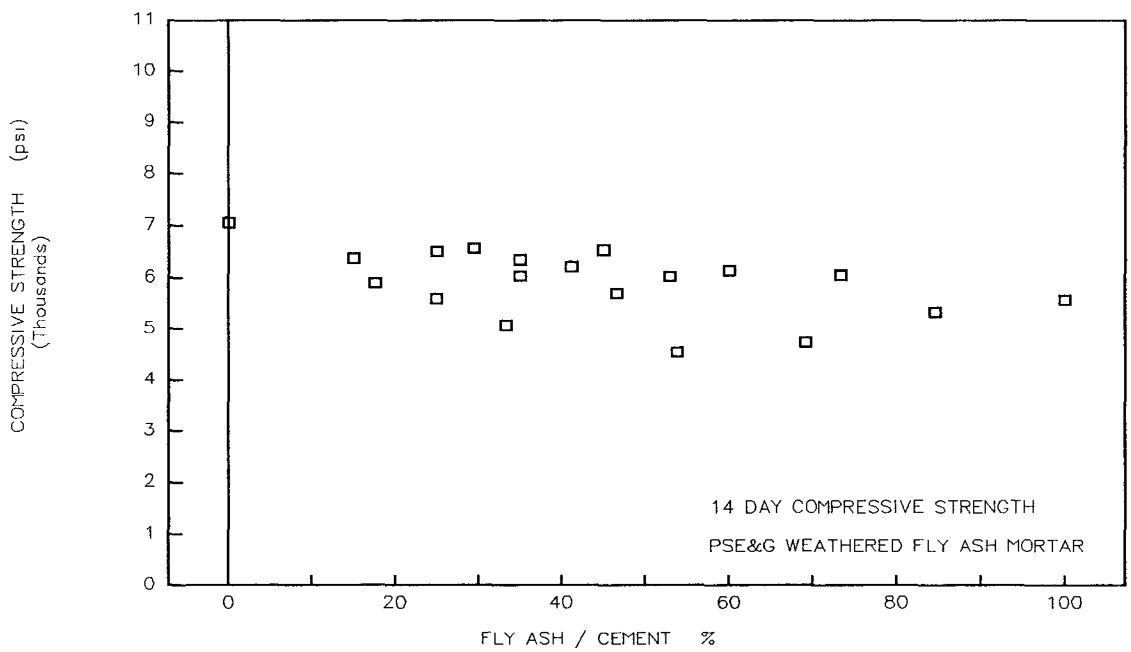

Fig. D.47 Compressive strength at 14 days age and fly ash/cement ratio

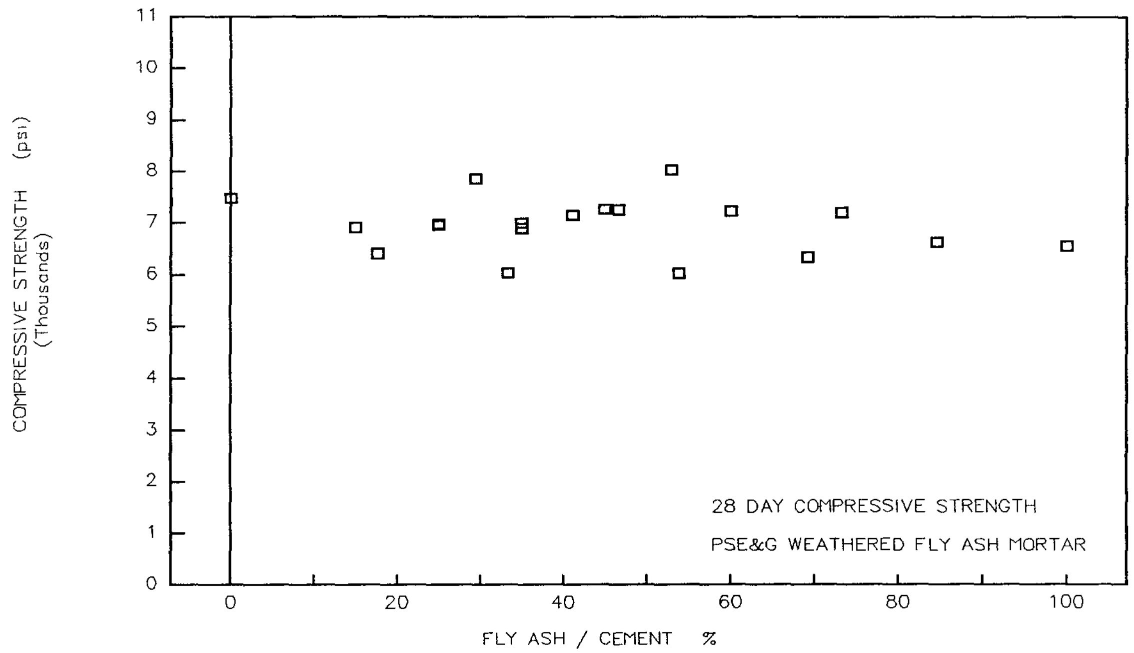

Fig. D.48 Compressive strength at 28 days age and fly ash/cement ratio.

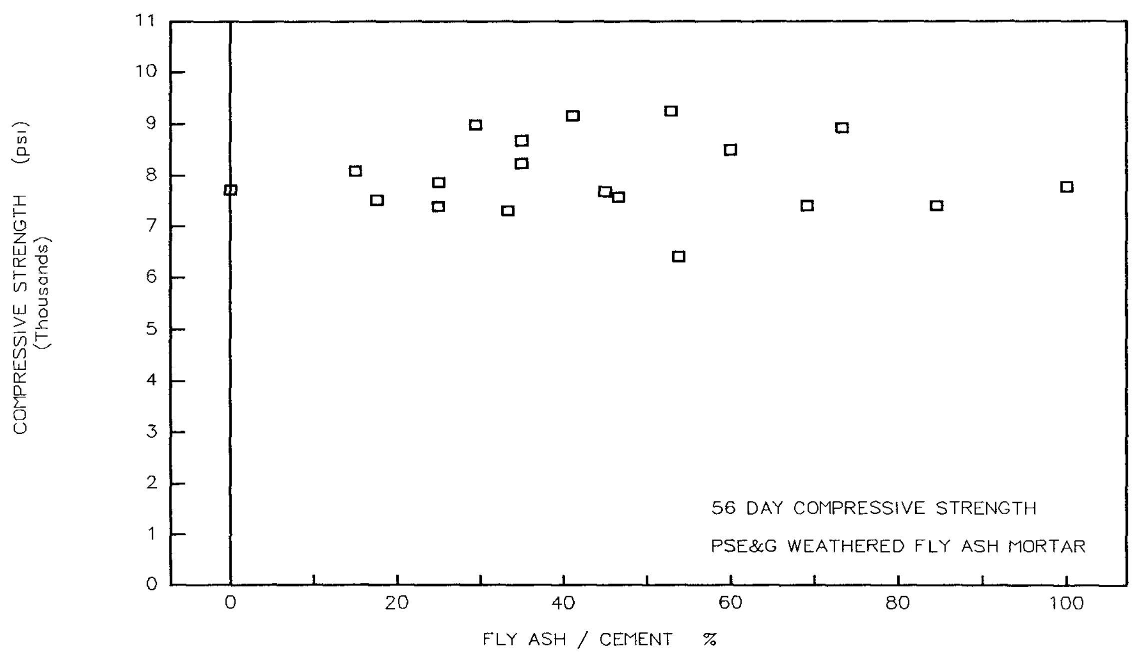

Fig. D.49 Compressive strength at 56 days age with fly ash/cement ratio.

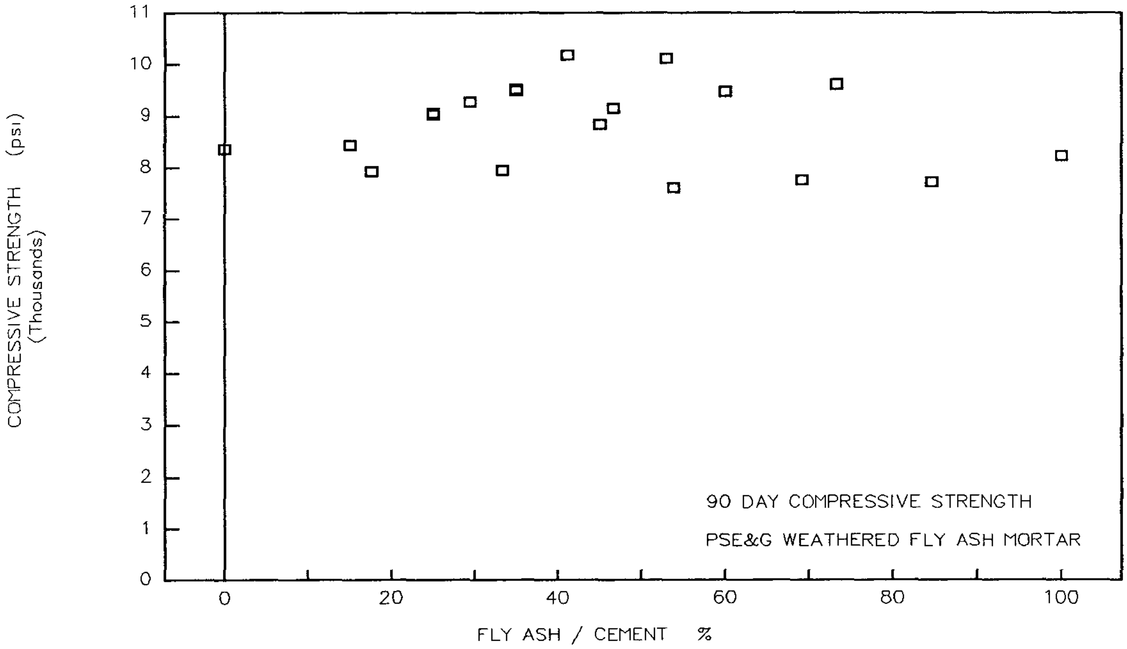

Fig. D.50 Compressive strength at 90 days age with fly ash/cement ratio.

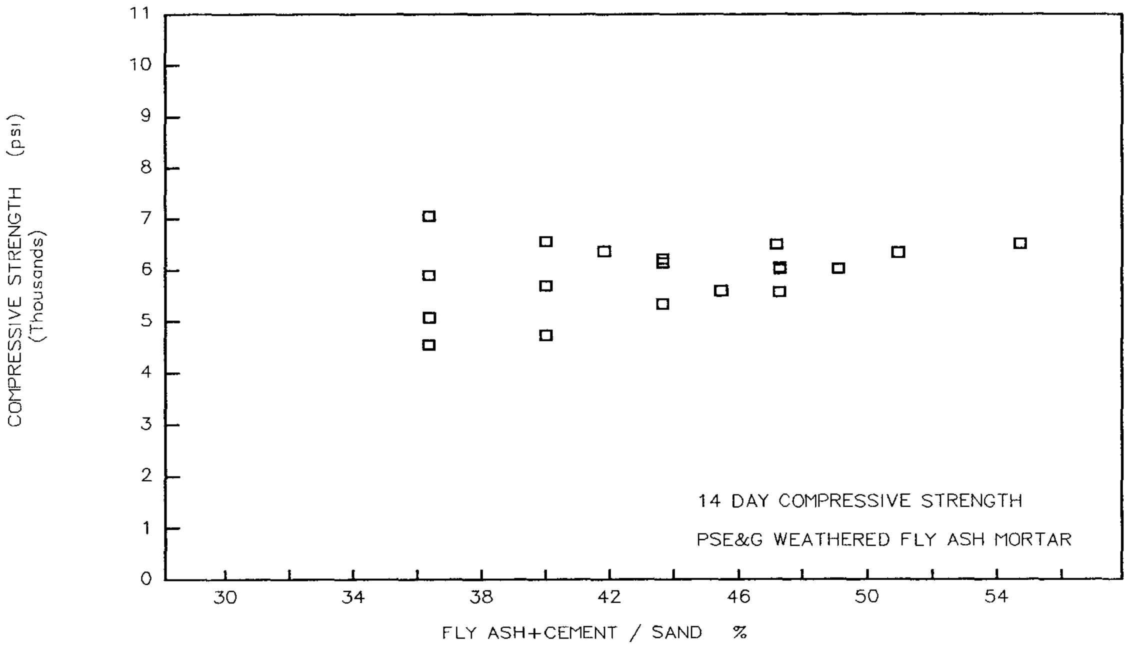

Fig. D.51 Compressive strength at 14 days age with (fly ash+cement)/sand ratio.

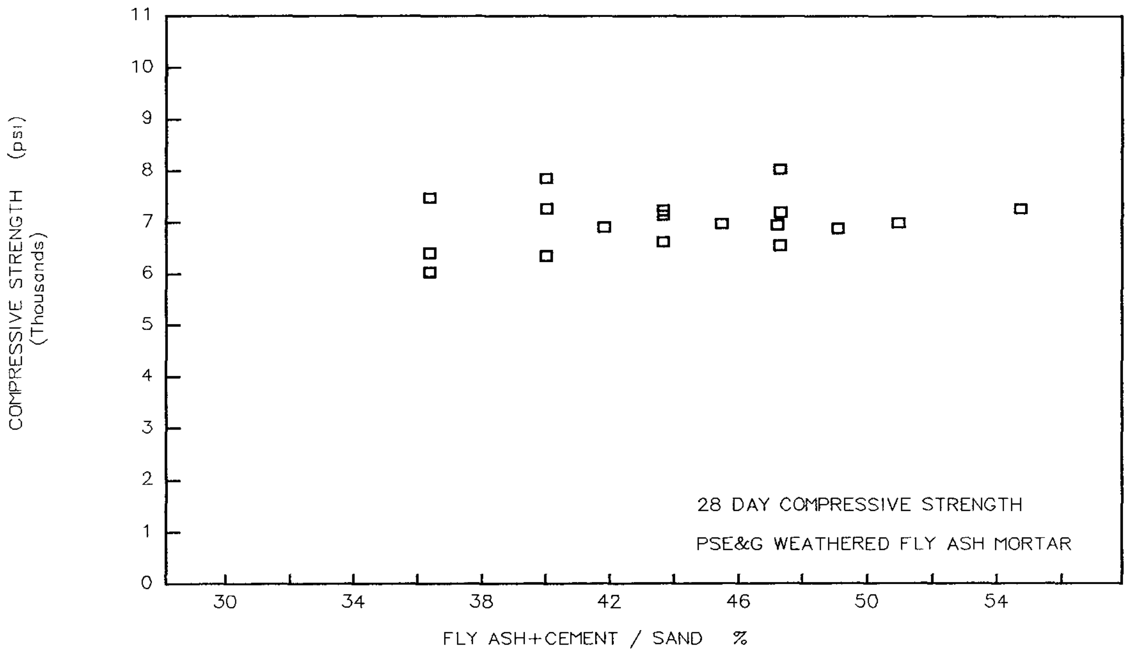

Fig. D.52 Compressive strength at 28 days age with (fly ash+cement)/sand ratio.

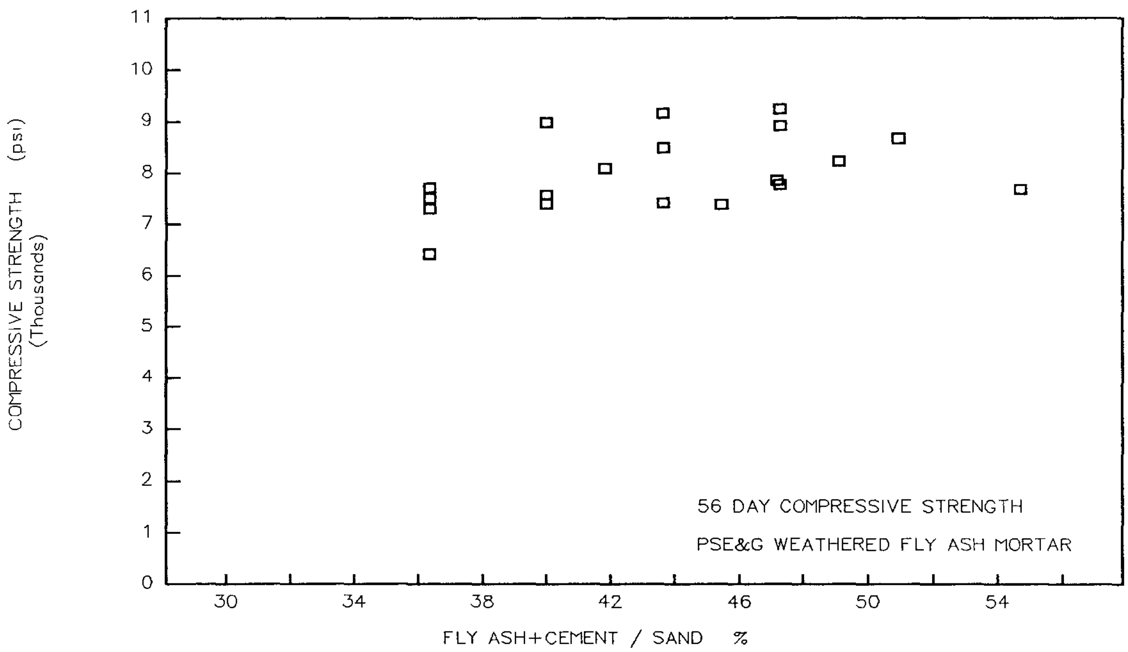

Fig. D.53 Compressive strength at 56 days age with (fly ash+cement)/sand ratio.

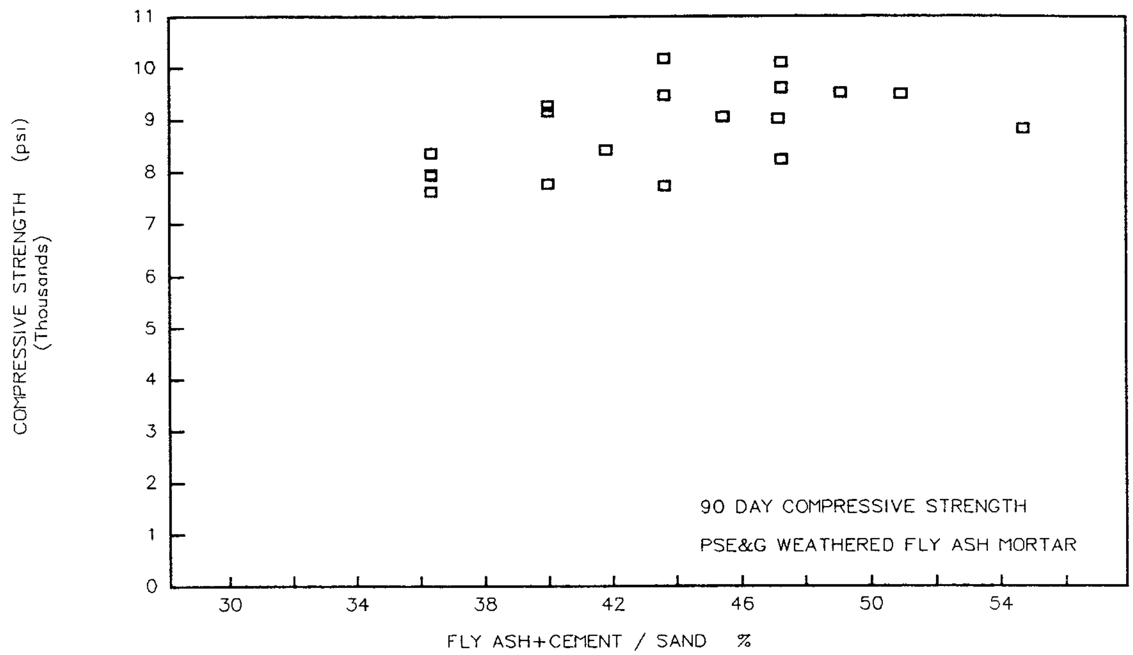

Fig. D.54 Compressive strength at 90 days age with (fly ash+cement)/sand ratio.

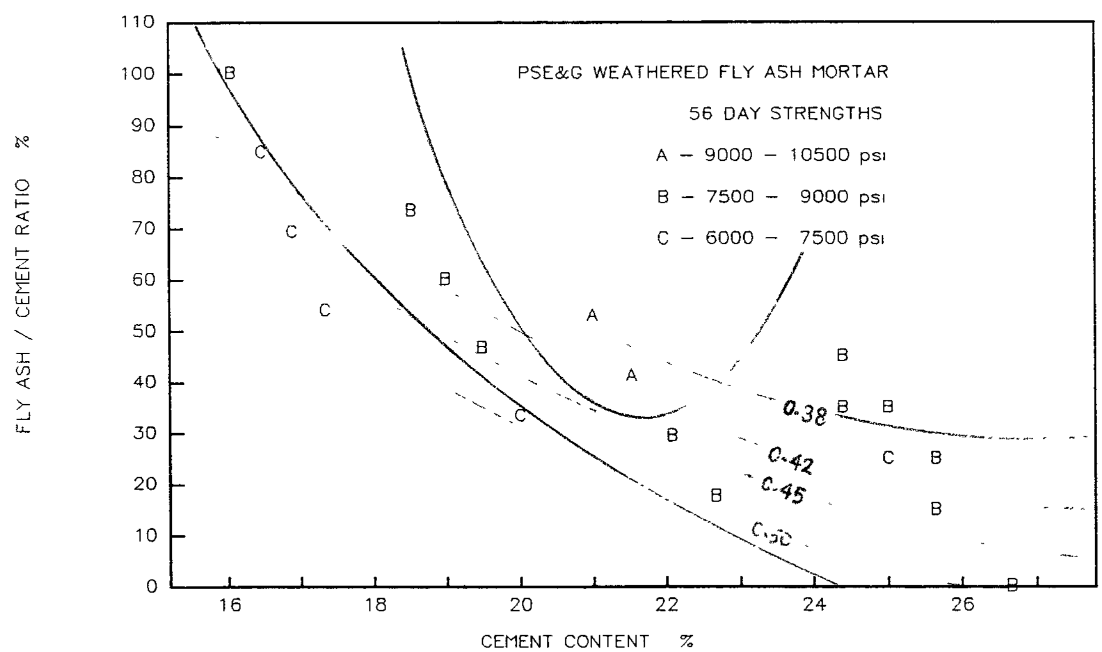

Fig. D.55 Contours of strength at 56 days and water/cementitious ratios.

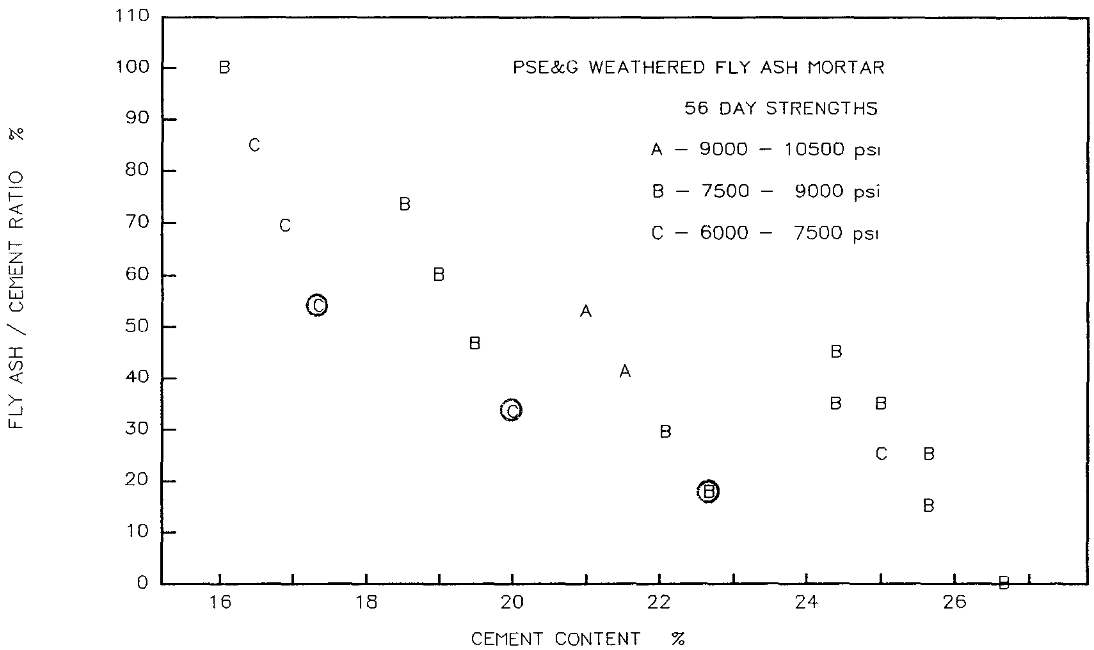

Fig. D.56 Compressive strength of Replacement method mortars at 56 days age.

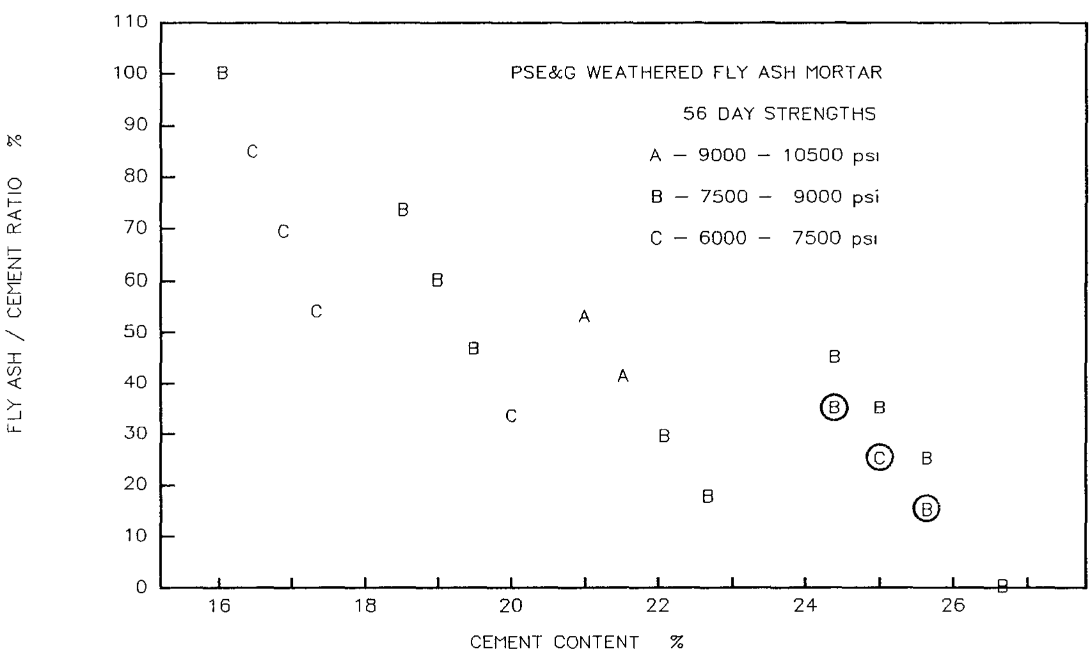

Fig. D.57 Compressive strength of Addition method mortars at 56 days age.

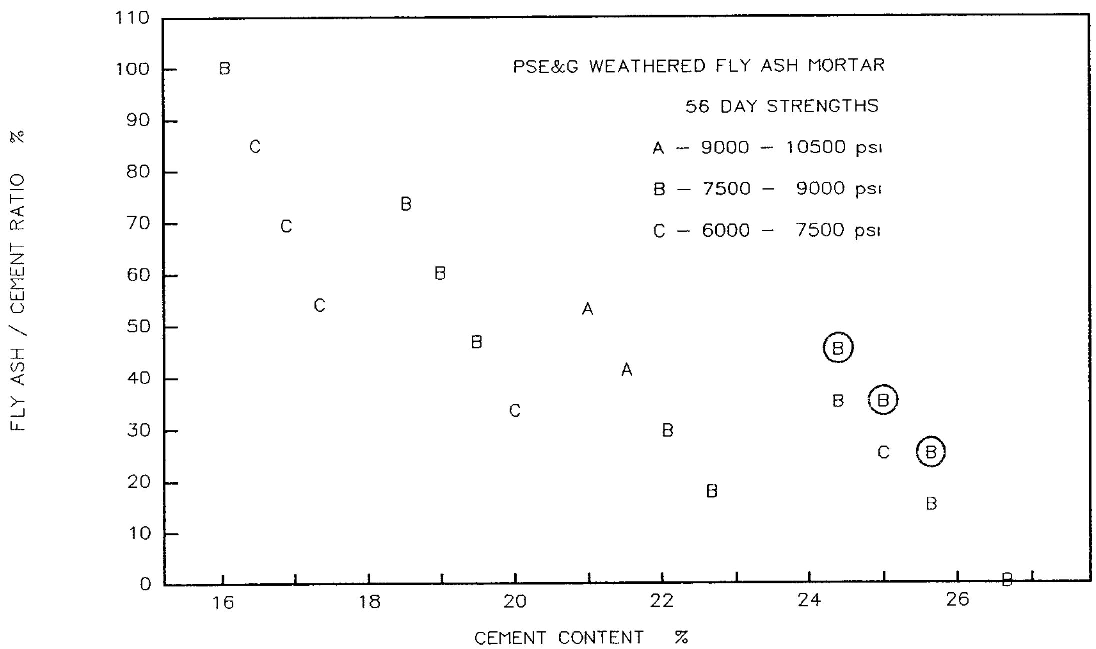

Fig. D.58 Compressive strength of Modified replacement method mortars at 56 days age. (sand replaced - test series 2C)

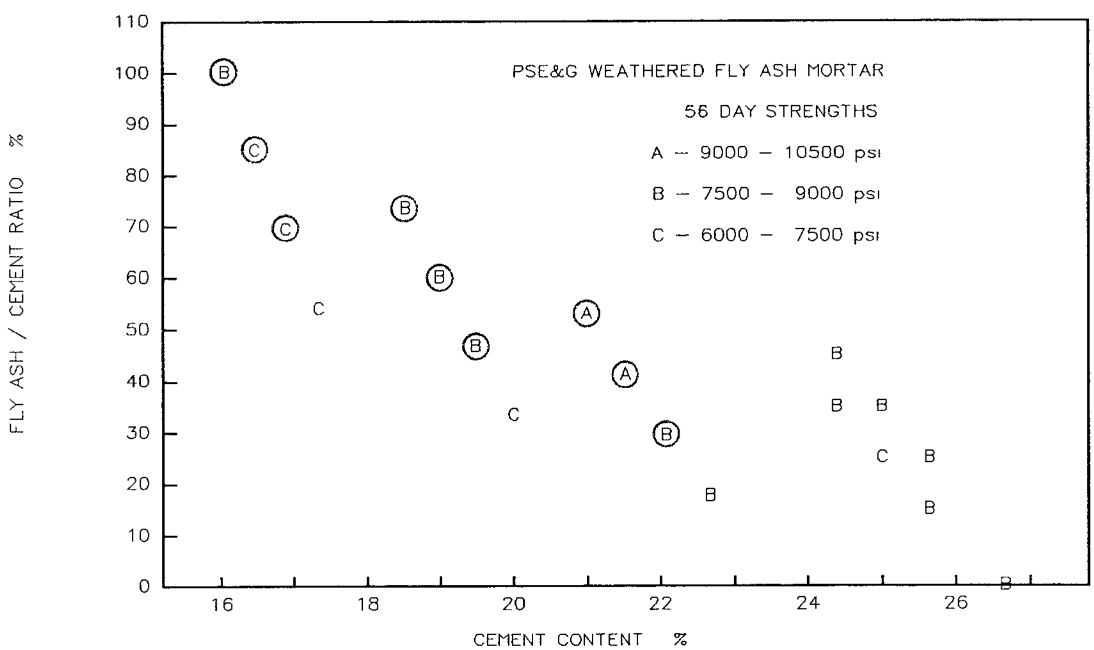

Fig. D.59 Compressive strength of Modified replacement method mortars at 56 days age. (cement replaced - test series 2D)

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