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Utilization of fly ash in concrete

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ABSTRACT

UTILIZATION OF FLY ASH IN CONCRETE

by

Chai Jaturapitakkul

ABSTRACT

Fly ash, a by-product of coal burning power plants, is produced in large quantities each year. It is commonly known that fly ash possesses pozzolanic behavior which can enhance the properties of concrete. Due to a lack of proper understanding on the formation of fly ash and its performance in concrete, the question of quality assurance has frequently been a major concern of engineers using fly ash in their construction projects. As a result, much fly ash is disposed of as waste material in landfills. Recent environmental concerns and a shortage of landfill space have rapidly escalated the disposal cost of fly ash and therefore, the need to seek better utilization of fly ash in concrete is then critical.

The objective of this investigation is to study the effect of fly ash on the strength development of mortar and concrete and to develop models to predict its performance in these cementitious composites. The fly ash used was carefully selected and defined as to its origination, formation, physical and chemical compositions, and the storage condition. The original fly ash was fractionated into six particle size ranges, each having a relatively uniform particle size, with maximum sizes ranging from 5 to 300 microns. The rate of strength gain of these fly ash concretes was monitored from 1 to 180 days. The compressive strength for each series was correlated to the conditions of fly ash used to determine the major parameters affecting the performance of fly ash in mortar and concrete.

The results from this study show that the particle size of fly ash has a significant effect on the strength development of concrete. The combustion condition in the boiler has some influence on the performance of fly ash in cementitious composites. Of particular importance is the finding that certain portions of fly ash when used as cement replacement can improve the strength of concrete beyond normal cement as early as 14 days. A correlation to predict the compressive strength of fly ash concrete is proposed and provides good agreement with experimental results both from this study as well as from other investigators.

UTILIZATION OF FLY ASH IN CONCRETE

by

Chai Jaturapitakkul

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Doctor of Philosophy

Department of Civil and Environmental Engineering

May 1993

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Utilization of Fly Ash in Concrete

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The author dedicates this dissertation to
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CHAPTER 1

INTRODUCTION

1.1 Statement of the Problems

Fly ash, a by-product of coal burning power plant, is produced in large quantities worldwide each year. In 1988 approximately 84 million tons of coal ash were produced in the U.S. in the form of fly ash (60.7%), bottom ash (16.7%), boiler slag (5.9%), and flue gas desulfurization (16.7%), (Tyson 1990). Out of the approximately 50 million tons of fly ash generated annually, only about 10 percent is used in concrete (ACI 226 1987) while the remaining portion is mostly disposed of as waste in the landfill. It is generally more beneficial for a utility to sell its ash, even at low or subsidized price, rather than to dispose of it in a landfill since this will avoid the disposal cost. In the 1960's and 70's this was not too important since the cost of ash disposal was typically less than $ 1.00 per ton. However, due to the more stringent environmental regulations starting in the late 1970's, the cost of ash disposal has rapidly increased to from $2.00 to $5.00 per ton and is still rising higher (Bahor and Golden 1984). The shortage of landfill due to environmental concerns has further escalated the disposal cost. The Environmental Protection Agency (EPA) estimated in 1987 that the total cost of waste disposal at coal fired power plants ranged from $11.00 to $20.00 per ton for fly ash and bottom ash (Courst 1991). This increasing trend of disposal cost has caused many concerns and researchers are urgently seeking means for better utilization of fly ash.

The cement and concrete industries were the largest users of fly ash averaging 43% of the total ash sold during 1979 to 1983 (Kelly 1984). Fly ash is used in concrete in two distinct ways, one as a replacement for cement and the other as a filler. The first is primarily because fly ash possesses pozzolan which, when it reacts with lime or calcium hydroxide, can enhance the strength of cementitious composites. The latter is a result of the fine particles of fly ash filling the voids between the cement and fine aggregates. The presence of fly ash in concrete has its advantages and disadvantages. According to Lane and Best (1982) the advantages are: a) improved workability, b) reduced segregation, c) reduce bleeding, d) reduce heat evolution, e) reduce drying shrinkage, f) increased resistance to sulfates, g) increase ultimate tensile and compressive strength, and h) reduced permeability. The disadvantages when fly ash replaced cement on a one-to-one basis by weight are: a) lower early strength, b) lower resisting to freezing and thawing, and c) increased air-entraining admixture requirement for equal air content. The main shortcomings are the fact that fly ash is relatively inert and its contribution takes up to 90 days to materialize. The slow rate of strength development could not be accepted by the concrete and construction industry since formworks have to be removed by 7 to 14 days at which time concrete has to have gained its required strength. Furthermore, fly ash from the utility tends to vary significantly from batch to batch depending on the type of source coal, its physical and chemical compositions, combustion condition and type of boiler, and the storage conditions. With all these variables and the fact that fly ash is just a by-product from the power industry, the quality assurance of fly ash has always been a major concern to the end users in the concrete industry.

Fly ash has complex characteristics, each differing in fineness, morphology, mineralogical composition, and glass content. These characteristics of fly ashes tend to affect the hydration process, the hardening and the microstructural development of the blend cement paste system (Larbi and Bijen 1990). While much of the experimental data reported so far seems to indicate that fly ash enhances the quality of concrete, the exact contribution, remains unclear and cannot be determined solely by any simple variable alone, such as the physical or chemical characteristic of the ash but rather it varies widely in different concretes (Popovics 1986). It is then difficult and maybe inaccurate to predict concrete performance based on typical characterization of fly ash alone. Therefore, fly ash acceptability with regard to workability, strength development, and durability must always be investigated through trial mixtures of concrete containing fly ash (ACI 226 1987). Obviously, such a process is tedious and time consuming.

Utilization of fly ash in concrete is hampered mainly by the lack of understanding 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 more than half a century we have not yet achieved a complete and detailed knowledge of fly ash. Research on fly ash has taken us deeper in to a maze and the physical and chemical characteristics that govern its behavior are only beginning to be understood.

1.2 Scope of Investigation

The present study was initiated with the concept that fly ash incorporated into concrete does not undergo any special treatment except being wet and present in the lime environment of cement hydration. During the 90 days waiting period for the concrete enhancement by the fly ash, the author believes that the glassy phase of fly ash is being resolved. Since fly ash from the utility is available in two different forms, i.e. as **dry fly ash** coming straight out from the electrostatic precipitator and as **weathered fly ash** which is the unsold fly ash stored in a pond in the wet condition for 6 to 12 months awaiting disposal, the weathered fly ash was believed to have gone through the stage of resolving the glassy phase. As such, the weathered fly ash should be more reactive than the dry fly ash and therefore more suitable for use in concrete. A series of investigation were then conducted to evaluate the properties of the dry and weathered fly ash as well as their performance in concrete. Fly ash was used as cement replacement, partial replacement, and additive in mortar and concrete. The study later revealed that the weathered fly ash did not perform as expected. This was ultimately attributed to its larger particle size distribution which was a result of being lumped together while in the pond.

It was then concluded that particle size and the size distribution of the fly ash may be important parameters affecting the strength development of fly ash concrete. Studies were carried out to determine the behavior and performance of different particle sizes of fly ash in concrete. Fly ash was first fractionated into six small ranges of different particle sizes with maximum size ranging from 5 to 300 microns. Since fly ash properties vary significantly with the combustion condition and the type of boiler, the fly ashes studied here were obtained from two different types of boiler, a **dry bottom boiler** and a **wet bottom boiler**. The main difference between the two boilers is that the dry bottom boiler is designed to have the flame below the fusion temperature of the coal ash whereas the wet bottom boiler is higher (Liskowitz et al. 1983). This produces two different kinds of fly ash and obviously different properties. The studies conducted here were also intended to investigate the effect of combustion condition and the type of boiler on the properties of the fly ash generated.

Test results show that certain finer sizes of fly ash particles exhibit higher rates of reactivity and can provide the same and higher strength of concrete as cement as early as 14 days. This finding is extremely critical not just to the question of quality assurance of fly ash but also to future potential development of high strength concrete using fly ash. While a few researchers have reported previously on the early strength development of concrete with finer particle fly ash, they did not systematically and quantitatively justify their conclusions regarding the exact fineness of the particle size to be used and its performance related to other potential factors which may influence the final strength of fly ash concrete.

The present study investigated further to evaluate the properties of concrete made with these fractionated fly ashes. Of particular interest is the resistance of fly ash concrete to sulfuric acid attack. The results of this study indicate that concrete with a large volume percentage of fly ash as cement replacement exhibits excellent resistance to sulfuric acid attack. This finding provides a new cementitious material which is suitable for structures in highly corrosive environments. The present study has resulted to several important findings and major breakthroughs which have never been reported elsewhere.

Finally, a model is developed to predict the strength of fly ash concrete, using the fineness of the fly ash, the percentage of cement replaced by fly ash in concrete, control concrete strength, and the age of concrete as the key variables in the model. The predicted results are in good agreement with the observed experimental data from this study as well as those reported by other investigators. Details of all the investigations mentioned above are further elaborated in this dissertation.

CHAPTER 2

LITERATURE SURVEY

2.1 Pozzolanic of Fly Ash

ACI 116 (1990) 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". Although it was originally identified as an artificial pozzolan, fly ash is now used as a part of the composite that forms the concrete mass, i.e. 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 (ACI 226 1987). These aspects are compressive strength, workability, heat of hydration, etc.

Pozzolan, as define by ASTM C-593 (1990), is " a siliceous or alumino-siliceous material that in itself possesses little or no cementitious value but that in finely divided form and in the presence of moisture will chemically react with alkali and alkaline earth hydroxides at ordinary temperatures to form or assist in forming compounds possessing cementitious properties".

The pozzolanic reaction is the reaction between constituents of the glass phase of fly ash and calcium hydroxide. It is generally assumed to take place on the surface of fly ash particles, between silicates and aluminates from the glass phase and hydroxide ion in the pore solution (Plowman 1984). The rate of solubility and reactivity of these glassy phases in different types of fly ash is unclear since the glassy phase of fly ash depends essentially on the combustion condition and type of boiler. Fly ash obtained from different boilers such as dry bottom boilers or wet bottom boilers, tends to behave differently. As a pozzolan, it is essential that fly ash be in a finely divided form as it is only then that silica can combine with calcium hydroxide (liberated by the hydrated portland cement) in the presence of water to form stable calcium silicates which possess cementitious properties (Neville 1983). Although fly ash generally comes in a dry and finely divided form, in many instance, due to weathering and transportation process fly ash is being wet and often forms lumps. Such fly ash remains reactive but to a lesser extent. During hydration portland cement produces a surfeit of lime that is released to the pore spaces. It is the presence of this lime that allows the reaction between the silica components in fly ash and calcium hydroxide to form addition calcium silicate hydrate [C-S-H]. He Jun-Yuan, Scheetz, and Roy (1984) showed that the content of crystalline calcium hydroxide in the fly ash-portland cement pastes decreases as a result of the addition of fly ash, most likely resulting from a reaction of calcium with alumina and silica from the fly ash to form addition C-S-H. This process stabilizes the concrete, reduces permeability and increases resistance to chemical attacks. He Jun-Yuan, Scheetz, and Roy (1984) also suggested that silica in fly ash has to be amorphous, as crystalline silica has very low reactivity.

Fly ash makes efficient use of the products of the hydration of portland cement: (1) solution of calcium and alkali hydroxide which exist in the pore structure of the cement paste and (2) the heat generated by hydration of portland cement, an important factor in initiating the reaction of fly ash (ACI 226 1987). The reaction between fly ash and lime released by hydrolysis of clinker silicates not only depends on the specific surface of fly ash but also on the calcium hydroxide availability which can be related to the rate of hydration of cement and its fineness (Costa and Massazza 1983). It seem that the availability of calcium hydroxide is generally accepted as one of the key factors affecting the performance of fly ash in concrete. However, no one has ever quantitatively verified the need for calcium hydroxide to accelerate the rate of strength gain of fly ash concrete. This issue will be addressed here.

All cement particles in the paste of mortars or concrete do not necessary take part in hydration. The hydration usually starts from the finest cement particles (Neville 1983). The hydrated cement envelopes unreacted cement particles and continues to grow from within. However, this reduces the rate of hydration continuously so that even after a long time appreciable amounts of unhydrated cement may remain in the paste. When fly ash is incorporated in the paste as an addition, the cement enveloping process is reduced. Fly ash particles act as neuclei for the hydration reaction, thus generating more hydrated products than otherwise (Butler and Mearing 1986).

Fly ash can react with $Ca(OH)_2$ from the cement hydration to form calcium silicate hydrates similar in composition to those formed by portland cement. However, the rate at which this process occur is very much slower than that of portland cement (Berry and Malhotra 1980). This is primarily due to the inert glassy phase of fly ash and possibly the availability of calcium hydroxide at that instant. The pozzolanic reaction of fly ash in the portland cement paste investigated at 20^oC can only start after one or two weeks, because only then is the alkalinity of the pore water high enough to dissolve the fly ash (Fraay, Bijen, and de Haan 1989). Halse and Pratt (1984) conducted tests to measure the $Ca(OH)_2$ content and compressive strength at several ages. They concluded that in the fly ash cement systems the $Ca(OH)_2$ content reached a maximum value after 7 to 14 days thereafter decreasing as a result of the pozzolanic reaction. This decrease in $Ca(OH)_2$ content followed dissolution of the fly ash surfaces augmenting the strength of the fly ash concrete. Therefore, the rate of strength gain of fly ash concrete is slow at early ages (7 days or before), especially when a high percentage of fly ash is used (Naik and Ramme 1989). The unavailability of $Ca(OH)_2$ at early age may be one of the factors causing the slow rate of strength development of fly ash concrete. Therefore, one of the possible solutions to problem is to provide addition lime to fly ash concrete mixture. This approach will be evaluated here in this investigation. After 28 days, the pozzolanic activity of fly ash continues to contribute to the strength gain of fly ash concrete. Compared to the strength at 28-day, the strength of fly ash concrete at one year increases by 50 percent while concrete without fly ash increases only 30 percent (ACI 226 1987). To achieve an acceptable strength at early age as comparable to conventional concrete, a modified concrete mixture (by reducing water to cementitious ratio), or some kind of admixture such as superplasticizer must be used (Swamy et al. 1983).

Fly ash can contribute to the strength of concrete in three ways, namely; by a reduction of the water content needed for a given slump, increasing the volume of paste in the mixture, and by pozzolanic reaction. Fly ashes from different sources may have different effect to concrete. The same fly ash may behave differently with portland cements of different types (Popovics 1982), since different type of portland cement (type I to V) have different chemical composition.

Many questions on the pozzolanic properties of fly ash have not yet been answered. These are the issue of lime availability, the rate of solubility and reactivity of the glassy phase in different fly ash, and the proper mix proportion to ensure early strength development of fly ash concrete.

2.2 Chemical Composition of Fly Ash

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 to the composition of chemical oxides but with little success (ACI 226 1987). Studies conducted so far have revealed that chemical composition is not the sole governing criterion for the behavior of fly ash in concrete (Manz 1986). Cabrera et al. (1986) examined the chemical and mineralogical compositions, and properties of 18 samples of fly ashes produced from bituminous coals and concluded that their study failed to produce a parameter which could explain or predict the strength differences observed. It should be noted that besides the combustion conditions in the different types of boiler which may influence the formation of fly ash, different fineness and particle size distribution of fly ash may have significant effect on its performance in concrete. The studied carried out here will address and explain some of these issues in more details.

Generally, fly ash derived from various coals have differences in chemical composition, but the principal chemicals compositing of fly ash are SiO_2, (25% to 60%) Al_2O_3, (10% to 30%) and Fe_2O_3 (5% to 25%). The MgO content of fly ash is generally not greater than 5% (Davis et al. 1937). Usually, fly ash from the combustion of sub-bituminous coals contains more CaO and less Fe_2O_3 than fly ash from bituminous coal (Berry and Malhotra 1980). The color of fly ash may range from light tan to gray to almost black, depending on the type and quality of the coal and on the boiler operation. High carbon content changes the color to gray or black (Lane and Best 1982).

The present ASTM classification of fly ash, C-618 (1990) classifies fly ash in to two groups as Class C and Class F. Class F is generally as ash produced by burning anthracite or bituminous coal while ash from sub-bituminous coal or lignite is defined as Class C. The CaO content of the Class C fly ash is usually higher than 10% with the sum of the oxides of SiO_2, Al_2O_3 and Fe_2O_3 not less than 50%. For Class F fly ash the CaO content is normally less than 10 % and the sum of the above mentioned oxides is to be no less than 70%.

Aitcin et al. (1986) studied the physico-chemical properties of three Class F fly ashes, one French, one Canadian and one American and of four Class C fly ashes, two American and two French. They reported that fly ashes from one particular class can behave very differently. Two Class F fly ashes have been found to be purely pozzolanic, whereas three others, one F and two C, were more or less hydraulic at the early stage of hydration before behaving like a more or less pozzolanic material.

Their study shows that the reactivity of a particular fly ash can be a very complex phenomenon that can not be related to just its SiO_2 + Al_2O_3 + Fe_2O_3 content. While Aitcin studied the behavior of fly ash from different sources such as US, Canada, and France, he did not realize that even the ash from the same source may behave differently if the combustion condition changes (Liskowitz et al. 1983). Furthermore, fly ash from the same utility with different particle size distribution and storage conditions also perform differently.

Gebler and Klieger (1986) noted that pozzolanic activity index with cement did not show consistent significant correlations with compressive strength. Poor correlation between laboratory tests and field performance has often been a concern and therefore there is a need to develop a system of parameters controlling performance of fly ash in concrete. The high CaO content of many of the lignite and subbituminous ashes was misinterpreted as pozzolanic property, they will often form cementitious products without any addition of calcium hydroxide. As a result, there has been much controversy over the pozzolanic activity tests with cement and lime, since persistent poor correlations exist between the results of either test and the actual performance in the field when fly ash is used in concrete (Manz 1983).

2.3 Fineness of Fly Ash

In general, fly ashes are much finer than portland cements (Davis et al. 1937). Fly ash particles are typically spherical, ranging in diameter from 1 to 150 microns (Berry and Malhotra 1980). The experiment conducted by Aitcin et al. (1986) showed that if the average diameters, D_{50}, of fly ash are smaller, the surface area of the fly ash will be larger than those with larger average diameters. According to Lister (1984) the fineness of fly ash is controlled by the pulverized coal fineness, mill type and burner type. The factors mentioned here are just a few of many parameters which may influence the fineness of fly ash. Among the important factors not listed by

Lister are the storage condition, ash collection process, and the combustion condition. Korac and Ukraincik (1983) reported that the combustion temperature was the single most important factor in controlling the quality of fly ash, with better physical and pozzolanic properties being produced at higher temperatures. This conclusion may be misleading, since in their study the coal was burned at low temperature and some coal residue remains, resulting in large porous particles of fly ash. It should be noted that the Korac and Ukraincik study is different from this investigation in that the fly ashes from the wet and dry bottom boilers used in this report were from coal that was completed burned. The main difference among the two types of boiler is one reaches the fusion temperature of ash while the other does not.

There are generally two methods to measure the fineness of fly ash. The first is by measuring the residue on the 45 microns (No. 325 sieve) and the second is the surface area method by air permeability test. Luxan et al. (1989) shows that there is no relationship between the percentage of particles retained on 45 microns sieve and the type of the original coal. Opinions differ as to whether sieve residue or surface area are better prediction of fly ash fineness (Cabrera et al. 1986). In the United States, the fineness of fly ash is specified by the residue on the 45 microns only. Ravina (1980) found that pozzolanic activity is better indicated by specific surface area measurements. However, Lane and Best (1982) suggested that 45 microns sieve residue is a more consistent indicator than the surface area. White and Roy (1986) concluded that the reactivity of fly ash as measured by the fraction with particle size less than 45 microns was an important factor controlling the strength of the final fly ash concrete. Their conclusion was derived from the ASTM recommendation that fly ash be classified by using the 45 microns sieve. Obviously, the portion finer than 45 microns should perform better than the larger portion. This can simply be explained by the fact that finer particles have a larger surface area which results in a higher reactivity rate. Furthermore, finer particles can serve as filler and reduced voids between cement particles. However, these assumptions were never quantitatively verified.

ASTM C-618 (1990) specifies that not more than 34% by weight of a given fly ash be retained on a 45 microns sieve. This specification tends to improve the fly ash quality by reducing the LOI (loss on ignition) content since the unburnt carbon present in fly ash composes a larger part of the coarser particles (Neville 1983). On the contrary Berry et al. (1989) found that the total carbon content in the ash materials showed little dependence upon particle size. Particle sizes of fly ash in the range of 10 to 50 microns, having much less surface area, often exhibit a slower chemical reactions compared to the 1 to 5 microns size. However, these fly ashes have been used as micro-aggregate of virtually ideal particles shape. According to Slanicka (1991), coarse fly ash was suitable only as a substitute for a portion of fine aggregates or as a substitute for unsuitable shape and grading of aggregate. This may be due to the fact that coarse particle fly ash is more inert and less reactive than a fine one. Ravina (1981) showed that large quantities of coarse fly ash may be used efficiently in concrete under thermal curing conditions, with a significant improvement in the compressive strength, in contrast to the rather limited improvements under normal curing conditions at ages up to 28 days.

Many researchers have observed that there is a direct increase in strength with the increase of fineness. Research carried out by Ukita et al. (1989) showed that as the percentage of finer particles ranging from diameters of 1 to 20 microns increases, the corresponding strength gain is notable. Similar results have been observed by Giergiczny and Werynska (1989). They examined two types of fly ash, a low calcium and high calcium fly ash. Variability of chemical composition with grain size of fly ashes was analyzed for fractions, 0-20 microns, 20-40 microns, 40-60 microns, and >60 microns. They found that it is the 0-20 microns fraction that brings about the lowest strength decrease in the mortars. While both groups of researchers seem to emphasize their study on the performance of finer particle fly ashes, their fly ashes were different from each other as to its formation. The differences between these two studies are the method of collecting different sizes of fly ash. Ukita et al. (1989) collected fly ash from different locations of the electrostatic precipitator whereas Giergiczny and Werynska (1989) ground the original fly ash into different sizes. Both cases have certain variables induced in their fly ashes. Fly ashes collected by Ukita will have different chemical properties (Liskowitz 1983). For the second, grinding fly ash often adds additional metal into the fly ash and also tends to change the shape of the fly ash. Slanicka (1991) observed two kind of fly ashes with similar chemical and mineralogical composition but with considerably different fineness. One has a specific surface of 2008 cm^2/g and the other, 5327 cm^2/g. He concluded that fly ash of similar chemical and mineralogical composition but with different fineness has different influence on the property of concrete. The finer seems to perform better. The finer fractions (those less than 45 microns) allow the hydration and pozzolanic reactions to proceed more rapidly. The study of Harris, Thompson, and Murphy (1987) showed that both fineness and water requirements have significant correlation with pozzolanic activity. The pozzolanic reactivity with portland cement was influenced by several characteristics of the fly ash, one of which is the fineness of fly ash as measured by the 45 microns (No. 325) sieve.

The pozzolanic activity of fly ash was also found to increase with the increase of the specific surface area (Raask and Bhaskar 1975; Ravina 1981). Since specific surface area is directly proportional to the fineness of fly ash particles, they have attempted to relate the fineness with the compressive strength of fly ash concrete. Their results showed that up to 7 days, the strength was little affected by the fineness of fly ash which only demonstrated favorable effect after 28 days and became pronounced after 90 days. On the contrary, very high fineness of fly ash was reported to fail to show any significant advantages (Costa and Massazza 1983). Ukita et al. (1989) reported that the strength was increased significantly for concrete with finer fly ash particles only after 90 days and to achieve a strength equivalent to plain concrete, it would take up to 90 days and with fly ash content as high as 30%. This finding, although supports the concept that finer particles of fly ash may be more reactive, does not in suggest a means to accelerate the strength of fly ash concrete so it would be equivalent to cement at early age. During the hydration of pozzolanic cements made by mixing fly ash (30%) and portland cements (70%), and ground to different fineness, Costa and Massazza (1983) found that the reduction of the free lime content became appreciable after 7 days when fly ash was very fine (6940 cm^2/g) and after 28 days when the fly ash used was as received (3260 cm^2/g). Butler and Mearing (1986) suggested that 10 microns be the cutoff point between reactive and non-reactive particles since reactivity was a function of surface area and glass content and crystalline materials in low calcium ashes were generally non-reactive. However, they did not carry out any experiment to supported their conclusions.

Berry et al. (1989) studied the properties of so called "beneficiated" fly ash in mortar. The beneficiated fly ash was defined as fly ash with particle size smaller than 45 microns. The glass content and the proportion of spherical particles were found to increase in the beneficiated fly ash compared to the original fly ash. Beneficiated ashes showed improved pozzolanic activity, reduced water demand, and enhanced ability to reduce alkali-aggregate reactivity. The surface area data are entirely consistent with the particle size distributions. The surface area of the particles less than 10 microns is almost twice that of the raw ash, reflecting the large total surface of the small spherical particles. The <10 microns product was found to exhibit excellent strength development. Although beneficiated fly ash seem to show promising results in terms of improved performance of fly ash in mortar, other researchers concluded otherwise when used in concrete. Giaccio and Malhotra

(1988) also conducted the tests using the beneficiated fly ashes. They showed that for concrete made with ASTM type I cement, the use of beneficiated fly ash and condensed silica fume, did little to enhance the properties of concrete compared with the raw fly ash. Similar to Ukita et al. (1989), Berry simply reported that a finer particle size of fly ash performance better. They both failed to clearly identify the extent these beneficiated fly ashes perform as compared to regular cement, at early age in particular. The cut-off size used is the 45 microns suggested by ASTM. There is a need to carry out a through investigation on how the finer particles perform to achieve the performance of normal cement.

It should be noted that general perception was the use of beneficiated fly ash or fly ash with finer particle size improved the performance of concrete. However, at this moment none has yet demonstrated what type or size of fly ash will provide strength performance comparable to conventional cement at an early age. Without this definite qualitative and conclusive information, fly ash will not be attractive to concrete industry.

2.4 Loss on Ignition (LOI) of Fly Ash

ASTM C-618 (1990) limits the loss on ignition of fly ash to not more than 6% for Class C and Class F. For high strength concrete, a fly ash with an ignition loss of 3% or less is preferable (Task Force Report No. 5 1977). The loss on ignition of fly ash is performed at the temperature of 750^{O}C. It is assumed that the loss on ignition is approximately equal to the carbon content (ACI 226 1987; Cabrera et al. 1984). According to Lister (1984), carbon in the ash is controlled by mill fineness, excess air, oil firing and furnace burning conditions, particularly the fuel air mixture, and furnace velocity.

In general, the fly ashes of low carbon content were considerably finer than those of high carbon content (Davis et al. 1937). Microscopic examination reveals that carbon particles coarser than the No. 325 sieve are usually more porous and amorphous than the finer particles and may have an adverse effect due to absorption of air-entraining admixture (Lane and Best 1982). The results tested by Raask and Bhaskar (1975) showed that there was a significant decrease of the specific surface area of fly ashes after removal of carbon. This would suggest that the silicate particles have a much lower specific surface area compared with that of carbon residue. Although this conclusion may be justified, the author strongly question the validity of this finding since carbon content in most fly ash is in general small.

It will be observed that on the average the strengths of pozzolan-lime-sand mortar were considerably higher for the fly ashes of low carbon content than for those of high carbon content. The cement containing a fly ash which was moderately high in carbon and high fineness exhibited a high water requirement. It is commonly accepted that carbon serves as the weak link in the concrete matrix. Carbon also absorbs large amount of water as compared to other constituents in the concrete mix. In general, the finer the fly ash and the lower the carbon content, the greater the activity and the greater the contribution to the strength of mortars and concretes (Davis et al. 1937).

Class F fly ashes usually have loss on ignition values less than 1%, but Class C fly ashes range from this low level to value over 10%. The coarse fly ash usually contains a higher proportion of carbon than the fine fly ash. The form of the carbon particle in fly ash may be very similar to porous activated carbon, which is a product manufactured from coal used in filtration and absorption processes (ACI 226 1987). Carbon in fly ash was reported to act as activated carbon (Liskowitz 1983). This finding makes fly ash with high carbon content a good material for waste stabilization and solidification. High loss on ignition of fly ash is often an indicator of the air-loss problem; so far, the problem seems to be confined to the Class F fly ashes (ACI 226 1987).

2.5 Fly Ash-Kiln Dust Mixture

Kiln dust, as the name implies, is collected from the gases emanating from rotary kiln as a waste product of cement manufactures. It also has some cementitious properties since the main constituent of kiln dust is calcium oxide (CaO).

The cementitious and pozzolanic qualities of kiln dust and fly ash are enhanced in the combination with each other. This action can be understood by analyzing their chemical compositions. Kiln dust, which is rich in calcium oxide, (CaO) contributes calcium while fly ash contributes silicon oxide (SiO_2) to produce the C-S-H gel. This process is believed to increase the calcium silicate hydrate of low calcium fly ash (Class F). Ramakrishnan (1986) studied the use of cement blended with kiln dust versus the properties of concretes made with plain portland cement. A blending of 5% kiln dust and 95% of cement was used. He found that the addition of kiln dust prolongs the setting time of blended cement and concrete. The properties of the harden concrete made by blended cement are almost the same as those of plain concrete. Although this study simply evaluated how kiln dust can enhance the properties of harden concrete, it does not have a justified basis for the experiment. However, the mix of kiln dust with fly ash has a different perspective in the sense that fly ash consists of about 50% of SiO_2 while kiln dust has about 50% CaO. The two products when combined enhance the overall cementitious property of the mixture. Study of the properties of fly ash-kiln dust mix can lead to a beneficial utilization of both waste products.

Recent study on the utilization of fly ash has emphasized large volume uses of fly ash. These applications are mostly as structural fill, highways base material, and landfill. Such fill is often a mixture of kiln dust or lime, fly ash, and aggregate such as sand. The mix proportions for each application must be designed for easy placement, good compaction, adequate strength, and be economical.

Examples of these large volume uses of fly ash are the following. The largest single project involving the combined use of lime, portland cement and fly ash in a base or subbase application was the construction during the 1970's of runways, taxiways and aprons for the expansion of the Newark Airport. Field tests showed that stabilized layered mixtures of hydrated lime, portland cement, fly ash, dredged sand, and crushed stone would provide a suitable base for the new pavements. A total of 2 million square yards of pavement were placed using a multi-layered pozzolanic stabilized base system ranging in thickness from 26 to 40 inches, depending on its location. The total cost saving attribute to the use of the lime, portland cement, fly ash base was $21 million. Another more than 50,000 tons of lime-fly ash-aggregate base course materials were used for the construction of all the parking lots for Veteran's Stadium and the Spectrum in South Philadelphia (Collins 1990).

Duquesne Light Co. trucked coal ash from two of its power plants to East Street to fill a valley 1500 feet long up to 45 feet deep, and up to 250 feet wide. The project used 353,000 tons of fly ash and stabilized scrubber sludge to built East Street Valley Expressway linking Pittsburgh to its northern suburbs in 1987 (Bickerton et al. 1990). The most widely used criteria for the acceptability of pozzolanic base materials is the compressive strength. A minimum strength value of 400 psi is specified by ASTM C-593 (1990) for fly ash used with lime or kiln dust. For parking lot construction, 7 day strengths in the 300 to 500 psi range are generally sufficient.

It should be noted that these applications did not emphasize achieving products of higher strength. As a result, final products are simply piles of materials in various places. In this study, the author intends to explore the potential use of the strength development of kiln dust-fly ash mixture. An optimum mix-proportion of these two materials may lead to a low cost cement which can be used for general cementing applications such as secondary structural members.

2.6 Fly Ash as a Cementitious Material

It was the intensive studies undertaken by Davis et al. (1937) that introduced the use of fly ash for partial cement replacement in concrete. Since then, thousands of papers on the studies of fly ash have been published. At present, National Standards on fly ash have been established and are accepted worldwide.

Incorporation of fly ash in concrete improves workability and thereby reduces the water requirement with respect to the conventional concrete. 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 times (ACI 226 1987). The slump is higher when fly ash is used (Ukita et al. 1989). However, the use of fly ash in concrete has many drawbacks such as high variability, low air entrainment and low early strength development. According to Thomas, Matthews, and Haynes (1989), curing is important in fly ash concrete. With the reductions in curing period resulting in lower strength and more permeable concrete. The strength of fly ash concrete appears to be more sensitive to curing than plain concrete. The sensitivity tends to increase as the fly ash content increases.

The use of fly ash as cementitious material even though it seems rather promising, the quality assurance of the fly ash is very much uncertain. For instance, the 3 day compressive strength of fly ash concrete is normally reduced by the use of Class F fly ashes and may be reduced with Class C fly ashes (ACI 226 1987). This is because Class C fly ash has higher CaO content which contributes some cementitious properties so the early strength does not decrease as much as Class F fly ash. For fly ash to be used as a replacement for cement, it must be comparable to cement in terms of strength contribution at any age. This result was also confirmed by Langley, Carette, and Malhotra (1989). This is probably the most greatest deficiency that needs to be improved. The low early strength of fly ash concrete occurred under hot and humid conditions too. Tests conducted by Ravindrarajah and Tam (1989) showed that the compressive strength of fly ash concrete at early ages are lower than those for the control concrete. The general behavior of concrete with fly ash was similar to that reported in available literature in spite of the tests being conducted under hot and humid environment. It should be noted that most of the reported studies tend to show a lower concrete strength due to the presence of fly ash, none has yet suggested a solution to actually enhance the property of concrete economically.

Significant economies could be made by using high fly ash contents in most concretes. Cost saving can be as high as 25% of the cost of materials when compared with conventional portland cement concretes provided the strength are comparable (Munn 1984). For optimum economy, Class F fly ash is normally used at the rate of 15% to 25% of total cementitious materials while Class C fly ash is in the range of 15 to 35% (ACI 226 1987). If fly ash is used in high quantity, it will lower the strength of concrete below the desired limit, thus making the concrete not suitable for use as structural members.

Apart from the quality of fly ash and cement, mix proportioning is believed to be the most single important factor influencing the properties of fly ash concrete. Chen and Hsu (1987) showed that the fly ash concrete with proper proportioning can exhibit a strong structural performance similar to that of normal concrete and also be able to provide some cost advantages. Proportioning of fly ash concrete with the aim of achieving higher strengths and/or enhancing desirable properties has naturally been a major point of interest. However, it remains a challenge with no major break through. Since fly ash essentially depends on the hydration process of cement, with careful proportioning of cement and fly ash optimum mixes could be achieved. In proportioning the fly ash concrete mixes, the concept of water-cement ratio in conventional concrete has to be modified into the so-called "water-cementitious ration" (Popovics 1982). The term "cementitious" includes all binding materials which include cement, kiln dust, fly ash, and silica fume, if available.

The proportioning techniques seem to treat fly ash as a substitute for other basic materials in concrete. Three basic methods of mix proportioning have been used over the years (Berry and Malhotra 1980; Swamy, Ali, and Theodorakopoulos 1983).

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 cement in conventional concrete. Swamy (1984) showed that 30% replacement by weight would give all the desirable material properties and structural behavior almost identical to those of concrete of similar strength without fly ash. This statement is not accurate since other materials such as high dosage of superplasticizer were used. Since, fly ash is an inert material without some special treatment it is practically impossible to compare with cement. Costa and Massazza (1983) reported that replacing 30% of portland cement by fly ash reduced 1 day strength by about 50%. Fly ash concretes with cementitious ratios of up to 75% by weight and an aggregate-cement ratio of 6 were found to have adequate compressive and flexural strengths to be used as lean concrete base or subbase in pavement structures (Haque, Langan, and Ward 1984). Malhotra and Painter (1989) concluded that concrete incorporating high volume of Class F fly ash (200 kg/m^3 of concrete) had high density, satisfactory early age strength, and high later age strength. Again, the mix proportion used in their study contains significant amount of superplasticizer. It is unclear whether the strength observed was a contribution of fly ash or the additive.

Furthermore, due to the high cost of superplasticizer, mix proportions were not economical. Much research has shown that any percentage replacement of portland cement in concrete with fly ash on a one for one basis (either by volume or by weight) results in lower compressive and flexural strengths up to about 3 months of curing, with the development of greater strengths at and beyond 6 months (Berry and Malhotra 1980; Munday, Ong, and Dhir 1983). This may be attributed to the resolution of fly ash particles which enable silica content to react with the existing $Ca(OH)_2$ in the concrete matrix. The low early strength of the fly ash concrete, it is believed that the glassy phase remains intact and therefore no reaction occurs.

The second method is simply a direct addition of fly ash to the conventional mixes and usually will result to higher compressive strengths since the amount of cementitious materials (cement + fly ash) is increased. It was found that addition of fly ash generally increased strength of concrete at all ages (Berry and Malhotra 1980). However, the addition of fly ash was found to prolong the initial and final setting times of cements (Costa and Massazza 1983). This is mainly because fly ash is an inert material and therefore slowed down the overall rate of reaction. ACI Committee 226 (1987) concluded that the use of fly ash in concrete generally caused an increase in both the initial and final setting time.

The technique of modified partial replacement requires either cement or fine aggregate to be replaced with fly ash and further addition of fly ash as in the second method. Partial replacement of both the portland cement and of the fine aggregate were found to be the most effective way to improve the strength of concrete (Butler and Mearing 1986). Since the size of fly ash is normally smaller than both cement and fine aggregate, any replacement of these two constituents by fly ash will result in better workability and less water demand for the mix.

Each of these three methods of proportioning yields concretes of different qualities. To achieve desirable properties of a fly ash concrete, one has to carefully design the needed mix proportions. So far, there is no standard guideline for the procedures to be used. Trial mixes have been the way of life for this process, largely because of lack of understanding of the actual characteristics and performance of fly ash in concrete. The present study will attempt to address these problems and pin-point certain key factors for designing mix proportions.

2.7 High Strength Fly Ash Concrete

ACI 363 committee on high strength concrete has specified high strength concrete as concrete with a compressive strength of 6000 psi (41 MPa) or greater (ACI 363 1990). The basic concept to produce high strength concrete is to lower the water/cement ratio as much as possible, usually in the range of 0.25 to 0.30. In achieving this w/c ratio, many high strength concretes incorporate chemical admixtures, such as water reducing agents or high-range water reducing agents or superplasticizers and mineral admixtures such as fly ash or silica fume. The use of a good quality fly ash, meeting specification of ASTM C-618 Class F, is a must in the production of high strength concrete (Task Force Report No. 5, 1977). The fly ash added serves two purposes, one as pozzolanic material to provide additional C-S-H, and the other as filler to reduce voids between cement particles. Optimum amounts are in the range of 10% to 15% by weight of the cement. This may vary considerably in different areas due to the physical and chemical properties of the pozzolan and its reaction with various cements. When the combination between silica fume and fly ash was used, the optimum mix is a combination of 10% silica fume with 15% fly ash or slag by volume (Mehta and Aitcin 1990). Silica in the combined mixture provides early strength to concrete while fly ash which is an inert material serves as retarder but provides long term strength. Most high strength concrete mixes presently used contained both silica fume and fly ash.

Researchers at CANMET have developed high strength concrete of 50 MPa

(7250 psi) at 28 days by using water-reducing superplasticizer and incorporating of up to 40% fly ash by weight of cement (Malhotra 1984). Baoyu, Anqi, and Pengfei (1989) presented experimental results on the use of concrete incorporating condensed silica fume and fly ash to reduce cement content, lower temperature rise due to hydration, and to enhance early strength. Both experimental and field studies indicated that compared with a reference concrete (without condensed silica fume and fly ash) the concrete mixture containing condensed silica fume, fly ash, helped to save 38% cement, lower the heat of hydration by 40%, and showed a slight increase in strength and durability.

The use of fly ash in high strength concrete undoubtedly has been demonstrated to be beneficial to the integrity of the composites as well as the economical aspect of the final products. In any event, it should be noted that in such an application, fly ash was often used as generic material. While global performance of the fly ash high strength concrete is satisfactory, a clear understanding of how fly ash actually performs in high strength concrete environment remains unknown. This is primarily due to the lack of understanding of the behavior of the fly ash use. The present study uses series of fly ash of known origin, formation, physical and chemical characteristics. With these information, the author intends to study the role of fly ash in high strength concrete. Of particular interest will be the key parameters of fly ash governing the strength development of the final products.

2.8 Corrosion Resistance of Fly Ash Concrete

In a highly corrosive environment, conventional concrete often corrodes rapidly due to chemical attack of both concrete and the steel reinforcement, costing an enormous amount of money annually for repairs and maintenance of these structures. To improve the resistance of concrete against corrosion, many new cement-based materials such as polymer concrete, sulfate resistance concrete, etc.

have been developed. Unfortunately, these products are expensive and often economically not feasible for use in practice. One of the common forms of corrosion in concrete is probably due to chemical attack. These forms of chemical attack are the leaching out of cement, attack from sulfate and chloride from sea water and acid solutions.

To improve concrete durability against acid attack, many methods have been suggested. In general, the concept is to make concrete denser to produce lower permeability. Such low permeability concrete can be obtained by lowering the water/cement ratio of the mixes. Other methods suggested are the addition of polymer materials as additive, the use of sulfate-resisting cement, high-alumina cement or pozzolanic materials.

Perhaps the weakest links of the concrete products which are vulnerable to chemical attack are calcium hydroxide and calcium carbonate. To prevent these constituents from acid attacks, pozzolanic materials, such as fly ash, are introduced into concrete. The silica content in the fly ash reacts with free lime or calcium hydroxide generated from the hydration process of cement to form calcium silicate hydrate compound. This process ties up the available calcium hydroxide components, making it unavailable for acid attack. Furthermore, the C-S-H gel tends to fill up the remaining air voids in between fine aggregates and cement particles, making concrete denser, more impermeable and therefore more durable (Lane and Best 1982; Butler and Mearing).

With this common knowledge, many researchers have used fly ash to enhance the ability of concrete to resist chemical attack. Nasser and Lai (1990) and Irassar and Batic (1989) reported that Class F fly ash was a good source of pozzolan which could improve resistance of concrete to sulfate attack. The data on corrosion resistance of concrete samples monitored for more than three years indicated that concrete samples with 20% of cement replaced by fly ash protect the reinforcing bars from corrosion better than plain concrete (Maslehuddin, Saricimen, and Al-Mana 1987). Sheu, Quo, and Kuo (1990) studied the corrosion resistant property of fly ash mortar with different particle sizes (37, 48, and 74 microns) of fly ash in sodium sulfate solution. They concluded that among those mortar specimens tested, the ones with finer particle size (37 microns) of fly ash had greater resistance to sulfate attack than the control sample (without fly ash). These reported studies confirm the common knowledge on sulfate resistance of fly ash concrete but have not clearly revealed the actual corrosion resistant process nor indicated the exact characteristics or quantity of fly ash needed to achieve effective sulfate resistance. This was partly because the fly ash used was generic in nature which tends to vary widely as stated earlier. Without knowing the exact characteristics of fly ash, it is impossible to draw any definite conclusions which can be practically implemented. Although, the minimum proportion of fly ash required for sulfate resistance in concrete was believed to vary it was suggested that the fly ash content should not be less than 20% (ACI 225 1988). This suggestion is not clear in the sense that no specific information was given about the type of fly ash to be used and what extent of resistance that the amount of fly ash can provide to concrete.

The above corrosion studies were all due to sulfate attack on concrete. Acid attack is often found to be another major problem for the durability of concrete. For values of pH in the range between 3 to 6, the attack of acid progresses at a rate approximately proportional to the square root of time (Neville 1983). Severe damage on concrete sewer systems can cause by the bacterial action of Thiobacillus concreteavor, especially in warm climates. Sulfur-reducing bacteria reduce the sulfates present in natural water to produce hydrogen sulfide as a waste product. Another group of bacteria takes the reduced sulfur and oxidize it back to sulfuric acid (Thornton 1978). Thus attack from sulfuric acid occurs and gradually dissolves and deteriorates the concrete surface. This process is commonly known as "crown corrosion" in sewage collection systems. If such a corrosion can be prevented using fly ash concrete, the result would be very importance and beneficial. Obviously, fly ash to be used must be clearly defined as to its size, origination, and characteristics so that a better understanding on the acid resistant performance can be established. This concept will be evaluated here using different sizes and quantities of fly ashes.

2.9 Fly Ash Concrete Strength Model

In 1918, Duff A. Abrams (Abrams 1918) emphasized the importance of water in concrete mixtures, and showed that the water is the most important ingredient, since a very small variation in water content produces more important variations in the strength and other properties of concrete than similar changes in other ingredients. The equation for this behavior is in the form of:

$$f'_c = A/B^x \tag{2.1}$$

where

f'_c is the compressive strength of concrete

x is the ratio of volume of water to the volume of cement

A and B are constants whose values depend on the quantity of the cement used, age of the concrete, curing condition, etc.

The relation given above holds so long as the concrete is not too dry for maximum strength and the aggregate not too coarse for a given quantity of cement (workable mix).

Neville (1983) mentioned that Abrams' law, although established independently, is a special case of a general rule formulated by Feret in 1896. This was in the form

$$f'_c = K\{c/(c+w+a)\}^2 \tag{2.2}$$

where

c, w, a are the absolute volumes of cement, water, and air respectively

K is a constant

These two equations serve as the basis of a relationship between strength and cementitious components. These equations do not incorporate any contribution from other cementitious materials such as fly ash, kiln dust, silica fume, etc.

Dunstan (1986) modified Feret's formula with the assumption that the actual strength of concrete will be the combined product of the strength produced by the portland cement and those contributed by the addition of fly ash. His proposed expression was

$$f_{c+f} = (1+?)\, f'_c \tag{2.3}$$

with the final formula in the form of:

$$f_{c+f} = [1 + E_m f(1-f)^n/(1-f)]\, K\, \{c/(c+w+a)\}^2 \tag{2.4}$$

where

f_{c+f} is the total strength produced by cement and fly ash

E_m is the maximum efficiency index of fly ash to portland cement

f is the fly ash content = weight of fly ash/weight of cement+fly ash

n is constant

The values of E_m and n can both be calculated from actual concrete strength data. Three mixes are normally needed since there are three unknowns in the equations to be solved for. These include the constant K in Feret's relationship, and the values of E_m and n. Therefore, a mix with no fly ash and mixes with two different percentages of fly ash material will permit the calculation of all three values. Dunstan's proposed equation is actually an empirical correlation derived from experiments.

Another basic equation which is often used to correlate strength with cement content was proposed by Bolomey (Eq. 2.5). Popovics (1982) modified the Bolomey formula from

$$f'_c = K\{c/w - Z\} \tag{2.5}$$

to include the effect of pozzolan, his equation is in the form of:

$$f'_c = B\{(c+p)/w - 0.5\} - CF^n \tag{2.6}$$

where

f'_c is standard compressive strength of concrete at 28 days

c is cement content

p is pozzolan content

w is water content

$(c+p)/w$ is cementitious materials-water ratio

F = fly ash content in the cementitious materials and equals to $100p/(c+p)$, percent by weight.

B, C, Z, and n are constants

The suggested equation is again an empirical correlation with all constants being obtained through series of experiment data. The final equation was in the form of

$$f'_c = 3250\,\{(c+p)/w - 0.5\} - 0.6F^2 \tag{2.7}$$

Eriksen and Nepper-Christensen (1981) also modified Bolomey's formula by considering fly ash as a portion of cement. They also incorporated air content factor into the water content term. Their formula is shown in Eq. (2.8):

$$f'_c = K\,[(c+kf)/(w+a) - 0.5] \tag{2.8}$$

where

k is the activity index of fly ash

Bolomey formula was later modified by Slanicka (1991) to also include the contribution of fly ash with an introduction of a new parameter k_i, the activity index of fly ash.

$$f'_c = K\,[c/(w+a) + k_i\{F_i/(w+a)\}^{q_i} - Z] \tag{2.9}$$

He also modified Abrams' rule to

$$f'_c = A/B^x \tag{2.10}$$

where

k_i is activity index of fly ash and used as 0.25

q_i is and empirical exponent corresponding to a given sort of fly ash F_i. The introduction of the exponent q_i is justified by the fact that with the increasing dose of fly ash its contribution to the strength of concrete does not increase in a linear way.

$$x = [c/w + k_i(F_i/w)^{q_i}]^{-1} \tag{2.11}$$

All of the fly ash concrete strength models (Eriksen and Nepper-Christensen 1981; Popovics 1982; Dunstan 1986; Slanicka 1991) are empirical models. The model proposed by Eriksen and Nepper-Christensen does not consider the fineness of fly ash and their constant, the activity index, "k", is a constant for all kinds of fly ash (Eriksen and Nepper-Christensen 1981). In Popovics's formula, which is only valid for Class F fly ash, there are three experimentally determined empirical parameters (Popovics 1982). For Dunstan's model, three mixes are needed to solve for the three unknown constants (Dunstan 1986). Only Slanicka's model considers the effect of the fineness of fly ash on the strength of fly ash concrete which is usually incorporated in k and q. Fly ash with different fineness will have different constants. But the values of empirical coefficients are dependent on the properties of the cement, fly ash, and aggregates used, as well as, the curing condition. The formula is valid only for the conditions for which the constants were derived (Slanicka 1991).

Since all these investigations were conducted on a generic original fly ash whose properties varied widely, the proposed empirical equations predict results only for a rather specific condition of fly ash concrete. These equations could not be applied to any other conditions of fly ash concrete. Therefore, it is essential to develop a new strength model which is developed from studying the properties of series of fly ash concrete produced from known properties and characteristics of fly ash. This study will be attempted here as part of the objectives of this dissertation.

CHAPTER 3

OBJECTIVES OF THE DISSERTATION

The purpose of this study is to establish a simple combination of easily determined characteristics which can predict the performance of fly ash when used in concrete. To achieve this, it is essential to determine the properties of fly ash which affect the strength of concrete. Chemical composition, particle size distribution, and boiler combustion conditions have been selected as important factors. At the end of this study, fly ash concrete strength model is proposed and compared to the results obtained from the experiment and from other researchers results. The experimental work is divided into 6 parts as follow:

3.1 Effect of Boiler Types on Fly Ash Product

To better understand the behavior of fly ash, one needs to know how it was formulated. In this study, fly ash from two types of boiler, dry bottom and wet bottom, were used to make fly ash concrete. The strengths these concretes were correlated to the properties of each fly ash which has different formation since one was formulated at a temperature above the fusion of ash and the another below. The results from this study will help us understand the effect of combustion condition on the property of fly ash in concrete.

3.2 Properties of Fly Ash

Most investigations reported previously used fly ash as generic materials and often did not thoroughly understand all the properties of the fly ash added into concrete. In this study, prior to using any of the fly ashes to make concrete, physical and chemical properties of each fly ash were determined in accordance with ASTM standard. Since fly ash contains different particle size (from 1 to 300 microns) and its properties tend to vary significantly, it is then critical to study the effect of particle size on the strength of concrete. Fly ashes were separated into 6 different sizes with each fractionated particle size distribution range between 0-5, 0-10, 0-15, 0-20, 0-30, and 0-45 micron. The fractionated fly ashes and the original feed of fly ashes were once again reevaluated for their physical and chemical properties. This is to verify whether any variations exist among the various particle size distributions due to the fractionated process. With all the physical and chemical characteristics known for each fly ash, it is now ready to proceed to make fly ash concrete.

3.3 Fly Ash Mortar and Fly Ash Concrete

Normal and high strength fly ash concrete were made using fly ash of different particle sizes. The compressive, bending, and splitting tensile strengths and modulus of elasticity of fly ash concrete were examined and compared with the control concrete. Fly ash concrete made from the original feed of fly ash were also tested in the same manner as the fractionated fly ash concrete. The strength of these fly ash concretes both from the fractionated and the original feed fly ashes should help us understanding the role of particle size and its effect on the strength development of fly ash concrete. Thus a mix design can be formulated with confidence to achieve the desirable strength and durability of fly ash concrete. High strength concrete with and without silica fume were also cast and tested. The effect of fractionated fly ashes and silica fume concrete were investigated and compared with the control concrete. Fly ash concrete if to be practical must produce compressive strength of the same or higher than the conventional concrete without fly ash at early age i.e., before 28 days.

Dry and weathered fly ash were also used to make fly ash concrete. The effect of the dry and weathered fly ashes were studied and compared with the control concrete when fly ash is used as a replacement, as a partial addition and replacement of sand, and as an additive to concrete. The objective of this study is meant to investigate the effect of storage condition and the develop a process to accelerate the rate of strength gain of fly ash concrete. The setting times of fly ash-cement paste were also evaluated.

3.4 Fly Ash-Kiln Dust Mortar

Kiln dust and fly ash were mixed together in a mixture with and without cement. The optimum mix proportion between fly ash and kiln dust was determined based on their compressive strengths. Setting times of fly ash-kiln dust paste were also examined and compared with the normal cement paste. The objective of this study is to develop a usable product of fly ash-kiln dust mixture which may be used as construction materials.

3.5 Corrosion Resistance of Fly Ash Mortar

The corrosion resistance of fly ash mortars was investigated using fly ashes of known physical and chemical characteristics. Fly ash is introduced as a pozzolan into mortar with the basic knowledge that it will react with the calcium hydroxide in mortar, thus reduces the amount of free lime which is vulnerable to acid attack. Fly ash mortar specimens made of different percentages of fractionated fly ash and normal cement were immersed into a concentrated sulfuric acid solution to evaluate for their resistance to acid attack. The strength and weigh losses due to acid attack will be monitored. The results should provide a definite rate of degradation and the exact type and quantity of fly ash needed to maintain the strength and integrity of the fly ash concrete.

3.6 Fly Ash Concrete Strength Model

Finally, the study will attempt to find a relationship between the properties of fly ash and its behavior in concrete. A fly ash concrete strength model will be proposed based on the key parameters affecting the properties of fly ash concrete. With this model, it is expected to predict the compressive strengths of fly ash concrete at any ages.

CHAPTER 4

MATERIALS AND EXPERIMENTAL METHODS

4.1 Experimental Program

In this chapter, the experimental programs for studying the influence of selected parameters on the compressive strength of mortar and concrete containing different kind of fly ashes with different particle sizes were conducted. Boiler types, chemical composition, fly ash fineness, and particle size distributions of fly ash are among the main parameters to be studied. The effect of fly ash on the compressive, bending, splitting tensile strength, modulus of rupture, and modulus of elasticity of mortar and concrete were carried out using different mix proportions and different fly ashes. The study also includes the development of high strength concrete using fly ash and investigation on the corrosion resistance of the fractionated fly ash concrete. In addition, fly ash-kiln dust mortars were also mixed and tested for their compressive strength.

Fly ashes used in this study were collected from a utility in the Northeastern section of the U.S. Fly ashes of different sources named DH, H, M, and P were used in this program. The last sample was obtained in both dry and weathered states as described earlier. Simulation of the storage condition as "washed and soaked" fly ash were produced in the laboratory.

The standard ASTM 2"x2"x2" cube and 3"x6" cylinder specimens for study the compressive strengths of mortar and concrete were used, respectively. The 3"x6"x27" beam specimens were selected for studying the bending or flexural strength of concrete. All tests were performed on a MTS closed-loop servo hydraulic testing machine. Details of these test programs are planned as follows:

4.2 Materials

Materials used in this study consist of standard portland cement type I, Ottawa sand, siliceous sand (river sand), coarse aggregate, fly ash, kiln dust, silica fume, superplasticizer, dispersing agent, and water.

Cement-A standard portland cement type I.

Sand-Two kinds of sand have been selected in this program. Graded sand predominant graded between the No. 300 (0.06 mm) sieve and the No. 100 (0.150 mm) sieve conforming to ASTM C-778 (1990) was used as a standard sand. Another local siliceous sand (river sand) passing through sieve No. 4 (opening size 4.75 mm) was also used for casting mortar and concrete.

Coarse Aggregate-Crushed basalt coarse aggregate size of 3/8" was used for casting concrete.

Fly Ash-Four different kinds of fly ash were selected in this experiment:

1) DH fly ash
2) Dry and weathered fly ashes
3) Wet bottom fly ash
4) Dry bottom fly ash

Dry and weathered fly ashes were used to evaluate the affect of weathering on the property of fly ash. The Dry bottom and Wet bottom fly ashes were selected to study the influence of boiler and its combustion condition. The DH fly ash was used since it consists of known combustion condition at various states of power demand.

All fly ashes were generated in the local power plants. The local utility provided two kinds of fly ash of different storage conditions, dry and weathered. Dry fly ash is the type of fly ash coming out from the precipitators and is usually stored in the hopper or in the silo for immediate delivery if the demand exists. The excess fly ash is often mixed with agitated water from a nearby river and pumped into two big storage ponds. The ash in the pond is commonly known as weathered fly ash.

To investigate the effect of boiler types upon the fly ash product, wet bottom and dry bottom fly ashes are selected for the study. These two types of fly ashes were fractionated into different particle sizes. The fractionated fly ashes were cast and tested to study its effect on the strength of concrete and mortar.

Kiln Dust-Kiln dust used in this experiment was generated from a local cement manufacture.

Silica Fume-Silica fume is a by-product from the silicon metal industry. It often comes in very fine particle of size less than 1 micron. Normally consists of 96-98% of reactive SiO_2. Silica fume used in this study is in powder form. The addition of silica fume was intended to produce high strength concrete.

Superplasticizer-Superplasticizer is a common additive for concrete. It is normally used to lower the water-cement ratio in concrete. The process is often employed to produce high strength concrete.

Dispersing Agent-Sodium hexametaphosphate ($NaPO_3$) was normally used as a dispersing agent. The addition of dispersing agent in the fly ash concrete mix was to ensure that lumps of weathered fly ash were dispersed into fine particles and could, as a result, be more reactive.

Water-Tap water was used throughout the experiment program.

4.3 Test Program

4.3.1 Chemical Composition of Fly Ashes, Kiln Dust, and Cement

Chemical composition of fly ashes, kiln dust, and cement were determined by X-Ray Fluorescence (ASTM D-4326 1990).

4.3.2 Particle Size Analysis of Fly Ash

For DH, dry and weathered fly ashes, the distribution of particle sizes larger than 75 microns (retaining on 200 sieve) are determined by wet sieve analysis, while the distribution of particle sizes smaller than 75 microns are determined by sedimentation process, using a hydrometer (ASTM D-422 1989).

For the fly ash from the wet bottom and dry bottom, the particle sizes of fly ash larger than 75 microns were determined by wet sieve analysis while the particle sizes smaller than 75 microns were determined by Microtrac, a laser-based particle sizer.

4.3.3 Fly Ash Fineness

The fineness of fly ash were measured using two different methods; the Blaine air permeability and the fineness by the 45 microns (No. 325) sieve.

For the Blaine air permeability, the fineness was in term of the specific surface expressed as total surface area in square centimeters per gram, or square meters per kilogram, of fly ash. The results obtained from the Blaine fineness was a relative fineness rather than absolute fineness. The test procedure followed ASTM C-204 (1990).

The fineness of fly ash retained on the sieve 45 microns (No. 325 sieve) was determined by the amount of fly ash retained when wet sieved on the No. 325 sieve in accordance with the ASTM C-430 (1990) test method, except that the fly ash sample was used instead of hydraulic cement.

4.3.4 Setting Time of Cement-Fly Ash and Cement-Fly Ash-Kiln Dust Paste

Setting time of cement-fly ash and cement-fly ash-kiln dust paste were determined by Vicat needle and Gillmore needles. The test methods followed ASTM C-191 (1990) for Vicat test and ASTM C-266 (1990) for Gillmore test.

4.3.5 Fly Ash Mortar

Fly ash from DH, H, dry, and weathered fly ashes were mixed with cement and Ottawa sand. The replacement of a portion of portland cement by fly ash was varied, 0%, 15%, 25%, and 35% by weight of cementitious (cement + fly ash) materials. The specimens were mixed and cast in accordance with ASTM C-109 (1990). All specimens were cured in saturated lime water and tested at the age of 1, 3, 7, 14, 28, 56, and 90 days.

4.3.6 Fly Ash with Kiln Dust

Dry and weathered fly ashes were used to study the effect of fly ash, kiln dust, and cement on the strength of mortar. The standard ASTM 2"x2"x2" cube mortars were prepared and tested for their compressive strengths. The selection of a 2"x2"x2" cube rather than the standard 3"x6" cylinder was that fly ash mortar was more a resemblance of cement and the 2"x2"x2" cube is a standard specimens used for testing cement based on ASTM specification. These series of test were carried out in three phases as follows:

Phase I Dry and weathered fly ashes were mixed with kiln dust and river sand. The percentage of fly ash was varied, 20%, 40%, 60%, and 80% by weight of kiln dust plus fly ash. The specimens were tested for their compressive strengths up to 90 days.

Phase II Only weathered fly ash was mixed with kiln dust. The percentage of fly ash was varied from 10% to 90% with increments of 10%. The water to cementitious (fly ash + kiln dust) materials ratio was kept constant at 0.275. Fly ash-kiln dust samples were tested for compressive strength at the age of 1, 3, 7, 14, 28, 56, 90, and 180 days.

Phase III Dry and weathered fly ashes were mixed with kiln dust, river sand, and cement. The percentage of cement and fly ash were varied, 20%, 40%, 60%, and 80% by weight of cementitious (cement + fly ash + kiln dust) materials. All specimens were cured in saturated lime water and tested at the age of 1, 3, 7, 14, 28, 56, 90, and 180 days.

4.3.7 Fly Ash as a Replacement

Dry and weathered fly ashes were used as a replacement of cement. By keeping the water, river sand, and cementitious (cement+fly ash) materials as constants, cement was replaced by fly ash. The replacement of fly ash (dry or weathered) was varied from 10% to 40% by weight of cementitious materials. All the specimens were cured in saturated lime water. The compressive strengths of 2"x2"x2" cube mortars were tested at the age of 1, 3, 7, 14, 28, 56, 90, and 180 days.

4.3.8 Fly Ash as a Partial Addition and Replacement of Sand

In this test, 10% by weight of sand was replaced by fly ash and after that fly ash was added in mortar. The addition of fly ash was varied from 10 to 40% by weight of cement. Both dry and weathered fly ashes were used. All the specimens were cured in saturated lime water until the time of testing. This is to ensure that moisture and lime are available to provide any potential reaction which may occur. The compressive strengths of 2"x2"x2" cube mortars were tested at the age of 1, 3, 7, 14, 28, 56, 90, and 180 days.

4.3.9 Fly Ash as an Additive

Dry and weathered fly ashes were used as an additive in the mortar. By keeping the cement, river sand, and water as constants, fly ash was added directly in the mix. The addition of fly ash was varied from 10% to 40% by weight of cement. All the specimens were cured in saturated lime water and tested for their compressive strengths at the age of 1, 3, 7, 14, 28, 56, 90, and 180 days.

4.3.10 Soaked and Washed Fly Ash

Dry fly ash was soaked and washed for used in this experiment. The soaked fly ash was done by covering the dry fly ash with water for 1 week. Everyday the soaked fly ash was stirred to make sure that every particles of fly ash were soaked by water. After 7 days, the water of soaked fly ash and soaked fly ash were used for casting mortar specimens.

The washed fly ash was prepared by covering the dry fly ash with water, then stirring it until it mixed together. The fly ash slurry was then allowed to settle for one day and then the water was replaced with tap water. The process was repeated the next day. By repeating this process for 1 week, the washed fly ash was created for casting mortar specimens. The washed and soaked fly ash were used as an additive and as a replacement of cement. The 2"x2"x2" cube mortars were selected to investigate the compressive strengths. The compressive strengths were tested from 1 to 180 days. Table 4.1 shows the mix proportions of the experiment program from section 4.3.5 to 4.3.10

4.3.11 Effect of Fractionated Fly Ashes on the Strength of Concrete

Dry and wet bottom fly ashes were separated into different particle sizes by using the Micro-Sizer Air Classifying System (Figure 4.1). Six particle size distributions of each fly ash were fractionised from small to large. The fractionated fly ashes from dry, wet bottom, and the original feed fly ashes were used as a replacement of cement 15%, 25%, 35% and 50% by weight of cementitious materials. The compressive strengths of fractionated fly ash concrete were tested from 1 day to 180 days. The effect of particle size from 0-5, 0-10, 0-15, 0-20, 0-30, 0-44 micron, and the original feed fly ashes are investigated and compared with the control concrete. The 3"x6" cylinder was used to determine the compressive strength of fractionated fly ash concrete. The mix proportion of this test program is shown in Table 4.2.

Table 4.1 Mix Proportion

Series	Sam	C				S/C		$\frac{W}{C}$	D g/l
		Cem.	Dry FA	Wea. FA	Kiln Dust	Ottawa Sand	River Sand		
I	PC	100%	--	--	--	2.75	--	0.50	--
	PD15	85%	15%	--	--	2.75	--	0.50	--
	PW15	85%	--	15%	--	2.75	--	0.50	--
	PD25	75%	25%	--	--	2.75	--	0.50	--
	PW25	75%	--	25%	--	2.75	--	0.50	--
	PD35	65%	35%	--	--	2.75	--	0.50	--
	PW35	65%	--	35%	--	2.75	--	0.50	--
	DD25	75%	25%	--	--	2.75	--	0.50	40
	DW25	75%	--	25%	--	2.75	--	0.50	40
II	A	100%	--	--	--	2.75	--	0.485	--
	B15	85%	15%	--	--	2.75	--	0.485	--
	C25	75%	25%	--	--	2.75	--	0.485	--
	D35	65%	35%	--	--	2.75	--	0.485	--
III	C	100%	--	--	--	2.75	--	0.50	--
	FA15	85%	15%	--	--	2.75	--	0.50	--
	FA25	75%	25%	--	--	2.75	--	0.50	--
	FA35	65%	35%	--	--	2.75	--	0.50	--
IV	HC	100%	--	--	--	--	2.75	0.50	--
	HD15	85%	15%	--	--	--	2.75	0.50	--
	HW15	85%	--	15%	--	--	2.75	0.50	--
V	KD20	--	20%	--	80%	--	2.75	0.55	--
	KW20	--	--	20%	80%	--	2.75	0.55	--
	KD40	--	40%	--	60%	--	2.75	0.55	--
	KW40	--	--	40%	60%	--	2.75	0.55	--
	KD60	--	60%	--	40%	--	2.75	0.55	--
	KW60	--	--	60%	40%	--	2.75	0.55	--
	KD80	--	80%	--	20%	--	2.75	0.55	--
	KW80	--	--	80%	20%	--	2.75	0.55	--

Notes:

1. C - Cementitious Materials (Cement+Fly Ash+Kiln Dust)
   S - Sand
   W - Water
   D - Dispersing Agent, Sodium Hexametaphosphate($NaPO_3$)

2. Series: I. Dry or Weathered Fly Ash + Cement + Ottawa Sand
   II. DH Fly Ash + Cement + Ottawa Sand
   III. H Fly Ash + Cement + Ottawa Sand
   IV. H Fly Ash + Cement + River Sand
   V. Dry or Weathered Fly Ash + Kiln Dust + River Sand

Table 4.1 Mix Proportion (Continued)

Series	Sam.	C				S / C		$\frac{W}{C}$
		Cem.	Dry FA	Wea FA	Kiln Dust	Ottawa Sand	River Sand	
VI	WK10	--	--	10%	90%	--	--	0.275
	WK20	--	--	20%	80%	--	--	0.275
	WK30	--	--	30%	70%	--	--	0.275
	WK40	--	--	40%	60%	--	--	0.275
	WK50	--	--	50%	50%	--	--	0.275
	WK60	--	--	60%	40%	--	--	0.275
	WK70	--	--	70%	30%	--	--	0.275
	WK80	--	--	80%	20%	--	--	0.275
	WK90	--	--	90%	10%	--	--	0.275
VII	AKD00	20%	--	--	80%	--	2.75	0.50
	AKD20	20%	20%	--	60%	--	2.75	0.50
	AKW20	20%	--	20%	60%	--	2.75	0.50
	AKD40	20%	40%	--	40%	--	2.75	0.50
	AKW40	20%	--	40%	40%	--	2.75	0.50
	AKD60	20%	60%	--	20%	--	2.75	0.50
	AKW60	20%	--	60%	20%	--	2.75	0.50
	AKD80	20%	80%	--	--	--	2.75	0.50
	AKW80	20%	--	80%	--	--	2.75	0.50
	BKD00	40%	--	--	60%	--	2.75	0.50
	BKD20	40%	20%	--	40%	--	2.75	0.50
	BKW20	40%	--	20%	40%	--	2.75	0.50
	BKD40	40%	40%	--	20%	--	2.75	0.50
	BKW40	40%	--	40%	20%	--	2.75	0.50
	BKD60	40%	60%	--	--	--	2.75	0.50
	BKW60	40%	--	60%	--	--	2.75	0.50
	CKD00	60%	--	--	40%	--	2.75	0.50
	CKD20	60%	20%	--	20%	--	2.75	0.50
	CKW20	60%	--	20%	20%	--	2.75	0.50
	CKD40	60%	40%	--	--	--	2.75	0.50
	CKW40	60%	--	40%	--	--	2.75	0.50
	DKD00	80%	--	--	20%	--	2.75	0.50
	DKD20	80%	20%	--	--	--	2.75	0.50
	DKW20	80%	--	20%	--	--	2.75	0.50
	EK0	100%	--	--	--	--	2.75	0.50

Notes:
1 C - Cementitious Materials (Cement+Fly Ash+Kiln Dust)
S - Sand
W - Water
2. Series: VI. Weathered Fly Ash + Kiln Dust
VII. Dry or Weathered Fly Ash + Cement + Kiln Dust + River Sand

Table 4.1 Mix Proportion (Continued)

Series	Sam.	Cem. (g)	Dry FA. (g)	Wea. FA. (g)	River Sand (g)	Water (mL)
VIII	JC	500	-	-	1375	250
	RD10	450	50	-	1375	250
	RD20	400	100	-	1375	250
	RD30	350	150	-	1375	250
	RD40	300	200	-	1375	250
	RW10	450	-	50	1375	250
	RW20	400	-	100	1375	250
	RW30	350	-	150	1375	250
	RW40	300	-	200	1375	250
IX	ED10	500	100	-	1325	250
	ED20	500	150	-	1325	250
	ED30	500	200	-	1325	250
	ED40	500	250	-	1325	250
	EW10	500	-	100	1325	250
	EW20	500	-	150	1325	250
	EW30	500	-	200	1325	250
	EW40	500	-	250	1325	250
X	AD10	500	50	-	1375	250
	AD20	500	100	-	1375	250
	AD30	500	150	-	1375	250
	AD40	500	200	-	1375	250
	AW10	500	-	50	1375	250
	AW20	500	-	100	1375	250
	AW30	500	-	150	1375	250
	AW40	500	-	200	1375	250

Table 4.1 Mix Proportion (Continued)

Series	Sam.	Cem. (g)	Soaked FA (g)	Washed FA (g)	River Sand (g)	Water (mL)
XI	JC	500	-	-	1375	250
	JR15	425	75	-	1375	250
	JA15	500	75	-	1375	250
	TR15	425	-	75	1375	250
	TA15	500	-	75	1375	250
	JR25	375	125	-	1375	250
	JA25	500	125	-	1375	250
	TR25	375	-	125	1375	250
	TA25	500	-	125	1375	250

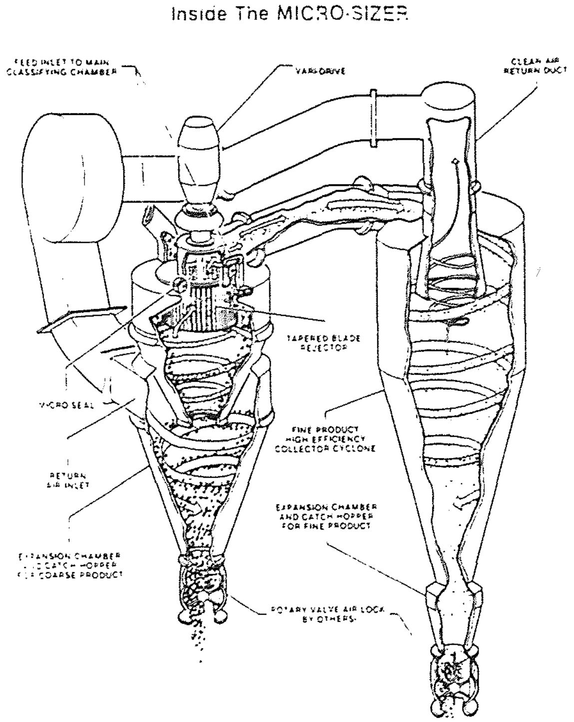

Figure 4.1 Micro-Sizer Air Classifying System

Table 4.2 Mix Proportion of Fractionated Fly Ash Concrete

Ingredients	Fractionated Fly Ash (Dry and Wet Bottom) by Weight				
	0	15%	25%	35%	50%
Cement	1.00	0.85	0.75	0.65	0.50
Fly Ash	--	0.15	0.25	0.35	0.50
Sand	2.00	2.00	2.00	2.00	2.00
Aggregate	3.00	3.00	3.00	3.00	3.00
Water	0.50	0.50	0.50	0.50	0.50
Water/(Cem+FA)	0.50	0.50	0.50	0.50	0.50

4.3.12 Effect of Fractionated Fly Ashes on the Strength of Mortar

For fly ash mortar, a standard size of 2"x2"x2" cube was used to determine the compressive strength of fractionated fly ash mortars. The mix proportion of fractionated fly ash mortar is shown in Table 4.3.

Table 4.3 Mix Proportion of Fractionated Fly Ash Mortar

Ingredients	Fractionated Fly Ash (Dry and Wet Bottom) by Weight			
	0	15%	25%	50%
Cement	1.00	0.85	0.75	0.50
Fly Ash	--	0.15	0.25	0.50
Sand	2.75	2.75	2.75	2.75
Water	0.50	0.50	0.50	0.50
Water/(Cem+FA)	0.50	0.50	0.50	0.50

4.3.13 Effect of Calcium Oxide (CaO) on the Strength of Fractionated Fly Ash Mortar

The fractionated fly ashes, 6F, 16F, 1C, 18C, and the original feed of dry and wet bottom fly ashes, are used to mix to form cement mortar. An extra calcium oxide is added into the mix in 10%, 20%, and 30% by weight of fly ash+calcium oxide. First, calcium oxide was allowed to absorb the mixing water for 3 to 5 minutes and then mixed together. Fly ash, then added into the mixer and mixed with the calcium oxide slurry. After that cement and sand were added and mixed with the calcium oxide-fly ash slurry. The fractionated fly ash mortar with calcium oxide was cast, cured, and tested as the previous section for fly ash mortar. The mix proportion of fractionated fly ash mortar with calcium oxide is shown in Table 4.4.

Table 4.4 Mix Proportion of Fractionated Fly Ash Mortar Mixed with Calcium Oxide

Sam No.	Type of Fly Ash	Mix Proportion			CaO/(Fly Ash+CaO) (%)
		Cement	CaO	Fly Ash	
CA0	-	1.00	-	-	0
DCA0	Dry	0.65	-	0.350	0
DCA10	Dry	0.65	0.035	0.315	10
DCA20	Dry	0.65	0.700	0.280	20
DCA30	Dry	0.65	0.105	0.245	30
WCA0	Wet	0.65	-	0.350	0
WCA10	Wet	0.65	0.035	0.315	10
WCA20	Wet	0.65	0.700	0.280	20
WCA30	Wet	0.65	0.105	0.245	30
6CA0	6F	0.65	-	0.350	0
6CA10	6F	0.65	0.035	0.315	10
6CA20	6F	0.65	0.700	0.280	20
6CA30	6F	0.65	0.105	0.245	30
16CA0	18F	0.65	-	0.350	0
16CA10	18F	0.65	0.035	0.315	10
16CA20	18F	0.65	0.700	0.280	20
16CA30	18F	0.65	0.105	0.245	30
1CA0	1C	0.65	-	0.350	0
1CA10	1C	0.65	0.035	0.315	10
1CA20	1C	0.65	0.700	0.280	20
1CA30	1C	0.65	0.105	0.245	30
18CA0	18C	0.65	-	0.350	0
18CA10	18C	0.65	0.035	0.315	10
18CA20	18C	0.65	0.700	0.280	20
18CA30	18C	0.65	0.105	0.245	30
CA10	-	0.965	0.035	-	0
CA20	-	0.930	0.070	-	0
CA30	-	0.985	0.105	-	0

Note: Water/(Cement+CaO+Fly Ash) = 0.50
(Cement+Fly Ash+CaO):Sand Ratio = 1:2.75

4.3.14 High Strength Fly Ash and Silica Fume Concrete

The very fine particle sizes of fly ashes, i.e. the particle smaller than 5 microns, were employed to produce high strength fly ash concrete. Fifteen and twenty five percent of fly ash by weight of cementitious materials were used in the concrete as a replacement for cement. Silica fume in the powder form was also used in the same proportion as the fly ash. The compressive strength of the high strength fly ash concrete and silica fume concrete were determined and compared. The mix proportion of high strength fly ash and silica fume concrete is shown in Table 4.5.

Table 4.5 Mix Proportion of High Strength Fly Ash and Silica Fume Concrete

Ingredient	CSF, Control (lb)	15% Repl. (lb)	25% Repl (lb)
Cement	10	8.5	7.5
Fly Ash or Silica Fume	--	1.5	2.5
River Sand	20	20	20
Aggregate, Basalt 3/8"	30	30	30
Super P.	100 ml	100 ml	100 ml
Water	4.17	4.17	4.17
Water/(Cementitious)	0.417	0.417	0.417

4.3.15 Bending Strength of Fly Ash Concrete

Concrete beams with dimension of 3"x6"x27" were used to evaluate the bending strength of fly ash concrete (using simple beam with third-point loading). The specimen has a test span within 2% of being three times its depth as tested. The test procedure was in accordance with ASTM C-78 (1990).

Fly ash concrete with a 25% replacement of the original feed of dry and wet bottom fly ashes as a cement in cementitious materials was used in this study. The bending strengths of fly ash concrete beams were determined at the age of 28 days and 90 days. The 3"x6" cylinders were also cast and tested at the same time as the concrete beams. Splitting tensile and compressive strengths were also tested on the same date of the beams. The relationship between compressive strength and bending strength of fly ash concrete and control concrete were evaluated.

4.3.16 Relationship between Tensile Strength (Splitting Test) and Compressive Strength of Fractionated Fly Ash Concrete

Splitting is an indirect method for measuring tensile strength of concrete. The standard test method for splitting tensile strength of cylindrical concrete specimen is given by ASTM C-496 (1990). The 3"x6" cylinders of fractionated fly ash concrete at the age of 180 days were used to investigate the compressive and splitting tensile strength.

4.3.17 Modulus of Elasticity of Fractionated Fly Ash Concrete

Compressive strengths of fractionated fly ash concrete were tested using the MTS closed loop machine. The rate of loading was control by 2-clip gages using the loading rate recommended by ASTM C-469 (1990). The test set up for compressive strength and modulus of elasticity is presented in Figure 4.2. Compressive load and displacement of concrete under the compressive load were recorded by data acquisition board and transferred to the computer. The modulus of elasticity of fractionated fly ash concrete was taken to be the slope of the stress-strain curve at 50% of the ultimate strength. The modulus of elasticity of fractionated fly ash concrete were determined by using 3"x6" cylinder specimens. Fractionated fly ash concretes with 15%, 25%, 35%, and 50% replacement were studied and compared.

4.3.18 Corrosion Resistance of Fly Ash Mortar

Fractionated fly ashes, 6F, 16F, and the original feed of dry bottom fly ash (DRY), and wet bottom fly ash (WET) were mixed with cement to form fly ash cement mortar. Standard 2-inch cubes were cast and cured in saturated lime water about 60 days before being put into the acid pond. The mix proportions used are tabulated in Table 4.6. The percentage of fly ash used in the mixes was 25 and 50 percent by weight of cementitious (cement+fly ash) materials. Fly ash was used as cement replacement. The water to cementitious materials ratio of all mixes was kept constant at 0.5. Fly ash cement mortar samples and the control samples (no fly ash) were then immersed in the H_2SO_4 acid solution with a concentration of 100 ml/l. All samples were kept under the same corrosive environment until the date of testing. To evaluate the extent of the damage caused by acid attack, the samples were removed from the acid pond and washed with tap water. The samples were then weighed at the saturated surface dry condition. The weight loss was then determined by comparison with the weight of original sample recorded earlier.

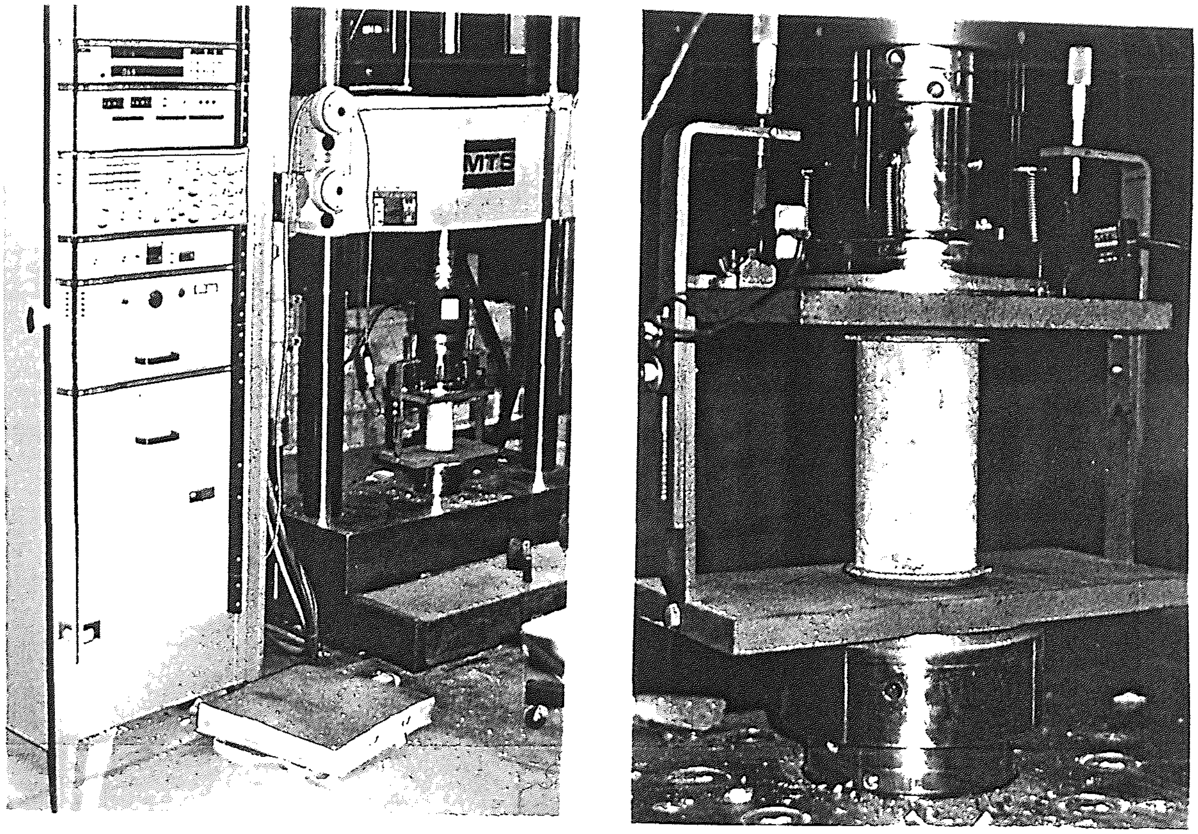

Figure 4.2 Test Set up for Compressive Strength and Modulus of Elasticity

Table 4.6 Mix Proportion of Fly Ash Mortar to Resist Acid Attack

Sample	Cement	Fly Ash	Sand	W/(C+F)	Type of Fly Ash
CF	1.00	-	2.75	0.50	-
DRY25	0.75	0.25	2.75	0.50	DRY ORIGINAL FEED
WET25	0.75	0.25	2.75	0.50	WET ORIGINAL FEED
6F25	0.75	0.25	2.75	0.50	6F
16F25	0.75	0.25	2.75	0.50	16F
DRY50	0.50	0.50	2.75	0.50	DRY ORIGINAL FEED
WET50	0.50	0.50	2.75	0.50	WET ORIGINAL FEED
6F50	0.50	0.50	2.75	0.50	6F
16F50	0.50	0.50	2.75	0.50	16F

4.3.19 Fly Ash Concrete Strength Model

Attempts are made to relate the compressive strength of fractionated fly ash concrete and selected parameters of fly ash. The results of fractionated fly ash concrete with different mix proportions were used to find the proposed model. After that, the data of fly ash concrete from other researchers were also used to verify the validity of the proposed model.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Chemical Composition

5.1.1 Chemical Composition of Fly Ashes, Kiln Dust, and Cement

Table 5.1 shows the chemical composition of fly ashes, kiln dust, and cement used in this study. According to ASTM C-618 (1990), all fly ashes are classified as Class F fly ash since the oxide of SiO_2 + Al_2O_3 + Fe_2O_3 are higher than 70%. Dry and weathered fly ashes have a little different in chemical composition. Dry fly ash has 53.53% of SiO_2 while the weathered fly ash has 50.15%. Al_2O_3 content for the dry and weathered fly ashes is 26.70% and 29.11%, respectively. The calcium oxide content which is believed to effect the rate of reactivity is 1.65% for the dry fly ash and 1.70% for the weathered. According to the results, there is no chemical change associated with the process of weathering.

Table 5.1 Chemical Composition of Fly Ashes, Kiln Dust, and Cement

Constituent	Dry FA	Wea FA	H Dry FA	DH FA		Kiln Dust	Cement Type I
				1983	1990		
SiO_2	53.57	50.15	50.64	50.50	50.95	12.29	19.96
Al_2O_3	26.70	29.11	27.19	29.10	29.30	7.07	8.92
CaO	1.65	1.70	2.31	1.55	1.39	43.23	59.33
MgO	0.77	0.81	0.79	0.70	0.88	2.73	3.10
Fe_2O_3	5.08	6.12	11.51	12.40	12.11	3.32	2.72
Na_2O	0.30	0.51	0.29	-	0.28	0.39	0.43
K_2O	1.99	1.95	2.18	2.69	1.90	2.59	0.88
SO_3	0.70	0.10	0.64	0.34	0.53	5.56	2.76
Moisture(%)	0.23	0.65	0.21	0.36	0.23	-	-

The results of chemical composition of DH fly ash, which was tested in 1983 (Liskowitz et al. 1983) and again in 1990, were very close. It can be concluded that the chemical composition of fly ash does not change with time when stored under dry condition. Also, Yasuda, Niimura, and Iizawa (1991) reported that fly ash stored under wet field conditions for about 3 months was not impaired in quality.

The chemical composition of kiln dust is close to cement because it is a by-product of cement manufactures. Since kiln dust has a high content of CaO, it processes some cementing property. It is noted that the SO_3 content of kiln dust is 5.56% while for cement is 2.76%. The moisture content of the fly ashes are found to be very close and low. The dry fly ashes have as little moisture content as 0.21% by the dry weight. However, the moisture content of weathered fly ash which was air dried in the laboratory about a month before use was a little higher than the other dry fly ashes. The moisture content of DH fly ash reduced from 0.36 in 1983 to 0.23 in 1990. According to ASTM C-618 (1990), the moisture content of fly ash can be allowed to be as high as 3%. All fly ashes used in this experiment have low moisture contents which are within the limit of ASTM C-618.

5.1.2 Chemical Composition of Fractionated Fly Ashes

The chemical composition of fractionated fly ashes are shown in Table 5.2. Sample CEM is the cement sample used in this study. Samples DRY and WET are the fly ashes from the original feed of dry and wet bottom ashes, respectively. 3F is the finest fly ash sample of the dry bottom ash and 13F is the finest sample of the wet bottom ash. The coarsest fly ashes samples of dry and wet bottom ash are 1C and 18C, respectively.

Both types of fly ashes are classified as Class F fly ash according to ASTM C-618 (1990). Most of the fractionated fly ashes have some slight variation in the oxide composition when the particle sizes changed. It has been reported that separation of Class F with high calcium fly ash into size fraction does not reveal major chemical morphological or mineralogical speciation between particles (Hemming and Berry 1986). The SiO_2 content tends to be lower when the particle size is larger. The major differences in chemical compositions of the two fly ashes are in the SiO_2, Fe_2O_3, and CaO contents. Samples of the dry bottom fly ash are about 10% richer in SiO_2 than the wet bottom fly ash. The CaO content of the dry bottom fly ash varies from 1.90% to 2.99%, while for wet bottom fly ash, the variation is from 6.55% to 7.38%. Fe_2O_3 content of wet bottom fly ash is two times higher than that of the dry bottom fly ash. The highest concentration of Fe_2O_3 of each type of fly ashes is in the coarsest particle sizes, i.e., 1C and 18C.

Table 5.2 Chemical Composition of Fractionated Fly Ashes and Cement

	Chemical Composition (%)								
Sam	LOI	SO_3	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	Na_2O
CEM	0.73	2.53	20.07	8.84	1.41	60.14	0.86	2.49	0.28
3F	4.97	1.69	49.89	26.94	5.43	2.99	1.76	0.99	0.33
5F	4.10	1.53	50.27	26.74	5.30	2.95	1.74	0.93	0.33
6F	3.12	1.09	51.40	26.54	4.91	2.72	1.71	0.74	0.31
10F	2.52	0.72	51.98	26.23	4.44	2.28	1.60	0.54	0.29
11F	2.04	0.53	51.27	26.28	4.42	2.02	1.55	0.49	0.26
1C	1.46	0.39	53.01	26.50	5.66	1.90	1.61	0.56	0.24
DRY	2.75	0.98	52.25	26.72	5.43	2.41	1.67	0.69	0.28
13F	2.67	3.81	38.93	24.91	12.89	6.85	2.10	1.55	1.31
14F	1.94	3.47	39.72	25.08	13.02	6.71	2.11	1.50	1.31
15F	1.88	3.33	40.25	25.02	13.12	6.60	2.11	1.47	1.30
16F	2.06	3.05	40.65	24.92	13.26	6.55	2.09	1.41	1.26
18F	1.94	2.94	41.56	24.47	14.21	6.58	2.01	1.40	1.17
18C	2.55	2.40	43.25	23.31	17.19	7.38	2.00	1.30	0.88
WET	2.05	3.13	41.54	24.74	14.83	6.89	2.07	1.43	1.17

It is interesting to note that after fly ash was fractionated into different sizes, loss on ignition (LOI) of the finest particle is the highest. The LOI content gradually decreases as the particle size increases. The coarser size of fly ash often has lower LOI content than the raw fly ash (Berry et al. 1989). Ravina (1980) also had the same observation, that the finest particle of fly ashes has the highest LOI values. The results obtained by Ukita, Shigematsu, and Ishii (1989) also showed that the chemical composition did not changed when the mean diameter of fly ash changed from 17.6 microns to 3.3 microns while LOI increased from 2.78 to 4.37. These results are in conflict with the report of ACI 226 Committee (1987) and of Sheu, Quo, and Kuo (1990) which stated that the coarse fraction usually has a higher LOI than the fine fraction.

5.2 Particle Size Analysis of Fly Ash

5.2.1 Particle Size Analysis of Dry, Weathered, H, and DH Fly Ashes

The particle size distributions of dry, weathered, H, and DH fly ashes are shown in Figures 5.1, 5.2, and 5.3 respectively.

In Figure 5.1, it can be observed that the weathered fly ash has more finer particles than the dry one. The extra finer particles are believed to be clay or dust since the weathered fly ash was in the pond for a long period of time and collected all kinds of contaminants from the river water which it was mixed. Furthermore, the average particle size of the weathered fly ash depends a great deal on the location in the pond where ash was collected. The closer to the discharge to the pond, the larger is the average particle size of fly ash.

Considering the particle size distribution of H dry and weathered fly ashes in Figure 5.2, it is seen that the distribution of both curves are very close. This means that the weathered fly ash, produces in the laboratory by soaked dry fly ash for 2 months, did not influence the particle size distribution of the ash.

5.2.2 Particle Size Analysis of Fractionated Fly Ashes

The particle size distributions of fractionated fly ashes from the dry and wet bottom boilers are shown in Figures 5.4 and 5.5, respectively. The curves for the original feed fly ashes are not as steep as others since it has a wider range of size distribution.

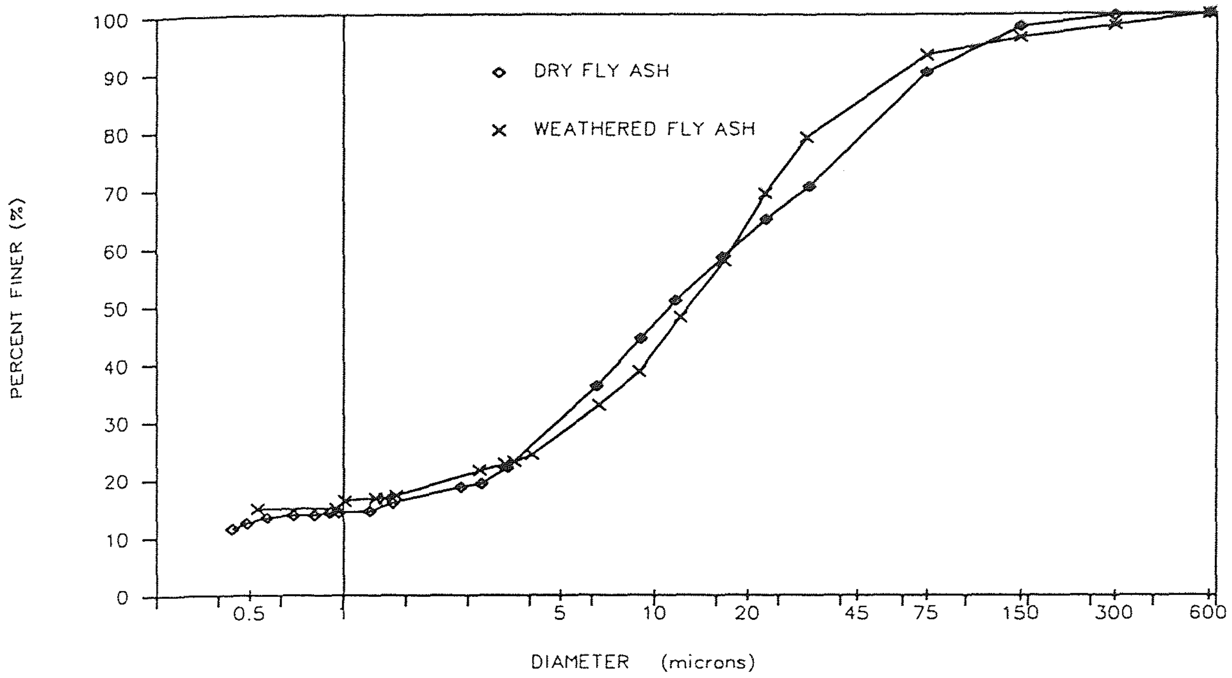

Figure 5.1 Particle Size Distributions of Dry and Weathered Fly Ashes

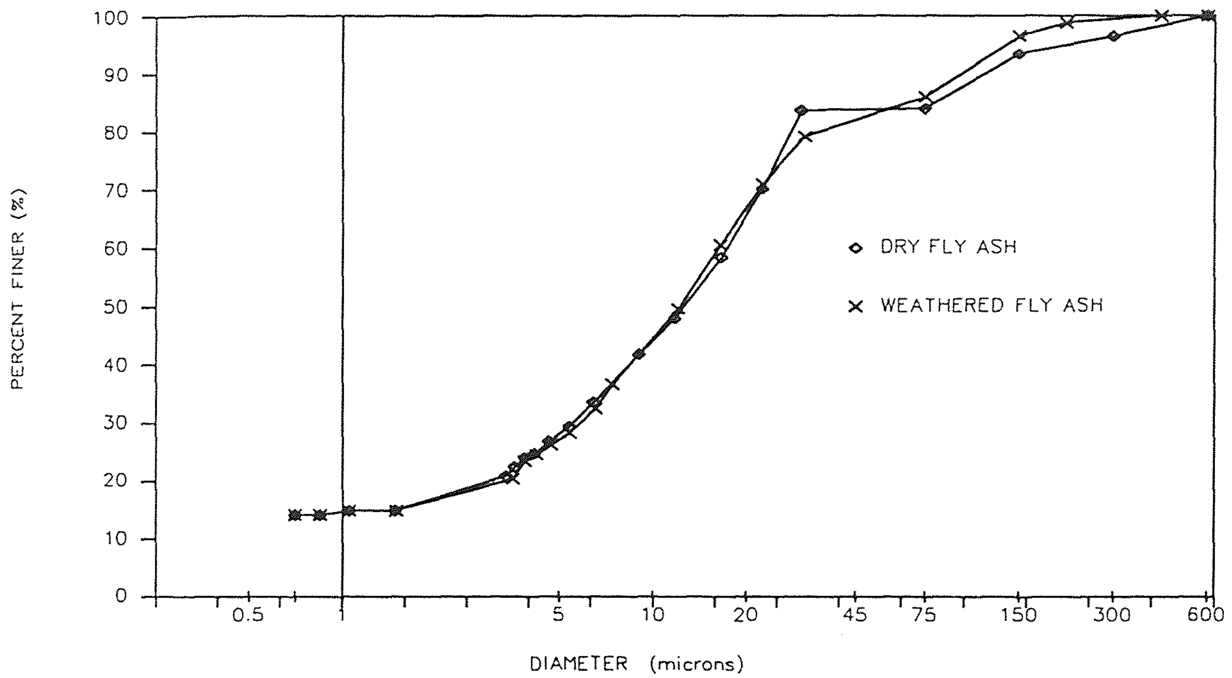

Figure 5.2 Particle Size Distributions of H Dry and Weathered Fly Ashes

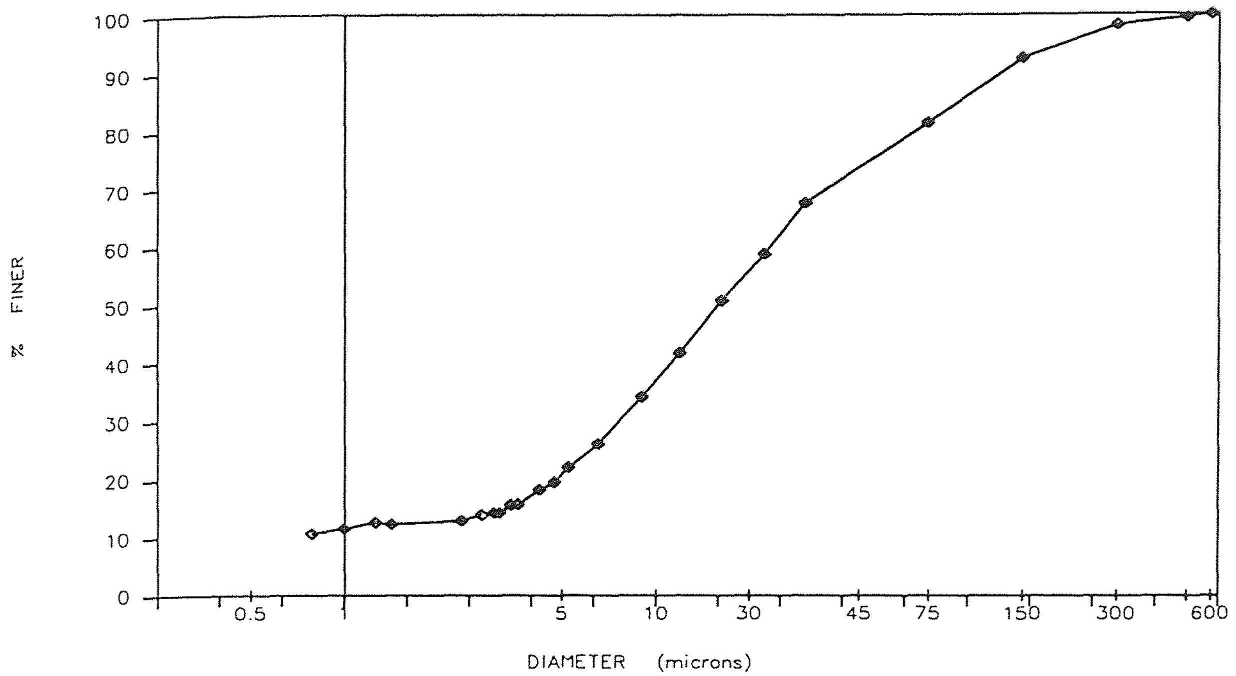

Figure 5.3 Particle Size Distribution of DH Fly Ash

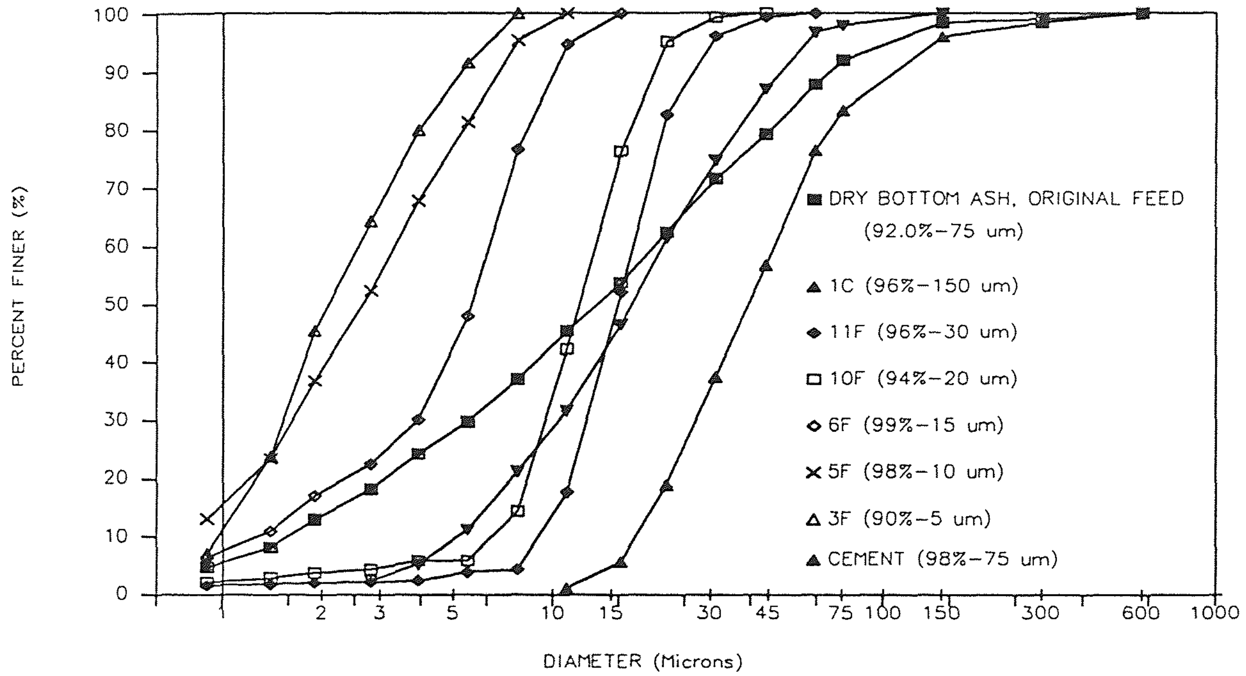

Figure 5.4 Particle Size Distributions of Fractionated of Dry Bottom Fly Ashes

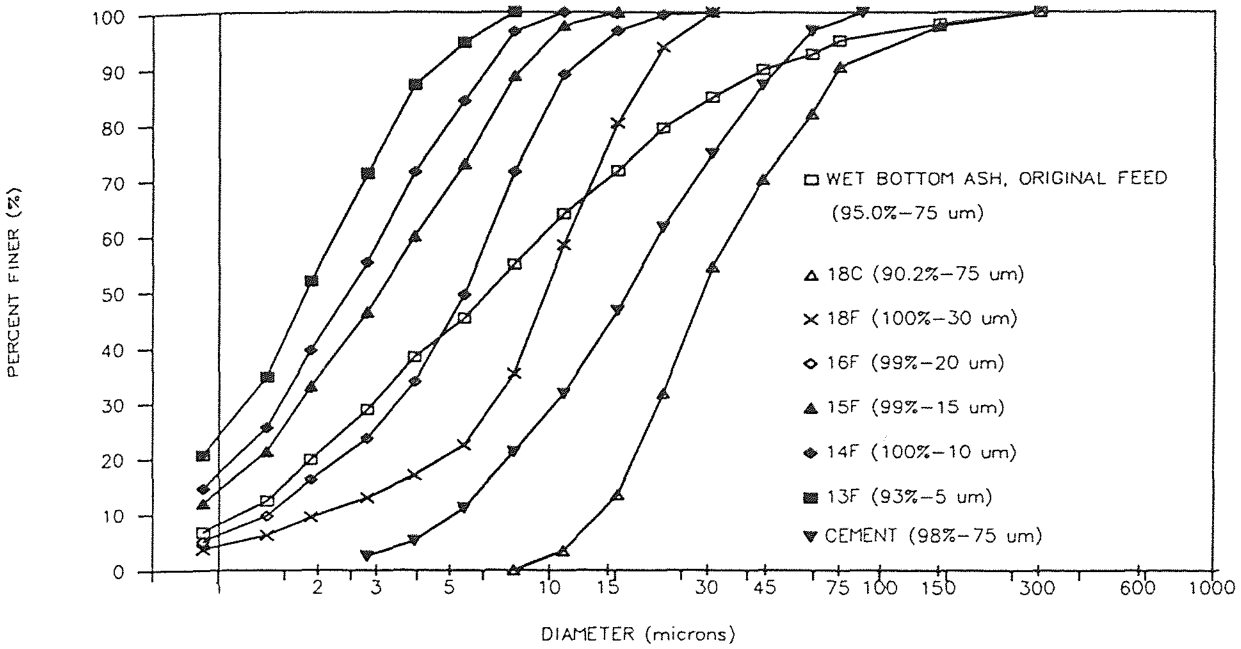

Figure 5.5 Particle Size Distributions of Fractionated of Wet Bottom Fly Ashes

From the original feed, each type of fly ash was fractionated into six ranges. As shown in Figures 5.4 and 5.5, the particle size of fly ash varied from 0-5.5 micron to 0-600 micron. In case of the 3F fly ash, the finest of dry bottom fly ash, 3F (90%-5 um) means that 90% of the fly ash particles are smaller than 5 microns. The mean diameters of 3F and 13F are 2.11 and 1.84 microns, respectively while the average diameters of the coarsest particle sizes, 1C and 18C, are 39.45 and 29.25 microns, respectively. For wet bottom fly ash, 13F is the finest with 18C as the coarsest. The original feed of wet bottom fly ash was found to be finer than the original feed of dry bottom fly ash. The particle sizes of original feed of dry fly ash vary from about 1 micron to 600 microns with the mean particle of 13.73 microns. For the original feed of wet bottom fly ash, the largest particle size are 300 microns with the average diameter of 6.41 microns. When the particle sizes are smaller, they are more spherical particles in the fraction (Hemming and Berry 1986).

The color of the fractionated of dry bottom fly ashes from fine to coarse varied from light gray to dark gray while for the wet bottom fly ashes the color changed from light brown to dark brown. This may be the coarser particles possess a higher portion of bottom ash which is in black color. Usually, the color of fly ash varies widely from light tan to brown and from gray to black (Lane and Best 1982). The same observation result on the variation of color was also reported by Yasuda, Niimura, and Iizawa (1991).

5.3 Fineness of Fractionated Fly Ash

The fineness of fly ashes both by wet sieve analysis and by the Blaine fineness together with the specific gravity of fly ashes are shown in Table 5.3. Mean diameter, the diameter of which 50 percent of particles are larger than this size, is also presented in this table. According to ASTM C-618 (1990), the fractionated 1C fly ash is the only sample that fails to meet the fineness requirement since the retained of the fly ash on sieve No. 325 is higher than 34%.

Two methods were used to measure the fineness of fractionated fly ashes. The first method is by determining the residue on the 45 microns (No. 325) sieve. Using the sieve No. 325 method, the fractionated fly ash samples 3F, 5F, 6F, 10F, 13F, 14F, 15F, 16F and 18F have the same fineness since all of them have zero value retained on this sieve. The second method is the surface area measurement by air permeability test. Opinions differ as to whether sieve residue or surface area are better indicator of fly ash fineness (Cabrera, et al. 1986). In the United States, the fineness of fly ash is specified by the residue on the 45 microns sieve only. Ravina (1980) found that pozzolanic activity is better indicated by specific surface area measurements but Lane and Best (1982) argued that the 45 microns sieve residue is a more consistent indicator than the surface area. White and Roy (1986) concluded that the fineness parameter given in the Blaine fineness is not as important as the fly ash size fraction less than 45 microns. The author disagrees with White and Roy especially in the case of fractionated fly ashes since the latter sections proves that the active particle size of fly ash are smaller than 45 microns.

Table 5.3 Fineness of Cement and Fractionated Fly Ashes

Sam. No.	Specific Gravity (g/cm^3)	Fineness		Mean Diameter (um)
		Retained 45 um (%)	Blaine (cm^2/g)	
CEM	3.12	-	3815	-
3F	2.54	0	7844	2.11
5F	2.53	0	6919	2.66
6F	2.49	0	4478	5.66
10F	2.42	0	2028	12.12
11F	2.40	1.0	1744	15.69
1C	2.28	42.0	1079	39.45
DRY	2.34	20.0	3235	13.73
13F	2.75	0	11241	1.84
14F	2.73	0	9106	2.50
15F	2.64	0	7471	3.09
16F	2.61	0	5171	5.54
18F	2.51	0	3216	9.84
18C	2.42	29.0	1760	29.25
WET	2.50	10.0	5017	6.41
DRY FA	2.25	22.0	3380	11.51
WEATHERED	2.20	18.0	2252	13.22
H	2.30	15.0	2748	13.15
DH	2.24	26.0	2555	18.30

It can be noted that the finer the particle size of fractionated fly ashes, the higher the specific gravity and the Blaine fineness. In general, higher fineness fly ash will have higher specific gravity than the lower ones, in agreement with previous investigation (Hansson 1989). Density of fly ash from different plants varied from 1.97 to 2.89 g/cm^3 but normally ranges between about 2.2 to 2.7 g/cm^3 (Lane and Best 1982). Work done by McLaren and Digiolia (1990) reported that Class F fly ash had a mean specific gravity value of 2.40. The specific gravity of fractionated fly ashes vary from 2.28 for the coarsest fly ash to 2.54 for the finest fly ash of the dry bottom fly ash and from 2.22 for the coarsest to 2.75 for the finest of the wet bottom fly ash. This result may be because the very fine particles are thick-walled, void free or, composed of more dense glasses and crystalline components (Hemming and Berry 1986).

The Blaine fineness is the highest in the finest sample, 13F, which is 11241 cm^2/g. Figure 5.6 shows the relationship between the Blaine fineness and mean diameter of fly ash. The relationship can be expressed as:

$$\text{Blaine fineness} = 15818*(\text{mean diameter})^{-0.7074} \quad \text{with } R^2 = 0.9396$$

It should be noted that this relationship is derived from analysis of both the dry and wet bottom fly ashes used in this study. The Blaine fineness increases inversely with the mean diameter. The result presented here also confirms with those reported by Aitcin et al. (1986), which showed that if the average diameters, D_{50}, of fly ash are smaller, the surface area of the fly ash will be larger than those with larger average diameters. The specific gravity of fractionated fly ashes increase with the decrease of the average particle size.

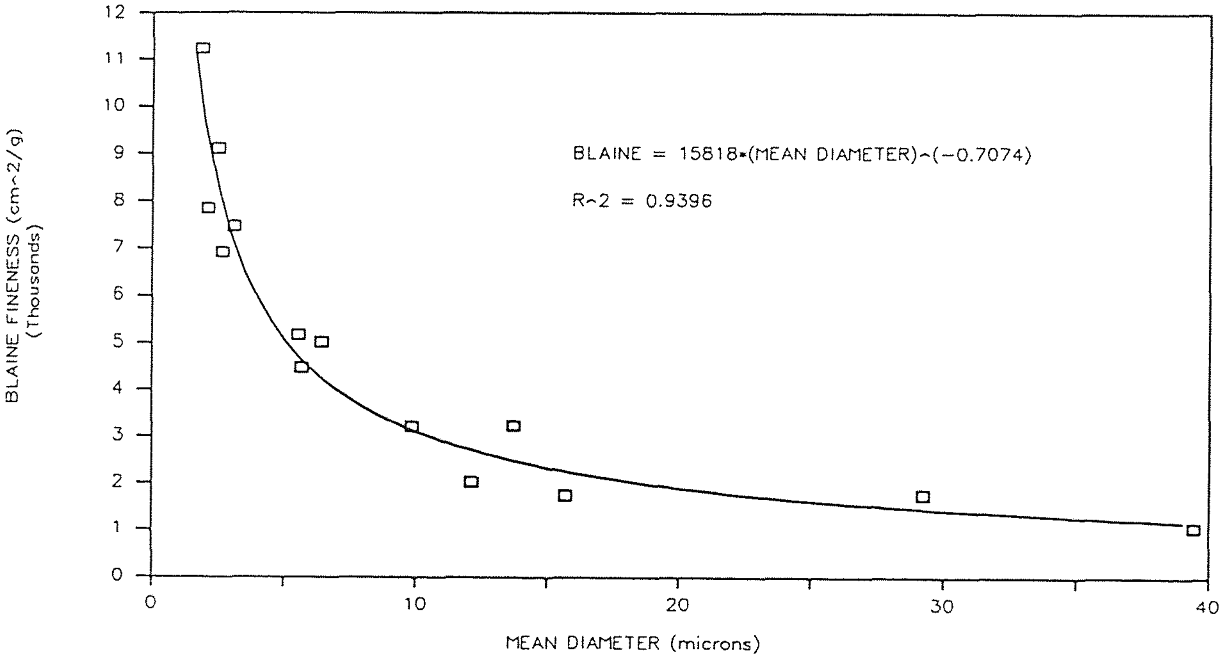

Figure 5.6 Relationship between the Blaine Fineness and the Mean Diameter (D_{50}) of Fly Ashes

5.4 Fly Ash Mortar with Ottawa Sand

5.4.1 Dry and Weathered Fly Ash Mortar

In this experiment, dry and weathered fly ashes were used as a replacement of cement of 0%, 15%, 25%, and 35% by weight of cementitious (fly ash+cement) materials. The mix proportion is shown in Table 4.1, series I.

It is seen in Tables 5.4 and 5.5 that all of fly ash specimens show lower compressive strength than the control (no fly ash) strength at the same age. For the same quantity of fly ash used, the dry fly ash produces higher strength than the weathered fly ash. The higher the percentage of fly ash in the mix, the lower the compressive strength.

Figures 5.7 and 5.8 show the effect of cement replacement using dry and weathered fly ashes on the strength of mortar. The rate of strength gain of fly ash mortar is slower than that of cement mortar at early ages (7 days or before). This effect always occurs when fly ash replaces cement on a one-to-one ratio by weight (David et al. 1937; Lane and Best 1984; ACI 226 1987; Courst 1991). The replacement of the dry fly ash 15% lowers the strength about 8% compared with the control strength at the age of 90 days while the weathered fly ash in the same amount lowers strength about 12%. The compressive strength with replacement of 35% with the dry fly ash varies from 59.2% at 1 day to 78.5% at 90 days of the control strength and varies from 35.4% at 1 day to 60.3% at 90 days for the weathered fly ash. The differences of the strength gain of the dry and weathered fly ash specimen may be due to the deleterious substances in the weathered fly ash. Since the weathered fly ash was in a pond of brackish water it probably contained organic impurities which were harmful to the strength of mortar. Another reason is that the weathered fly ash is coarser than the dry fly ash because the Blaine fineness of the weathered fly ash is 2252 cm^2/g which is lower than the dry fly ash (3380 cm^2/g).

Table 5.4 Compressive Strength of Dry and Weathered Fly Ash Mortar

Sample No.	Compressive Strength (psi)						
	1-day	3-day	7-day	14-day	28-day	56-day	90-day
PC	1601	2357	2715	3210	3303	3728	4158
PD15	1473	1954	2304	2637	3130	3615	3827
PD25	1032	1690	2083	2218	2535	3304	3559
PD35	948	1395	1842	1742	2003	2886	3263
PW15	1008	1711	1939	2534	2866	3592	3689
PW25	855	1383	1816	1953	2578	2900	3231
PW35	566	1383	1694	1915	2328	2414	2508
DD25	-	2153	2400	2775	3278	3487	3811
DW25	178	1705	1785	2371	2584	3078	-

Table 5.5 Percentage Compressive Strength of Dry and Weathered Fly Ash Mortar

Sample No.	Percentage of Compressive Strength (%)						
	1-day	3-day	7-day	14-day	28-day	56-day	90-day
PC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
PD15	92.0	82.9	84.9	82.1	94.7	97.0	92.0
PD25	64.5	71.7	76.7	69.1	76.7	88.6	85.6
PD35	59.2	59.2	67.8	54.3	60.6	77.4	78.5
PW15	63.0	72.6	71.4	78.9	86.8	96.4	88.7
PW25	53.4	58.7	66.9	60.8	78.1	77.8	77.7
PW35	35.4	58.7	62.4	59.7	70.5	64.8	60.3
DD25	-	91.3	88.4	86.4	93.2	93.5	91.7
DW25	11.1	72.3	65.7	73.9	78.3	82.6	-

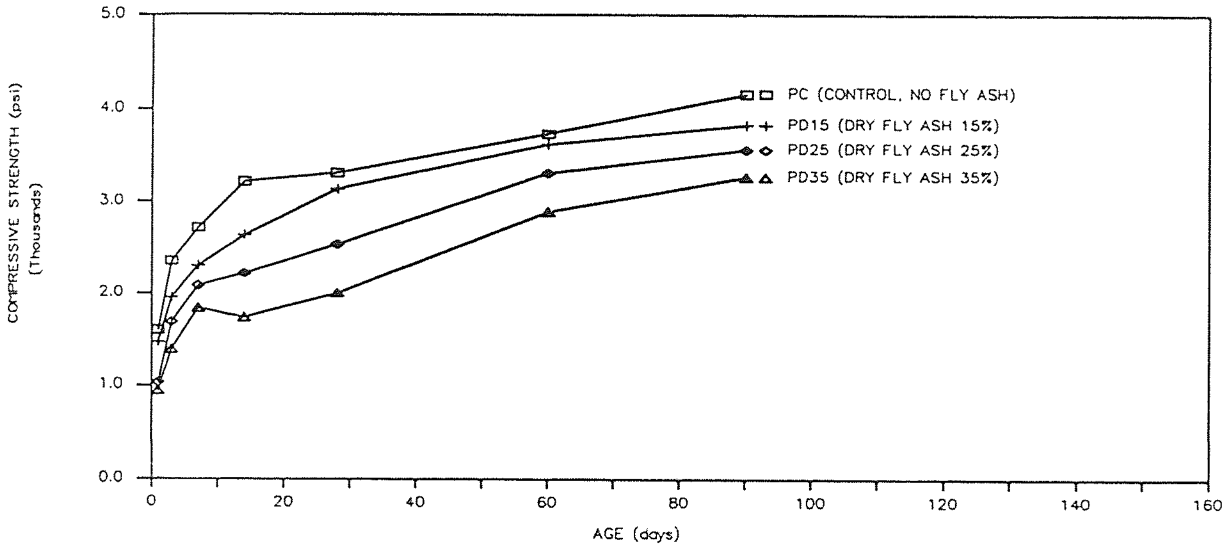

Figure 5.7 Effect of Replacement the Dry Fly Ash on the Strength of Mortar

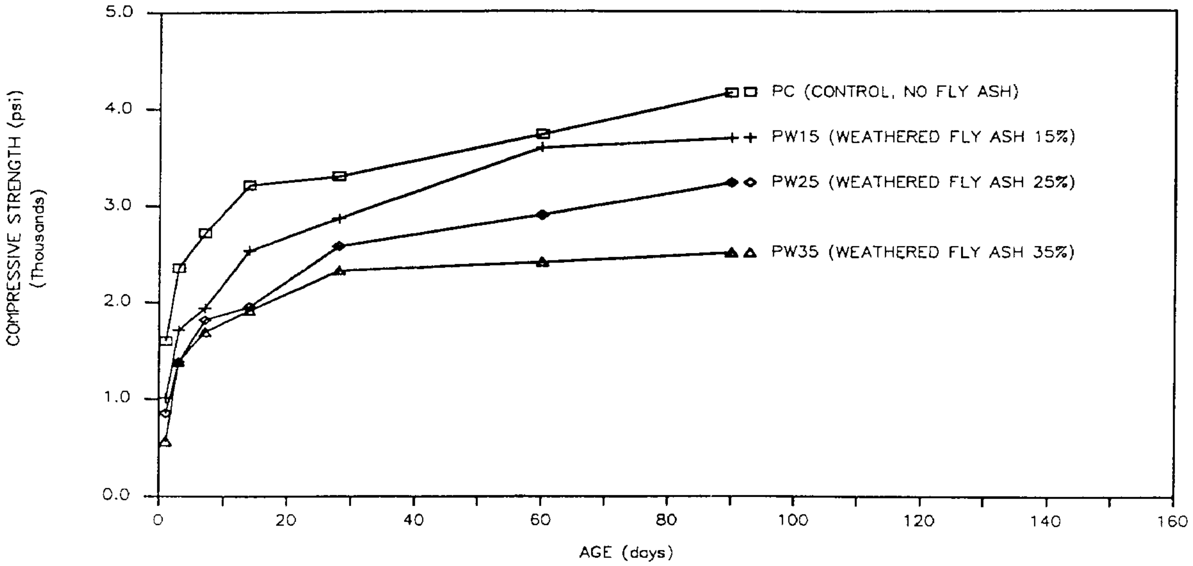

Figure 5.8 Effect of Replacement the Weathered Fly Ash on the Strength of Mortar

5.4.2 Compressive Strength of DH Fly Ash Mortar

DH fly ash from previous collection in 1983, was also used to replace cement. The percentage of fly ash in the mix was varied from 15% to 35% by weight of cementitious materials. The water/(cement+fly ash) ratio was kept constant at 0.485. The mix proportion is shown in Table 4.1 series II.

Tables 5.6 and 5.7 show the compressive strength and the percentage compressive strength of DH fly ash mortar relative to the control strength (sample A). Figure 5.9 shows that the compressive strengths of fly ash mortar are always lower than the control strength at the same age up to 90 days. With the replacement of 15% of the dry fly ash, the strength of mortar is 1074 psi at 1 day and 3554 psi at 90 days or 77.7% and 97.2% respectively, of the control strength. The strengths of fly ash mortar are 89.7%, 76.8%, and 58.8% of the control strength with 15%, 25%, and 35% cement replacement at 28 days. At the age of 90 days, the replacement 15% of fly ash has a higher compressive strength than the replacements of 25% and 35%.

Table 5.6 Compressive Strength of DH Fly Ash Mortar

Sample No.	Compressive Strength (psi)						
	1-day	3-day	7-day	14-day	28-day	56-day	90-day
A	1383	1843	2619	2974	3450	3551	3645
B15	1074	1548	2106	2310	3095	3497	3554
C25	1041	1351	1894	2086	2648	3201	3370
D35	804	1084	1435	1648	2029	2548	2732

Table 5.7 Percentage Compressive Strength of DH Fly Ash Mortar

Sample no.	Percentage Compressive Strength (%)						
	1-day	3-day	7-day	14-day	28-day	56-day	90-day
A	100.0	100.0	100.0	100.0	100.0	100.0	100.0
B15	77.7	84.0	80.4	77.7	89.7	98.5	97.2
C25	75.3	73.3	72.3	70.1	76.8	90.1	92.5
D35	58.1	58.8	54.8	55.4	58.8	71.8	74.9

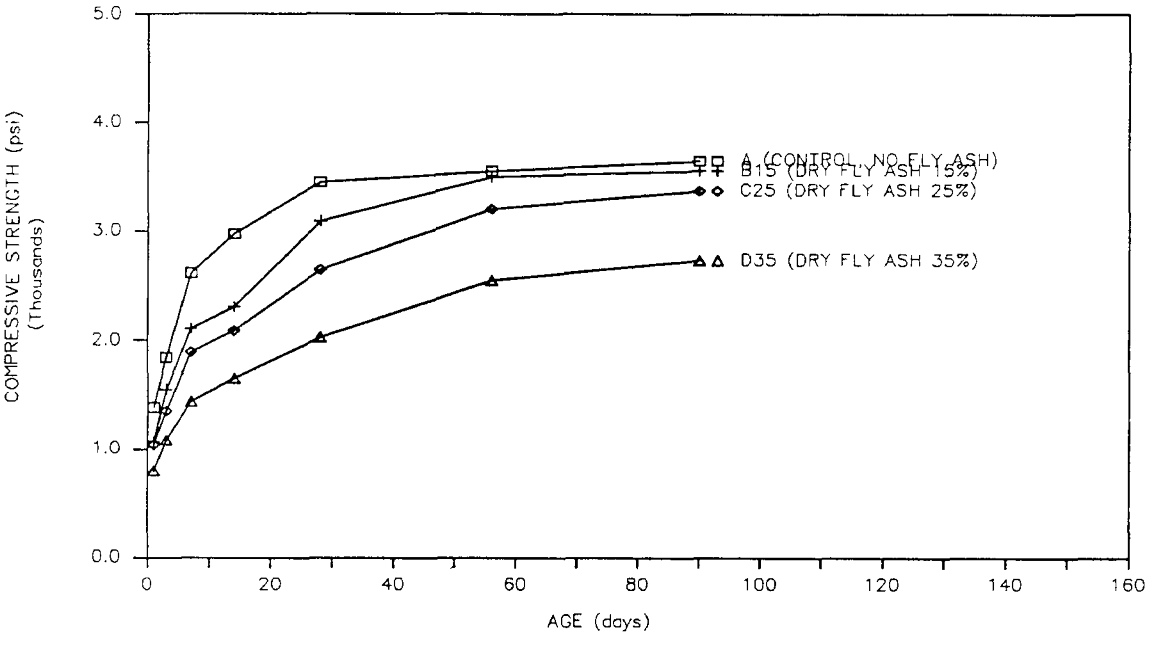

Figure 5.9 Effect of Replacement DH Fly Ash on the Strength of Mortar

The percentage of fly ash used as cement replacement dictates the strength of the composites, the more fly ash used, the lower the compressive strength will be. The extent of strength reduction of fly ash mortar from control mix is large at early age, up to 40% for the 35% replacement, and reduces to about 25% at the age of 90 days.

5.4.3 Compressive Strength of H Fly Ash Mortar

H dry fly ash from previous collection was used as a replacement of cement. The percentage of fly ash in the mix was varied from 15% to 35% by weight of cementitious materials. The water/(cement+fly ash) ratio was kept constant at 0.50. The mix proportion is shown in Table 4.1, series III.

Tables 5.8 and 5.9 show the compressive strength and the percentage compressive strength of H fly ash mortar comparing with the control strength (sample C). Figure 5.10 shows the effect of replacement H fly ash on the strength of mortar.

The replacement of cement by H fly ash in mortar results in a lower compressive strength up to 180 days. The higher the percentage of fly ash in the mix, the lower is the compressive strength. The 28-day strength of FA15, FA25, and FA35 are 2613 psi, 2311 psi, and 1917 psi, or 79.9%, 70.7%, and 58.6%, respectively, compared with the control strength. At 180 days, the 15% replacement gives a strength almost the same as the control strength. At 1-day, the strength of FA35 is only 46.8% compared to the control strength and increases to about 75% at 180 days. The use of fly ash for 25% replacement lowers the compressive strength about 7% of the control strength at the age of 180 days. It is seen that the use of H fly ash up to 25% gives a compressive strength of mortar nearly 95% of the control strength at 180 days.

Table 5.8 Compressive Strength of H Fly Ash Mortar

Sample No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
C	1682	2240	2687	3040	3269	3492	3604	3998
FA15	1013	1978	2169	2384	2613	3173	3416	3876
FA25	1101	1561	2084	2133	2311	2736	3010	3728
FA35	788	1321	1680	1754	1917	2400	2536	2996

Table 5.9 Percentage Compressive Strength of H Fly Ash Mortar

Sample No.	Percentage Compressive Strength (%)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
C	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
FA15	60.2	88.3	80.7	78.4	79.9	90.9	94.8	97.0
FA25	65.5	69.7	77.6	70.2	70.7	78.3	83.5	93.2
FA35	46.8	59.0	62.5	57.7	58.6	68.7	70.4	74.9

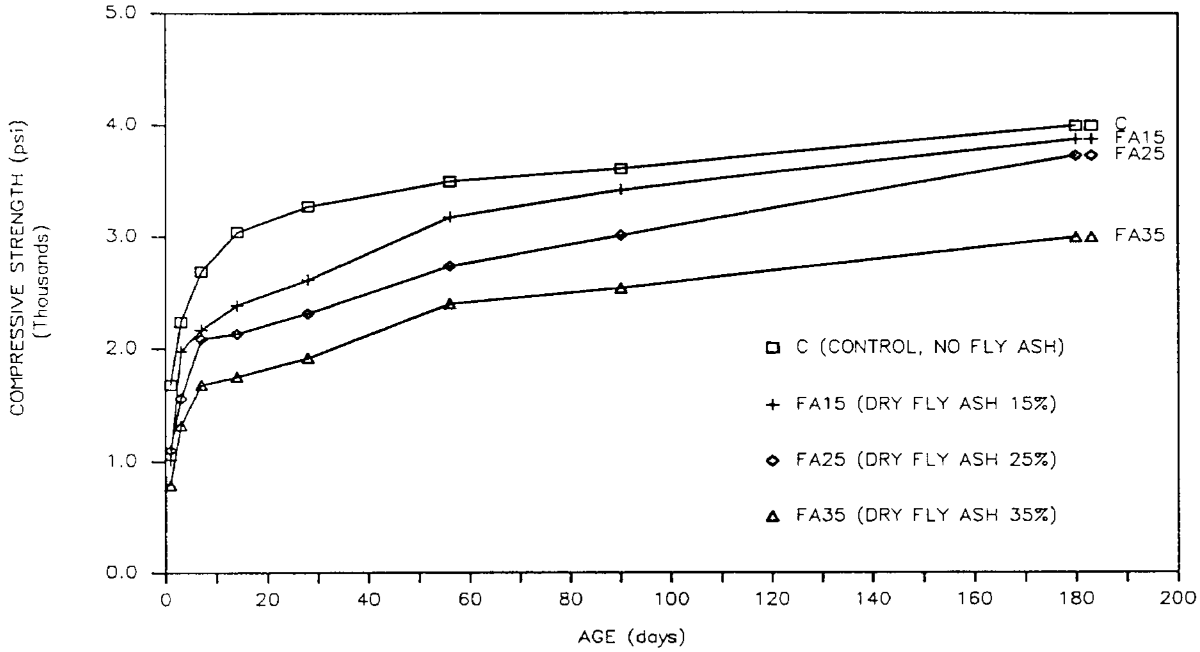

Figure 5.10 Effect of Replacement H Fly Ash on the Strength of Mortar

5.4.4 H Weathered Fly Ash

In this study, simulating H weathered fly ash was carried out in the laboratory by mixing H dry fly ash with water and soaking for about 2 months. The objective of this test is to study the difference between the use of dry and simulated weathered fly ashes on the strength of mortar. The use of the dry and weathered fly ashes was investigated and compared when 15% of fly ash was used as a cement replacement. The mix proportion of this program is shown in Table 4.1 series IV.

From Tables 5.10 and 5.11, the results show that the use of fly ash lowers the compressive strength of mortar at early ages. The effect of cement replacement using H dry and weathered fly ashes on the strength of mortar is shown in Figure 5.11. Replacing 15% of cement with H weathered fly ash lowers the compressive strength about 15% of the control strength at 28 days. After 7 days, the dry fly ash gives a slightly higher strength than the weathered fly ash. It is noted that the use of river sand in the mix results in higher strength than the use of Ottawa sand. At the age of 90 days, cement replacement 15% with the dry and weathered fly ashes give compressive strengths of 6208 psi and 5979 psi or 103.4% and 99.6%, respectively, of the control strength. The 2 months of simulated weathering of fly ash does not seem to have had any affect on the strength of the mortar. It can be concluded that both the dry and weathered fly ashes produce the same results when used as a 15% replacement of cement.

Table 5.10 Compressive Strength of H Dry and Weathered Fly Ash Mortar

Sample No.	Compressive Strength (psi)						
	1-day	3-day	7-day	14-day	28-day	56-day	90-day
HC	2303	3128	4260	4959	5231	5597	6002
HD15	1739	2798	3677	4380	4799	5456	6208
HW15	1755	2878	3463	4156	4479	5119	5979

Table 5.11 Percentage Compressive Strength of H Dry and Weathered Fly Ash Mortar

Sample No.	Percentage Compressive Strength (%)						
	1-day	3-day	7-day	14-day	28-day	56-day	90-day
HC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
HD15	75.5	89.5	86.3	88.3	91.4	95.7	103.4
HW15	76.2	92.0	81.3	83.8	85.3	89.8	99.6

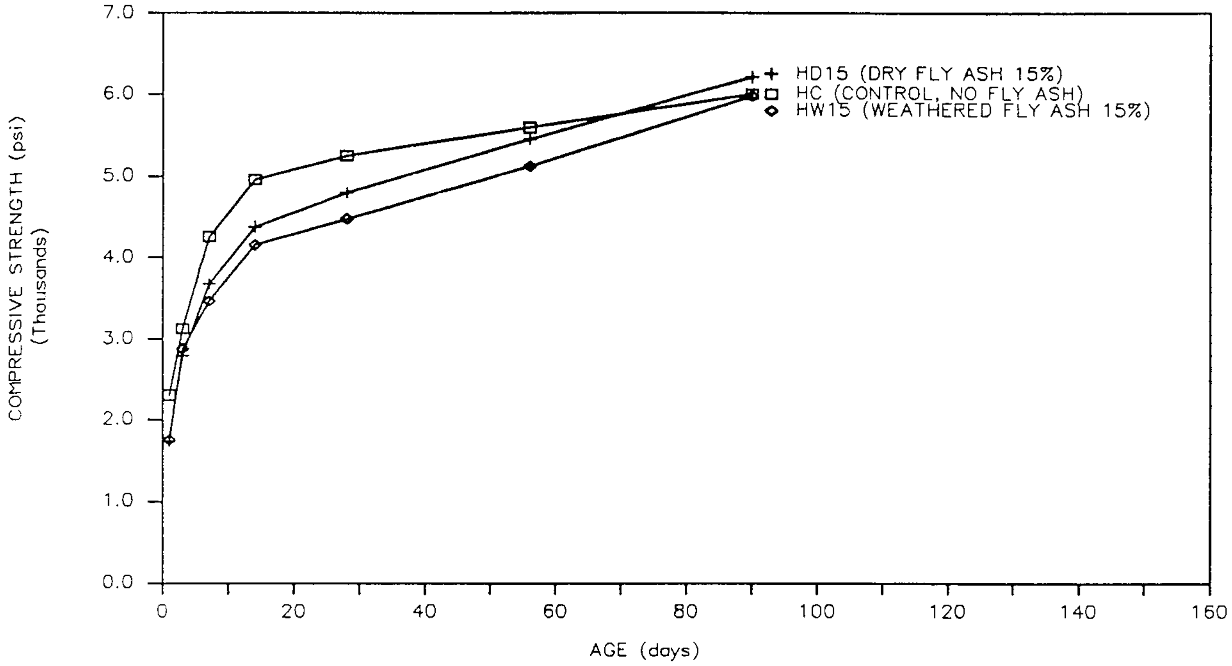

Figure 5.11 Effect of Replacement H Dry and Weathered Fly Ashes on the Strength of Mortar

5.4.5 Dry and Weathered Fly Ash Mortar with Dispersing Agent

In this experiment, 40 g/l of sodium hexametaphosphate ($NaPO_3$) was mixed with water. The objective is to use $NaPO_3$ to disperse all the particle of fly ash so that it can be mixed uniformly with mortar. The present of the dispersing agent made the fresh mortar more workable than for the specimen without dispersing agent. The mix proportion is shown in Table 4.1 series I.

The compressive strength and percentage compressive strength of fly ash mortar with dispersing agent are shown in Tables 5.4 and 5.5, respectively. The effect of replacement of fly ashes with and without dispersing agent on the strength of mortar are shown in Figure 5.12.

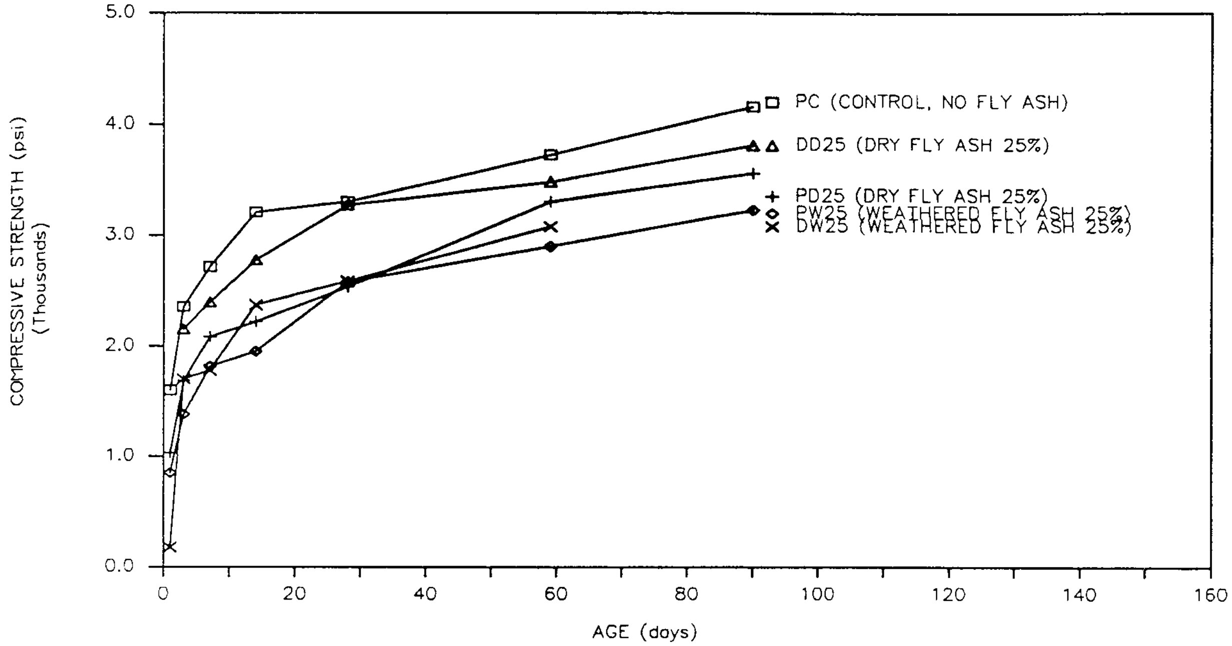

Figure 5.12 Effect of Replacement Dry and Weathered Fly Ashes with and without Dispersing Agent on the Strength of Mortar

At 1 day, the fly ash specimens with dispersing agent are very weak. For example, the compressive strength of DW25 (Weathered fly ash 25%) is only 178 psi or 11.1% of the control strength. After 3 days, the strength of DW25 is 1705 psi or a little higher than the 1 day control specimen (1601 psi). All the strengths of weathered fly ash mortar with dispersing agent are lower than the control strength at the same age. The use of the dry fly ash gives a better strength than that of the weathered fly ash. For DD25 (dry fly ash 25%) specimen, the compressive strength is about 85% to 90% of the control strength at the same age. For the 25% replacement of cement by the dry fly ash, the use of dispersing agent sample gives a little higher strength than the sample without dispersing agent at the age of 180 days. It is noted that fly ash mortar with dispersing agent is very weak at the age of 1 day.

This effect may be because the dispersing agent (Sodium hexametaphosphate) retards the hardening of mortar.

5.5 Fly Ash with Kiln Dust Phase I

The effect of fly ash and kiln dust on the strength of mortar without the presence of cement were investigated. The mix proportions for this experiment are shown in Table 4.1 series V. Dry and weathered fly ashes were mixed with kiln dust and river sand. The water/cementitious (fly ash+kiln dust) materials ratio was kept constant as at 0.55. 24 hours after casting, the specimens were removed from the molds and cured in air up to 56 days and after that transferred into saturated lime water. At the age of 1 day, all the specimens were very weak and disintegrated in water. Since fly ash-kiln dust specimens without any cement were so weak at 1 day, the specimens were tested at the age of 3, 7, 14, 28, 56, and 90 days.

Compressive strengths of fly ash-kiln dust mortar are shown in Table 5.12. It is seen that the compressive strength of mortar from the dry fly ash is higher than from the weathered fly ash with the same mix proportion. At ages up to 56 days (curing in air), the maximum compressive strength occurs in KD40 (the dry fly ash 40% and kiln dust 60%). This means that the combination of kiln dust and fly ash gives higher strength than for only kiln dust in the mix. This effect happens in both the dry and weathered fly ash mortar.

After curing in air up to 56 days, the compressive strength tends to decrease (See Figure 5.13), possibly due to the lack of water for the chemical reaction process between fly ash and kiln dust. After the samples were put in saturated lime water, most of the samples increased their strengths except for samples with amounts of fly ash higher than 60%, i.e. KD60, KD80, and KW80. The strengths of KD60, KD80, KW60, and KW80 at 180 days are 383 psi, 147 psi, 300 psi and 54 psi, respectively. The decrease of strengths are due to very low strength so that they are deteriorated in water.

Figures 5.14 and 5.15 show the relationship between compressive strength and percentage of fly ash in the cementitious materials. It is seen that at 90 days, the higher the percentage of fly ash in the mix, the lower the compressive strength.

Table 5.12 Compressive Strength of Fly Ash-Kiln Dust Mortar

Sam. No.	Compressive Strength (psi)					
	3-day	7-day	14-day	28-day	56-day	90-day
KD20	120	340	589	759	830	1014*
KD40	87	365	686	864	842	892*
KD60	64	497	596	555	546	383*
KD80	65	273	243	158	191	147*
KW20	120	282	410	460	305	663*
KW40	63	175	350	404	276	481*
KW60	38	115	258	194	190	300*
KW80	28	95	155	88	61	54*

* These specimens were cured in air up to 56 days, after that transferred into saturated lime water.

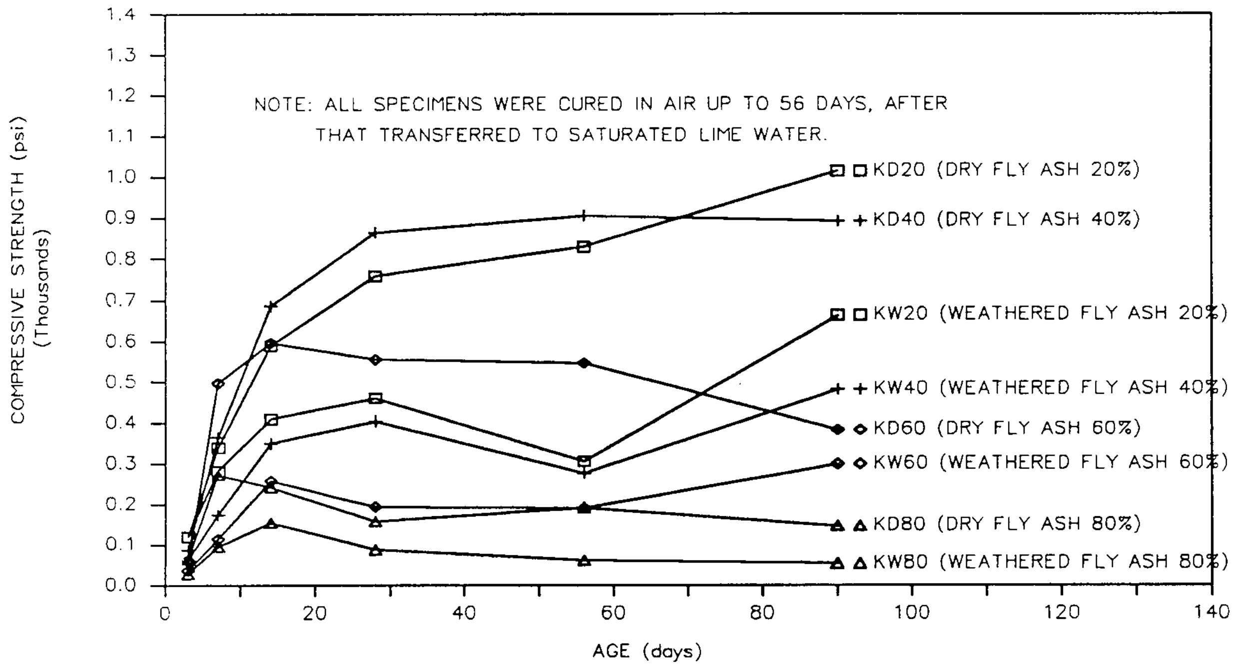

Figure 5.13 Effect of the Dry and Weathered Fly Ash-Kiln Dust on the Strength of Mortar

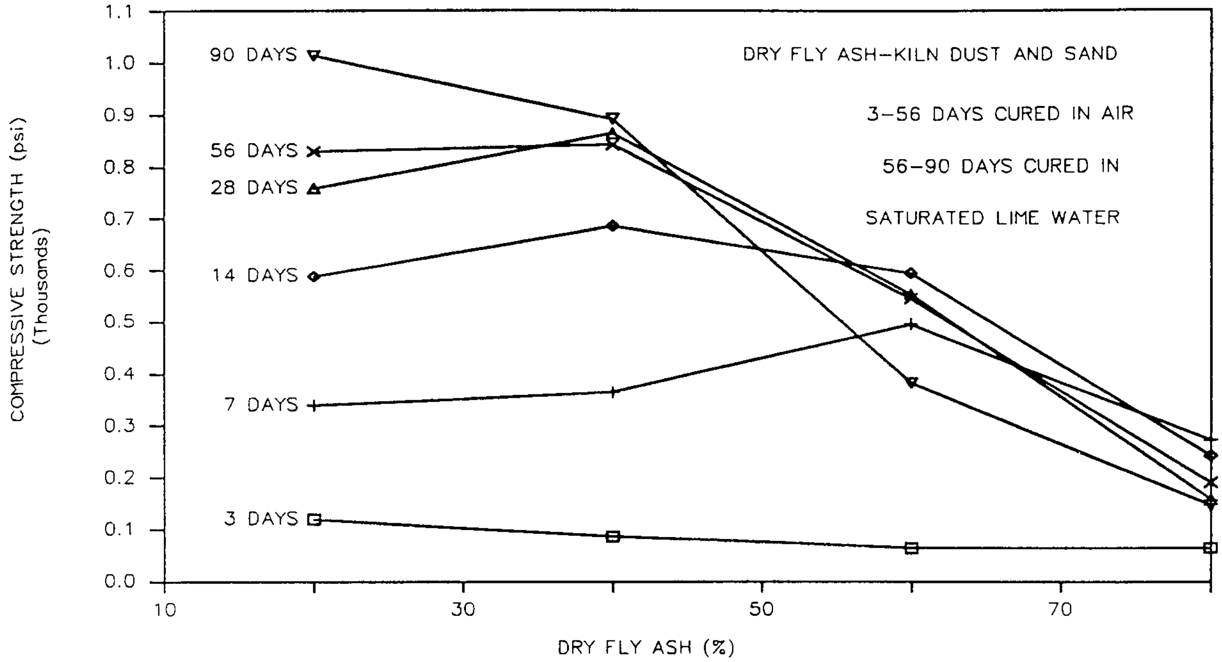

Figure 5.14 Relationship between Compressive Strength and Percentage of the Dry Fly Ash in Cementitious Materials

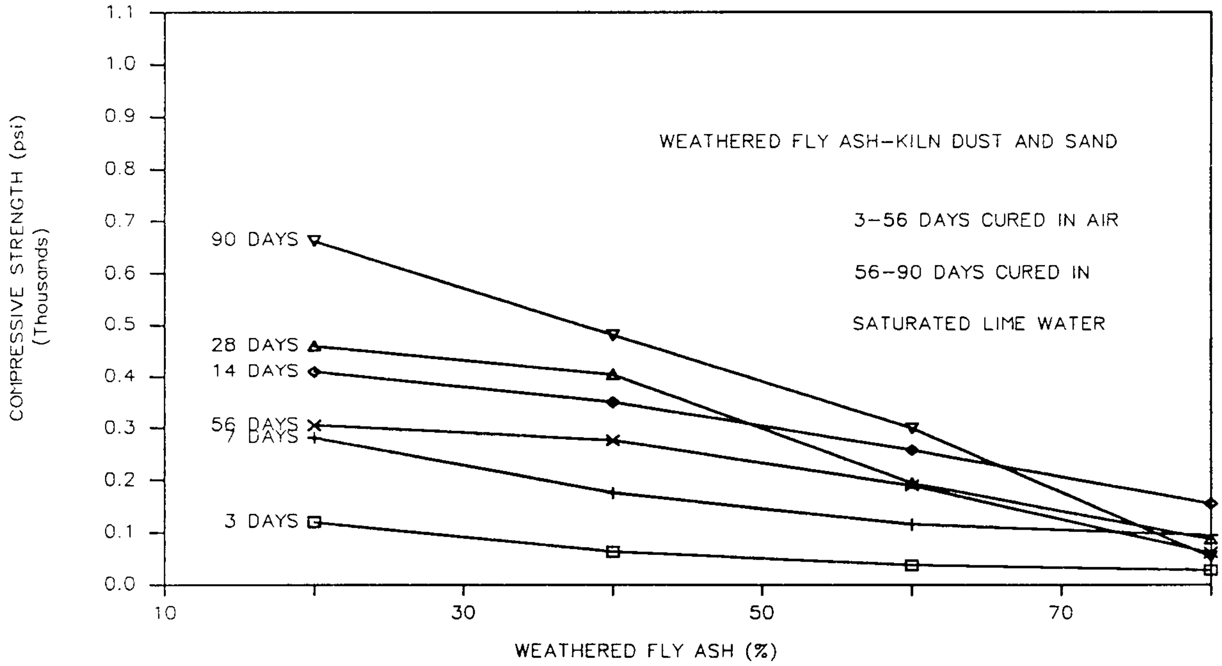

Figure 5.15 Relationship between Compressive Strength and Percentage of the Weathered Fly Ash in Cementitious Materials

5.6 Fly Ash with Kiln Dust Phase II

In this experiment, the weathered fly ash was mixed with kiln dust to form fly ash-kiln dust paste. The mix proportion is shown in Table 4.1 series VI. The water/cementitious (fly ash+kiln dust) materials ratio was kept as constant at 0.275. The objective of this experiment is to study the suggested use of weathered fly ash-kiln dust as a landfill material.

24 hours after casting, all specimens were removed from the molds and covered with a plastic sheet to reduce moisture loss. Since the specimens were very weak and disintegrated in water at early age, all samples were covered with plastic sheet until they were tested.

5.6.1 Compressive Strength of Fly Ash-Kiln Dust Paste

Table 5.13 shows the compressive strength of fly ash-kiln dust paste. The relationship between compressive strength of the weathered fly ash-kiln dust versus age is shown in Figure 5.16. As the age increases, the compressive strength of all samples also increases, except samples WK70, WK80, and WK90 which strengths drop after 90 days (See Figure 5.16). At early ages (1 to 3 days), it is seen that the specimens with higher percentage of kiln dust in the mix give higher compressive strength than the specimens with lower percentage of kiln dust. The compressive strength of WK10 (fly ash 10% and kiln dust 90%) is the highest up to the age of 7 days. After that, the strength of WK30 (fly ash 30% and kiln dust 70) is the highest. The strength of WK30 varies from 71 psi at 1 day to 4710 psi at 180 days. The strength of WK30 at the age of 180 days is more than 66 times of the 1 day strength.

Figure 5.17 shows that the optimum of fly ash in the mix is about 50% for the age up to 14 days but the optimum fly ash content shifts to about 30% when the age increases. For samples with high fly ash content, for examples, WK70, WK80, and WK90, strengths are very low and tend to decrease after 90 days. It is also observed that the compressive strength of WK90 increases from 33 psi at 1 day to 133 psi at

180 days or an increase of about 4 times.

5.6.2 Weathered Fly Ash-Kiln Dust Paste Cube in Water

After testing for compressive strength of fly ash-kiln dust paste at 180 days, the samples were immersed in water for 1 month. Specimens with fly ash up to 60% did not disintegrate in water, but the specimens with fly ash more than 60% disintegrated in water (See Figure 5.18). Specimen WK90 completely disintegrated in water while WK80 and WK70 only partially disintegrated. For this reason, the mix proportion of fly ash-kiln dust paste should contain kiln dust not less than 30% of total cementitious materials. It is noted that the strength of fly ash-kiln dust paste up to 3-day is very weak and will disintegrated in water.

Table 5.13 Compressive Strength of the Weathered Fly Ash-Kiln Dust Paste

Sam. No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
WK10	129	273	538	843	1717	2009	2648	3400
WK20	92	188	515	971	2316	2785	3254	4526
WK30	71	142	400	1122	3023	3359	3694	4710
WK40	60	101	451	1562	2964	3038	3111	3873
WK50	47	84	399	1634	2460	2485	2478	3585
WK60	46	68	490	1266	1607	1683	2190	2367
WK70	38	53	510	858	1079	1386	1462	1077
WK80	34	42	289	351	510	605	601	549
WK90	33	43	57	69	77	144	179	133

5.6.3 Density of Fly Ash-Kiln Dust Paste

The density of harden fly ash-kiln dust paste was observed to reduce with increased fly ash content (See Table 5.14). The higher the percentage of fly ash in the mix, the lower is the density. Since all specimens were not cured in water but covered with a plastic sheet, the water in the mix evaporates and therefore reduces the weight. The highest density is for WK10 which is 124 lb/ft^3 at 1 day and 115 lb/ft^3 at 180 days.

The density of fly ash-kiln dust paste is lower than that of mortar (135 lb/ft^3) and concrete (145 lb/ft^3). The lowest density is found in WK90 which is 108 lb/ft^3 at 1 day and 90 lb/ft^3 at 180 days.

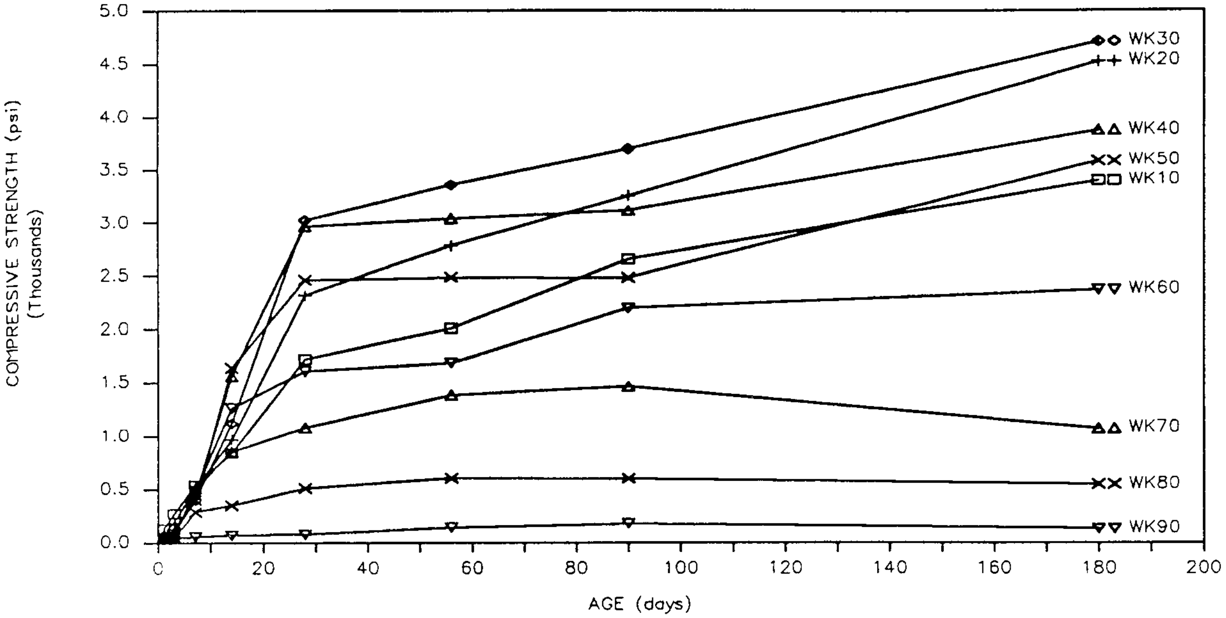

Figure 5.16 Relationship between Compressive Strength of the Weathered Fly Ash-Kiln Dust and Age

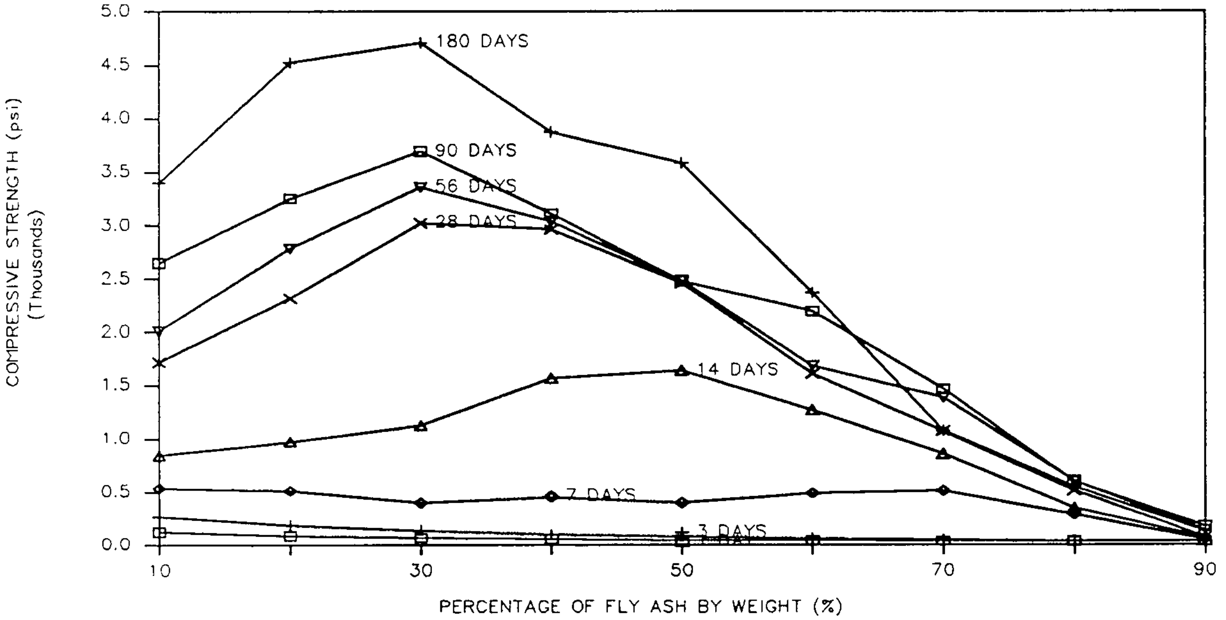

Figure 5.17 Relationship between Compressive Strength of the Weathered Fly Ash-Kiln Dust and Percentage of Fly Ash in the Mix

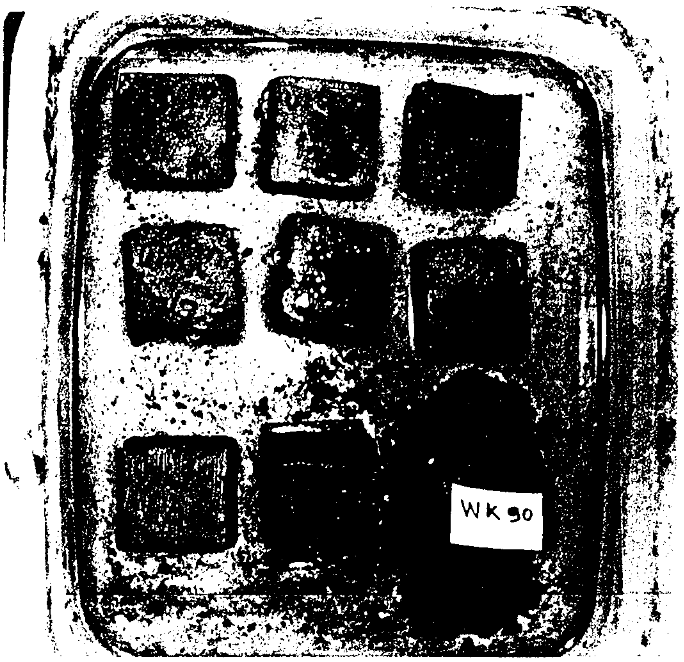

Figure 5.18 Weathered Fly Ash-Kiln Dust Paste After Tested and Immersed in Water for 1 Month

Table 5.14 Density of the Weathered Fly Ash-Kiln Dust Paste

Sam.	Density (lb/ft^3)							
No.	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
WK10	124	123	120	120	120	117	117	115
WK20	122	122	119	119	118	117	117	115
WK30	122	120	118	118	117	117	114	114
WK40	120	120	117	117	117	115	112	112
WK50	117	117	115	115	114	113	113	107
WK60	117	115	114	112	110	110	108	104
WK70	113	112	110	107	105	100	100	97
WK80	112	110	107	107	102	95	92	90
WK90	108	108	107	106	102	95	92	90

5.7 Fly Ash with Kiln Dust Phase III

In this experiment, dry and weathered fly ashes were mixed with cement, kiln dust, river sand, and water. Sand, water, cementitious (cement + fly ash + kiln dust) materials, and water were kept as constants, the percentage of fly ash was varied from 20% to 80% by weight of cementitious materials. Setting times of cement and combination of cement-fly ash-kiln dust paste were tested by both Vicat and Gillmore methods. The mix proportions are shown in Table 4.1 series VII. Tables 5.15 and 5.16 show the compressive strength and percentage compressive strength of mortar with partial replacement of fly ash and kiln dust.

Table 5.15 Compressive Strength of Cement-Fly Ash-Kiln Dust Mortar

Sam.	Compressive Strength (psi)							
No.	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
EK0	2177	4048	4748	5500	6280	7001	7448	8034
AK000	213	342	447	551	668	888	860	597
AKD20	186	304	473	917	1788	2540	2708	2875
AKD40	168	383	938	1590	2290	2907	3552	4196
AKD60	138	569	923	1463	2027	2406	2836	3265
AKD80	180	450	595	713	1035	1466	1548	1768
BK000	559	1042	1288	1858	2942	2988	3200	3408
BKD20	384	1547	2043	2521	3264	3721	4477	5888
BKD40	391	1504	1788	2371	3178	3834	4970	6110
BKD60	468	1060	1449	1768	2571	3022	4179	5461
CK000	1605	3090	3540	3890	4245	5058	5519	5981
CKD20	1553	2751	3327	3628	4038	5341	6080	6834
CKD40	1204	2295	2818	3610	4415	4975	6087	7078
DK000	1977	3936	4474	5272	5726	6123	6430	7145
DKD20	1700	3655	4366	4852	5583	6127	6642	7666
AKW20	181	336	501	964	1797	2358	2677	2995
AKW40	93	332	736	1233	2015	2469	2715	3447
AKW60	51	416	690	1041	1683	2106	2257	2467
AKW80	48	237	370	421	640	915	1010	1508
BKW20	299	1546	2099	2139	2922	3579	4219	5467
BKW40	233	1328	1597	1920	2769	3345	4103	5153
BKW60	196	853	1083	1493	2141	2290	3302	4400
CKW20	1158	2338	2861	3205	3548	4688	5439	6182
CKW40	848	1754	2043	2628	3213	3947	4926	5473
DKW20	1439	3180	3699	4158	4599	5432	6432	7163

Table 5.16 Percentage Compressive Strength of Cement-Fly Ash-Kiln Dust Mortar

Sam.	Percentage Compressive Strength (%)							
No.	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
EKO	100	100	100	100	100	100	100	100
AK000	9.8	8.4	9.4	10.0	10.6	12.7	11.5	7.4
AKD20	8.5	7.5	10.0	16.7	28.5	36.3	36.4	35.8
AKD40	7.7	9.5	19.8	28.9	36.5	41.5	47.7	52.2
AKD60	6.3	14.1	19.4	26.6	32.3	34.4	38.1	40.6
AKD80	8.3	11.1	12.5	13.0	16.5	20.9	20.8	22.0
BK000	25.7	25.7	27.1	33.8	46.8	42.7	43.0	42.4
BKD20	17.6	38.2	43.0	45.8	52.0	53.1	60.1	73.3
BKD40	18.0	37.2	37.7	43.1	50.6	54.8	66.7	76.1
BKD60	21.5	26.2	30.5	32.1	40.9	43.2	56.1	68.0
CK000	73.7	76.3	74.6	70.7	67.6	72.2	74.1	74.4
CKD20	71.3	68.0	70.1	66.0	64.3	76.3	81.6	85.1
CKD40	55.3	56.7	59.4	65.6	70.3	71.1	81.7	88.1
DK000	90.8	97.2	94.2	95.9	91.2	87.5	86.3	88.9
DKD20	78.1	90.3	92.0	88.2	88.9	87.5	89.2	95.4
AKW20	8.3	8.3	10.6	17.5	28.6	33.7	35.9	37.3
AKW40	4.3	8.2	15.5	22.4	32.1	35.3	36.5	42.9
AKW60	2.3	10.3	14.5	18.9	26.8	30.1	30.3	30.7
AKW80	2.2	5.9	7.8	7.7	10.2	13.1	13.6	18.8
BKW20	13.7	38.2	44.2	38.9	46.5	51.1	56.6	68.0
BKW40	10.7	32.8	33.6	34.9	44.1	47.8	55.1	64.1
BKW60	9.0	21.1	22.8	27.1	34.1	32.7	44.3	54.8
CKW20	53.2	57.8	60.3	58.3	56.5	67.0	73.0	76.9
CKW40	39.0	43.3	43.0	47.8	51.2	56.4	66.1	68.1
DKW20	66.1	78.6	77.9	75.6	73.2	77.6	86.4	89.2

Sample EKO is the control sample, without any kiln dust or fly ash. Series AK, BK, CK, and DK stand for the cement-fly ash-kiln dust mortar with a cement constant in the cementitious materials of 20%, 40%, 60%, and 80%, respectively. The numbers in each series indicate the percentage of fly ash in the mix. Letter D or W stands for the use of the dry or weathered fly ash.

5.7.1 Compressive Strength of Cement-Fly Ash-Kiln Dust Mortar with Constant Cement Content

Cement 20% of Cementitious Materials

In this test, the weight of cement is kept constant at 20% of the total cementitious materials. The results are shown in Figure 5.19. It is seen that most of the mortar strength increases with age, except for AK000 (kiln dust 80%, no fly ash) which strength drops after 90 days. This may be due to the unsoundness of the specimen in water. It is also noted that the compressive strength of AK000 at 180 days is only 597 psi. At 1 day, the compressive strength of AKD40 (the dry fly ash 40% and kiln dust 40%) is about 7.7% and increases to 52.2% at 180 days relative to EKO.

Figure 5.20 displays the effect of the weathered fly ash-kiln dust on the strength of mortar with cement content constant at 20%. The percentage compressive strength of AKW40 (the weathered fly ash 40% and kiln dust 40%) increases from 4.3% at 1 day to 42.9% at 180 days. With the replacement of fly ash and kiln dust up to 80% in AKD and AKW series, the compressive strength of fly ash-kiln dust mortar is about 10%-20% of the control strength at ages up to 7 days. As the age increases, a suitable combination of fly ash and kiln dust increases the compressive strength. For example, the use of 40% of the dry fly ash, 40% kiln dust, and 20% of cement (AKD40), gives a compressive strength of 4196 psi or 52.2% of the control strength at 180 days. For the same mix proportion, the dry fly ash mortar gives higher compressive strength than the weathered fly ash mortar.

Cement 40% of Cementitious Materials

Figure 5.21 shows that at the age of 180 days, the strength of BK000 (kiln dust 60%, no fly ash) is much lower than the other specimens with the same cement content. Specimen with a replacement of the dry fly ash or kiln dust are always lower than the control strength. The compressive strength of BKD40 increases from 18% at 1 day to 76.1% at 180 days compared with the control strength. It is noted that at the age of 180 days, the highest compressive strength in this series is for BKD40 which is 6110 psi, or 76.1% of the control strength.

Figure 5.22 shows that the strength of BKW20 (kiln dust 40%, the weathered fly ash 20%) is a little higher than BKW40 (kiln dust 20%, the weathered fly ash 40%). At the age of 180 days, the compressive strength of BKW20 is 5467 psi and of BKW40 is 5153 psi. At the same ages, the samples from series of BKD and BKW give higher strengths than the samples from series AKD and AKW. This is due to the higher percentage of cement in series BKD and BKW (40% of cement) than in series AKD and AKW (20% of cement). The highest strength in BKD and BKW series is BKD40 which is 6110 psi while in AKD and AKW series is AKD40 which is 4196 psi. It is noted that the use of the dry fly ash gives higher strength than that of the weathered fly ash when using the same mix proportion.

Cement 60% of Cementitious Materials

Figure 5.23 shows the effect of fly ash-kiln dust on the strength of mortar with cement content constant at 60%. At the early ages (1 to 14 days), the higher the percentage of kiln dust in the mix, the higher is the compressive strength. After 90 days, the strength of CKD40 (no kiln dust, the dry fly ash 40%) is higher than CKD00 and CKD20. This indicates that kiln dust which has high CaO content has an important role in the production of higher strength at early ages than fly ash. When the ages increase, the pozzolanic reaction of fly ash becomes dominant and produces higher compressive strengths than for the mixes with higher content of kiln dust.

The compressive strength of CKD40 varies from 1204 psi at 1 day to 7078 psi at 180 days or 55.3% to 88.1% of the control strength. In these series, the dry fly ash also gives higher compressive strength than the weathered fly ash.

Cement 80% of Cementitious Materials

In this series, the weight of cement is kept constant at 80% of the total cementitious materials. The effect of fly ash-kiln dust on the strength of mortar with cement constant at 80% is shown in Figure 5.24. At the early ages, the specimen DKD000 (cement 80% and kiln dust 20%) gives the highest strength. After 56 days, sample DKD20 (cement 80% and the dry fly ash 20%) gives the highest strength. This effect is similar to BKD series. Again, the compressive strength of the weathered fly ash samples are lower than the dry fly ash samples when using the same mix proportion. The compressive strengths of DKD20, DKD00, and DKW20 at the age of 180 days are 7666 psi, 7145 psi, and 7163 psi, respectively or 95.4%, 88.9%, and 89.2% of the control strength.

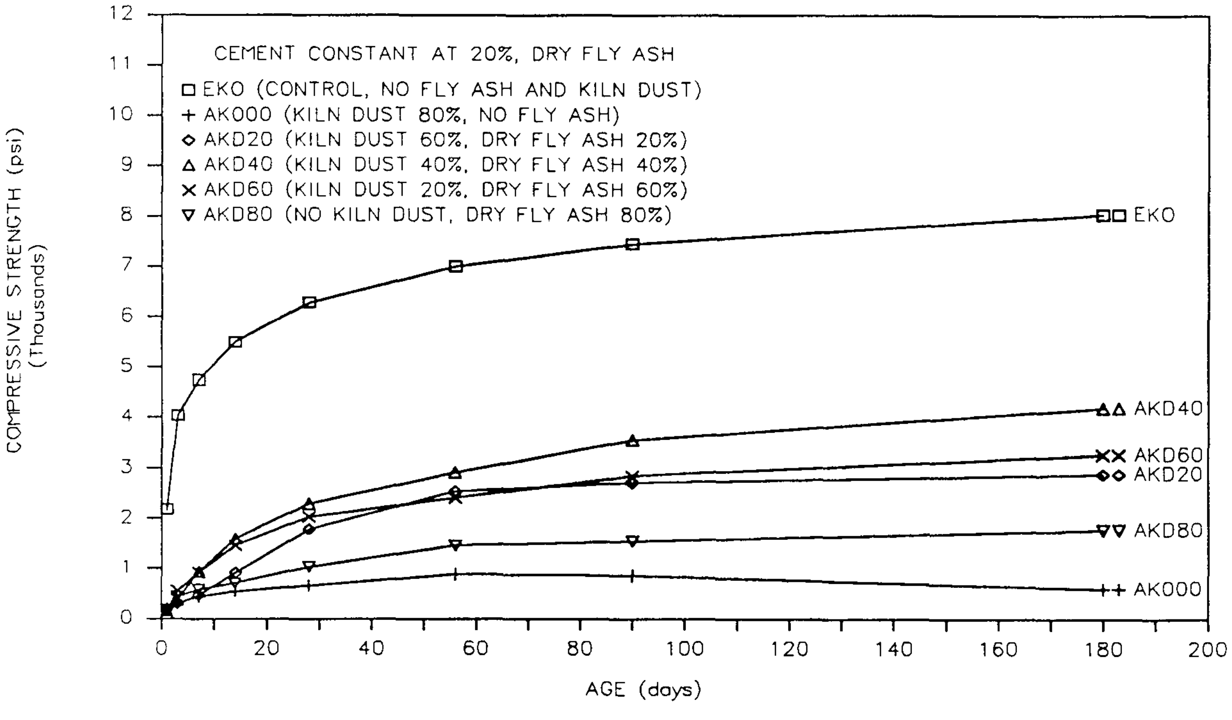

Figure 5.19 Effect of the Dry Fly Ash-Kiln Dust on the Strength of Mortar with Cement Constant at 20%

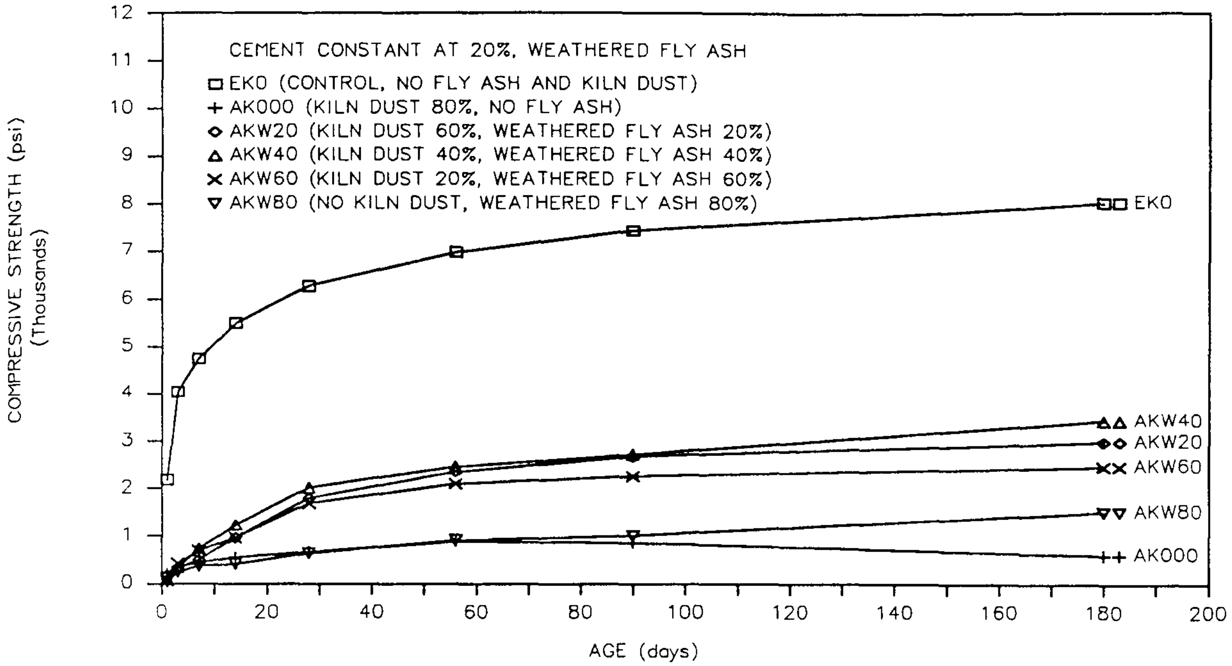

Figure 5.20 Effect of the Weathered Fly Ash-Kiln Dust on the Strength of Mortar with Cement Constant at 20%

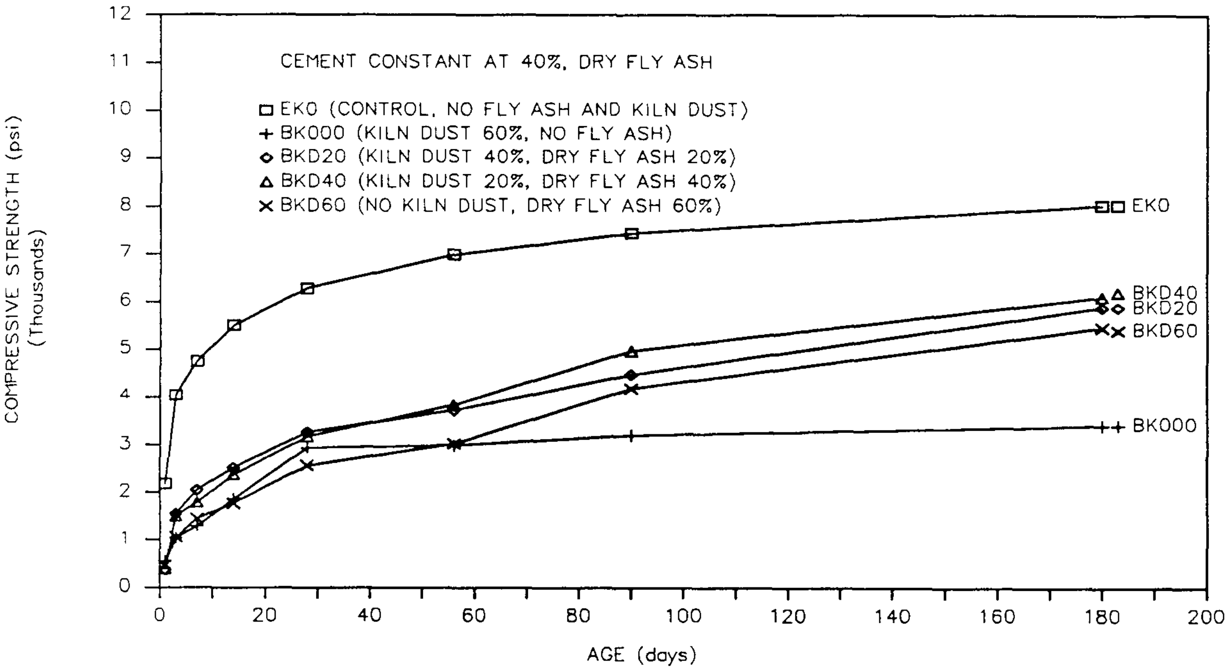

Figure 5.21 Effect of the Dry Fly Ash-Kiln Dust on the Strength of Mortar with Cement Constant at 40%

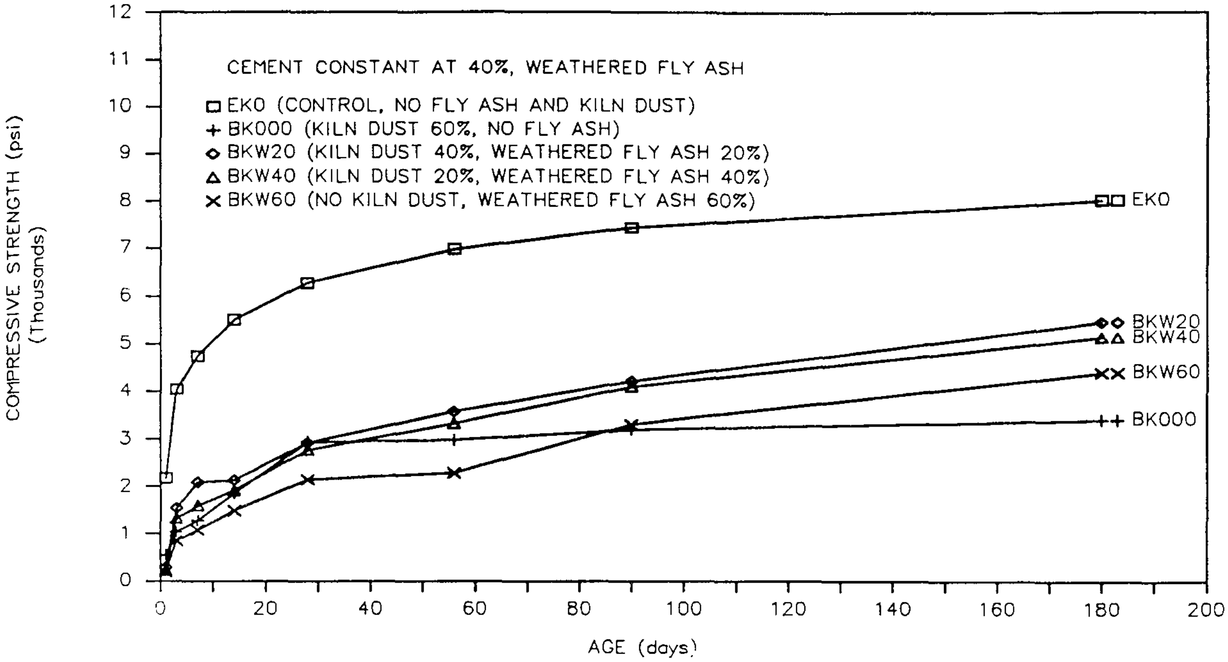

Figure 5.22 Effect of the Weathered Fly Ash-Kiln Dust on the Strength of Mortar with Cement Constant at 40%

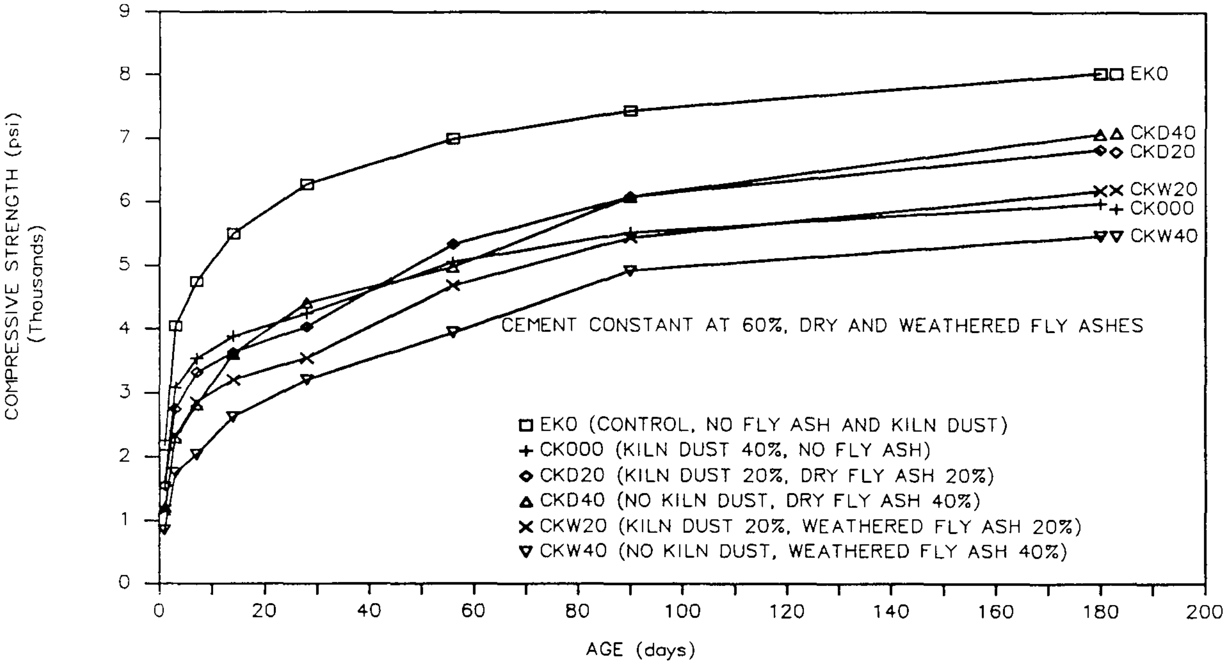

Figure 5.23 Effect of Fly Ash-Kiln Dust on the Strength of Mortar with Cement Constant at 60%

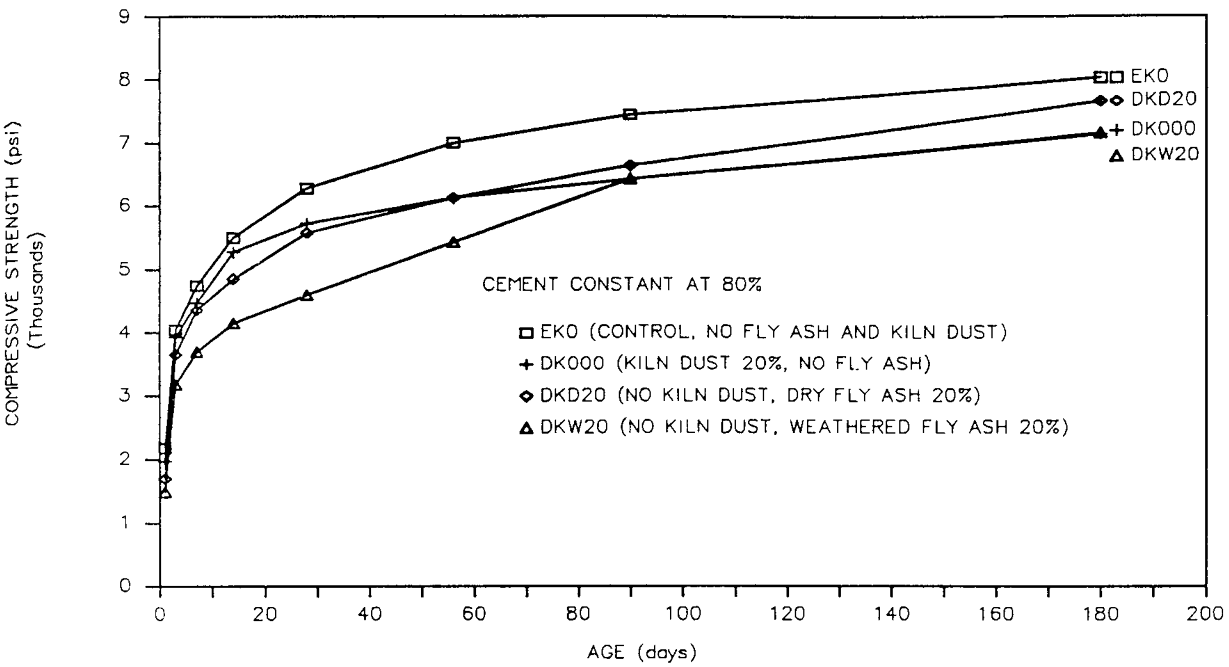

Figure 5.24 Effect of Fly Ash-Kiln Dust on the Strength of Mortar with Cement Constant at 80%

5.7.2 Optimum Mix of Fly Ash-Kiln Dust Mortar Phase III

Figures 5.25 and 5.26 show the relationship between percentage of fly ash (the dry and weathered) in cementitious materials and compressive strength of cement-fly ash-kiln dust mortar at the age of 180 days. It is seen that at low cement content, 20% to 40% by weight of cementitious materials, the use of fly ash or kiln dust alone does not give the highest strength. With the cement content constant, a suitable combination of fly ash and kiln dust are required to get the highest strength. For 20% cement, the optimum of fly ash to produce the highest strength is about 40% (fly ash 40% and kiln dust 40%). For 20% cement in cementitious materials, the optimum mix is fly ash 40% and kiln dust 40% for both the dry and weathered fly ashes. With 40% cement in cementitious materials, the optimum mix is fly ash 40% and kiln dust 20% for both the dry and weathered fly ashes. With 60% cement in cementitious materials, the optimum mix is fly ash 40% and no kiln dust for the dry fly ash and for the weathered fly ash, the optimum is fly ash 20% and kiln dust 20%.

For 80% cement in cementitious materials, the optimum mix is fly ash 20% and no kiln dust for both the dry and weathered fly ashes.

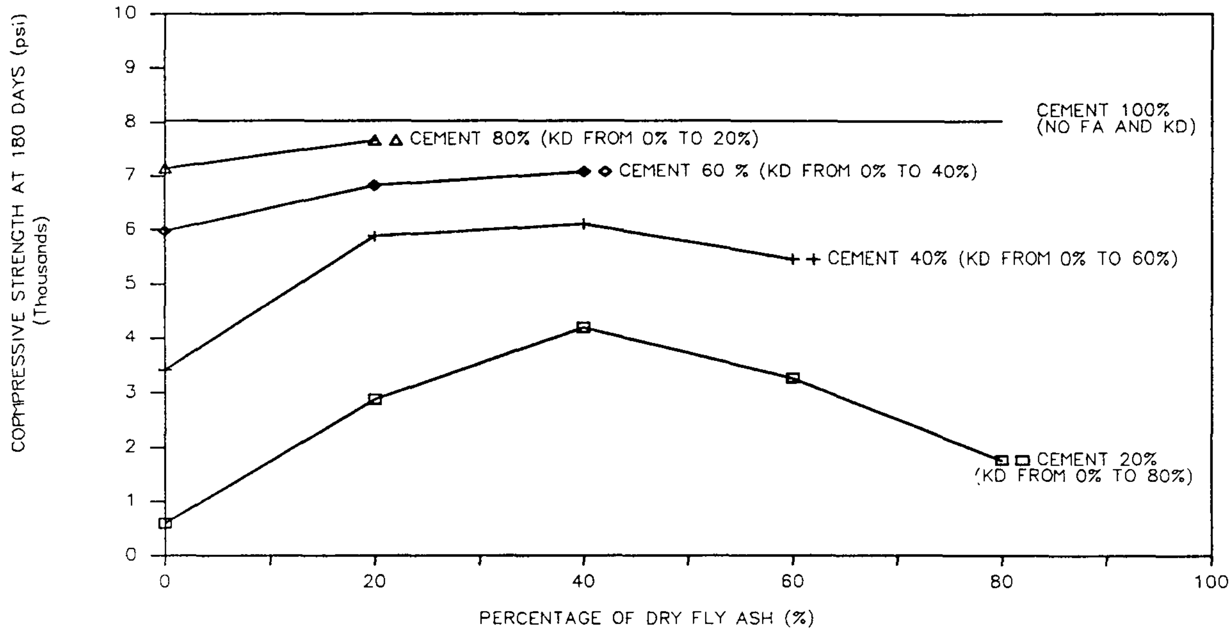

Figure 5.25 Relationship between Percentage of the Dry Fly Ash in Cementitious Materials and Compressive Strength of Fly Ash-Kiln Dust Mortar at the Age of 180-Day

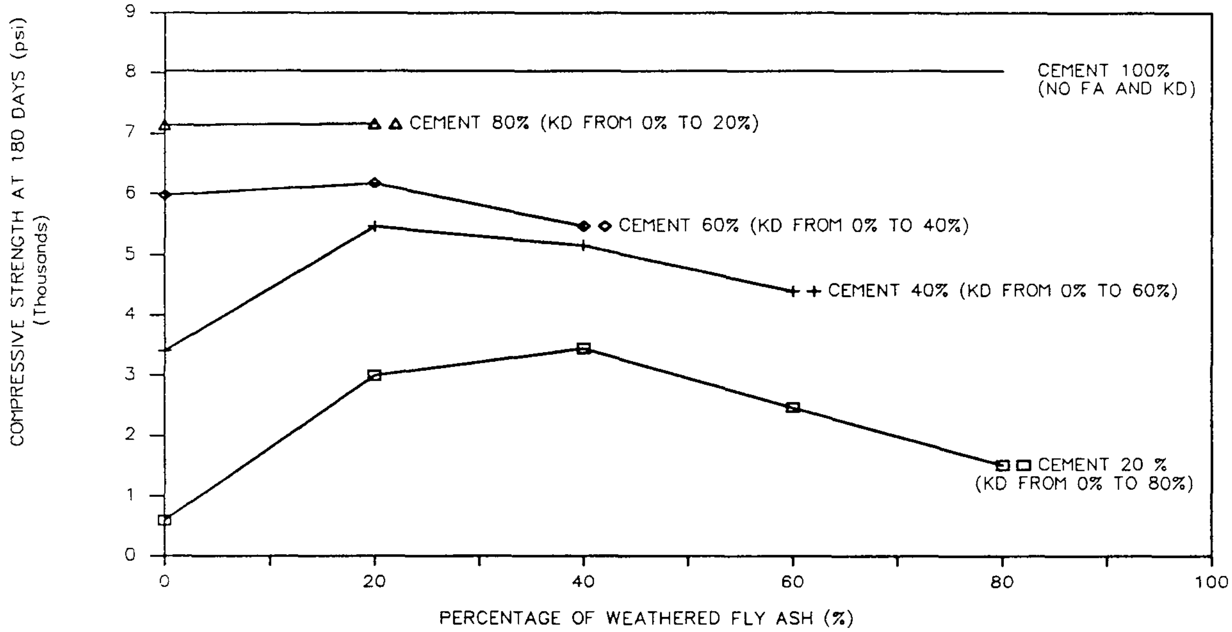

Figure 5.26 Relationship between Percentage of the Weathered Fly Ash in Cementitious Materials and Compressive Strength of Fly Ash-Kiln Dust Mortar at the Age of 180-Day

5.7.3 The Maximum Strength of Fly Ash-Kiln Dust Mortar in Each Series

Tables 5.17 and 5.18 show the maximum compressive strength and the maximum percentage compressive strength in each series. It is noted that at the age of 180 days, the maximum compressive strength of mortar with the cement content of 20%, 40%, 60%, and 80% are 52.2%, 76.1%, 85.1%, and 91.2% of the control strength, respectively. If the compressive strength of the control mortar at 28 days is used as the reference, the percentage of control's compressive strength of AKD40, BKD40, CKD20, and DKD20 at 180 days are 66.8%, 97.3%, 108.8%, and 122.1%, respectively (see Table 5.19). It is seen that the compressive strength is higher with the higher percentage of cement at all ages. With the lower cement content (series AKD and AKW), a high percentage of kiln dust is needed for higher compressive strength. When the cement content increase, the content of kiln dust should be reduced to get higher strength.

Table 5.17 Maximum Compressive Strength of Fly Ash-Kiln Dust Mortar in Each Series

Sam. No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
EK0	2177	4048	4748	5500	6280	7001	7448	8034
AKD40	168	383	938	1590	2290	2907	3552	4196
BKD40	391	1504	1788	2371	3178	3834	4970	6110
CKD20	1553	2751	3327	3628	4038	5341	6080	6834
DKD20	1700	3655	4366	4852	5583	6127	6642	7666

Table 5.18 Percentage Maximum Compressive Strength of Fly Ash-Kiln Dust Mortar in Each Series

Sam. No.	Percentage Compressive Strength (%)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
EK0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
AKD40	7.7	9.5	19.8	28.9	36.5	41.5	47.7	52.2
BKD40	18.0	37.2	37.7	43.1	50.6	54.8	66.7	76.1
CKD20	71.3	68.0	70.1	66.0	64.3	76.3	81.6	85.1
DKD20	78.1	90.3	92.0	88.2	88.9	87.5	89.2	95.4

Table 5.19 Percentage Compressive Strength of Fly Ash Kiln Dust Mortar in Each Series by Keeping 28 Days Control Strength as 100 %

Sam. No.	Percentage Compressive Strength (%)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
EK0	34.7	64.5	75.6	87.6	100.0	111.5	118.6	127.9
AKD40	2.7	6.1	14.9	25.3	36.5	46.3	56.6	66.8
BKD40	6.2	23.9	28.5	37.8	50.6	61.1	79.1	97.3
CKD20	24.7	43.8	53.0	57.8	64.3	85.0	96.8	108.8
DKD20	27.1	58.2	69.5	77.3	88.9	97.6	105.8	122.1

5.7.4 Setting Time of Cement-Fly Ash-Kiln Dust Paste

From Table 5.20, it is seen that the water-cement ratio for normal consistency varies from 28% in cement paste to 155.3% in AKD80 (cement 20%, dry fly ash 80%). If considers in terms of water-cementitious ratio, this ratio is almost constant between 28% to 31%.

Table 5.20 Setting Time of Cement-Fly Ash-Kiln Dust Paste

Sam. No.	Normal Consistency (%)		Initial Setting		Final Setting	
	W/C	W/(C+FA+KD)	Vicat h:min	Gillmore h:min	Vicat h:min	Gillmore h:min
AK000	153.8	30.7	3:15	3:15	8:30	8:00
AKD20	151.0	30.2	3:50	4:00	8:45	8:20
AKD40	149.2	29.8	4:10	4:25	9:15	8:30
AKD60	151.5	30.3	4:30	4:45	9:40	9:10
AKD80	155.3	31.0	4:45	4:50	10:15	9:25
BK000	77.6	31.0	4:00	4:05	7:20	7:20
BKD20	76.2	30.5	4:10	4:10	7:40	7:30
BKD40	76.1	30.4	4:20	4:25	8:00	7:50
BKD60	75.3	30.1	4:25	4:25	8:05	8:05
CK000	49.7	29.8	3:25	3:35	6:25	6:35
CKD20	47.1	28.3	3:30	3:34	6:40	6:40
CKD40	48.7	29.2	3:35	3:55	7:55	8:00
DK000	35.5	28.4	2:30	2:50	5:50	6:00
DKD20	35.0	28.0	2:35	3:00	6:00	6:05
CEM	28.0	28.0	2:20	2:40	5:30	5:30

The shortest setting times occurs in plain cement paste. The initial and final setting times measured by Vicat needle are 2 h 20 min and 5 h 30 min, respectively. Using Gillmore needles, the initial and final setting times are 2 h 40 min and 5 h 30 min, respectively. The longest setting time sample is occurred in AKD80 which the initial setting time, final setting time are 4 h 45 min, 10 h 15 min, respectively by Vicat needle and 4 h 50 min, 9 h 25 min, respectively by Gillmore needles. Note that ASTM C-150 (1981) specified the initial setting time of cement paste by Vicat needle should not be less than 45 min and not more than 8 h for the final setting time and for the Gillmore test, the initial set not less than 60 min and not more than 10 h for the final set. But in 1990, the Vicat method only specified the initial setting time should be between 45 min and 375 min, no final setting time was required (ASTM C-150 1990).

With cement content constant, the paste with higher percentage of kiln dust had a shorter setting times than the paste with less kiln dust. This is because that kiln dust has some cementitious materials thus accelerates the setting times. However, the cementing property of kiln dust is not as strong as cement but is stronger at early ages than fly ash.

5.8 Fly Ash as a Replacement

Dry and weathered fly ashes were used as a replacement for cement. Keeping the water, river sand, and cementitious (cement+fly ash) materials constants, cement was replaced by fly ash. The replacement of fly ash (dry or weathered) was varied from 10% to 40% by weight of cementitious materials. The mix proportions for this program are shown in Table 4.1 series VIII. Sample JC is the control sample. RD and RW are the samples with replacement of the dry and weathered fly ashes, respectively. Tables 5.21 and 5.22 show the compressive and the percentage compressive strength of fly ash mortar. It is seen that the use of fly ash as a replacement of cement reduces the compressive strength of mortar at early ages. This is a disadvantage when fly ash is replaced cement on a one-to-one ratio by weight (Lane and Best 1982; ACI 226 1987). Usually, the weathered fly ash lowers the compressive strength more than the dry fly ash for the same amount of fly ash. After 180 days, the replacement of the dry or weathered fly ash up to 30% gives compressive strengths at the same level of the control strength.

Table 5.21 Compressive Strength of the Dry and Weathered Fly Ash Mortar as a Replacement, as a Partial Addition and Replacement of Sand, and as an Additive

Sam. No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
JC	2144	4303	5252	6109	6884	7320	7448	7918
RD10	1845	4146	5004	5576	6170	6747	7214	7943
RD20	1700	3655	4366	4852	5583	6127	6642	7666
RD30	1375	3288	3932	4839	5668	5980	6805	8178
RD40	1204	2295	2818	3610	4415	4975	6087	7078
RW10	1826	3652	4378	4987	5819	6051	6844	7761
RW20	1439	3180	3699	4158	4599	5432	6432	7680
RW30	1029	2850	2969	3737	4340	5045	6213	7599
RW40	848	1754	2043	2628	3213	3947	4926	5473
ED10	2358	4948	5830	7017	7540	8099	9295	10143
ED20	2444	4306	5767	6434	7228	8138	9649	10275
ED30	2508	4776	5351	6109	6953	7527	8488	9593
ED40	2487	4631	5325	5788	6606	7322	7795	8825
EW10	2466	4948	6101	7005	7316	7928	9505	10563
EW20	2444	4862	5950	6995	7341	8655	9375	10618
EW30	2336	4948	5698	6666	7314	8121	9712	10949
EW40	2140	4905	5690	6386	7214	7841	8469	10084
AD10	2386	4389	5434	6313	7082	7584	7878	9342
AD20	2444	4286	5776	6845	7283	8134	8670	9768
AD30	2487	4359	5053	6195	7173	8051	8373	9331
AD40	2027	4541	5164	6244	6807	8009	8445	9120
AW10	2318	4469	5297	6255	6902	7675	7870	8819
AW20	2444	4342	5302	6410	7020	8055	8504	9463
AW30	2401	4790	5286	6104	6877	8600	9544	10554
AW40	2187	4613	5348	6291	6895	8579	9481	10158

Table 5.22 Percentage Compressive Strength of the Dry and Weathered Fly Ash Mortar as a Replacement, as a Partial Addition and Replacement of Sand, and as an Additive

Sam. No.	Percentage Compressive Strength							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
JC	100	100	100	100	100	100	100	100
RD10	86	96	95	91	90	92	97	100
RD20	79	85	83	79	81	84	89	97
RD30	64	76	75	79	82	82	91	103
RD40	56	53	54	59	64	68	82	89
RW10	85	85	83	82	85	83	92	98
RW20	67	74	70	68	67	74	86	97
RW30	48	66	57	61	63	69	83	96
RW40	40	41	39	43	47	54	66	69
ED10	110	115	111	115	110	111	125	128
ED20	114	100	110	105	105	111	130	130
ED30	117	111	102	100	101	103	114	121
ED40	116	108	101	95	96	100	105	111
EW10	115	115	116	115	106	108	128	133
EW20	114	113	113	114	107	118	126	134
EW30	109	115	108	109	106	111	130	138
EW40	100	114	108	105	105	107	114	127
AD10	111	102	103	103	103	104	106	118
AD20	114	100	110	112	106	111	116	123
AD30	116	101	96	101	104	110	112	118
AD40	95	106	98	102	99	109	113	115
AW10	108	104	101	102	100	105	106	111
AW20	114	101	101	105	102	110	114	120
AW30	112	111	101	100	100	117	128	133
AW40	102	107	102	103	100	117	127	128

5.8.1 Replacement of Cement with the Dry Fly Ash

The effect of replacement of the dry fly ash on the strength of mortar is shown in Figure 5.27. It is seen that RD40 has the lowest strength at all ages. Its strength varies from 1204 psi at 1 day to 7078 psi at 180 days or 56% to 89%, relative to the control strength. With the use of a high volume of fly ash as a replacement, i.e. 40%, the early strengths (1 day to 14 days) are about 50% to 60% and gradually increase with ages.

Figure 5.28 is the relationship between compressive strength of replacement the dry fly ash mortar and the dry fly ash/cement ratio. At the early ages, the compressive strengths of fly ash mortar decrease with the increase of the dry fly ash/cement ratio. The curves in Figure 5.28 do not show any optimum of fly ash content. After 28 days, the pozzolanic reaction of fly ash contributes strength to the sample and the optimum fly ash usage mix can be seen clearly after 90 days, somewhere between 20 to 30% by weight of cementitious materials.

5.8.2 Replacement of Cement with the Weathered Fly Ash

Figure 5.29 shows that the effect of the weathered fly ash on the strength of mortar is almost the same as the dry fly ash except that the weathered fly ash gives lower compressive strength than the dry fly ash when using the same amount of replacement. With 40% replacement of the weathered fly ash by weight of cementitious materials gives 40% at 1 day and 69% at 180 days of the control strength. All of the weathered fly ash mortars give lower compressive strength than the control mortar at all ages up to 180 days. In Figure 5.30, the compressive strength of the weathered fly ash mortar and the weathered fly ash/cement ratio shows no optimum of fly ash for use in cement.

The results on the compressive strength of this study do not agree with those reported by Yasuda et al. (1991). Their results showed that the strength of mortar or concrete contained wet-stored fly ash increased. They explained that weathered fly ash may raise the adhesion capability between fly ash and cement particles due to slight roughness of fly ash particle surface, and by the increase in activation of fly ash particles. Finally, they concluded that fly ash dumped at an ash disposal area for 7 years had not deteriorated. This may be true if one considers the chemical composition of the dry and weathered fly ashes presented in Table 5.1. However, this study found that apparent particle size distribution tends to change with damped storage condition.

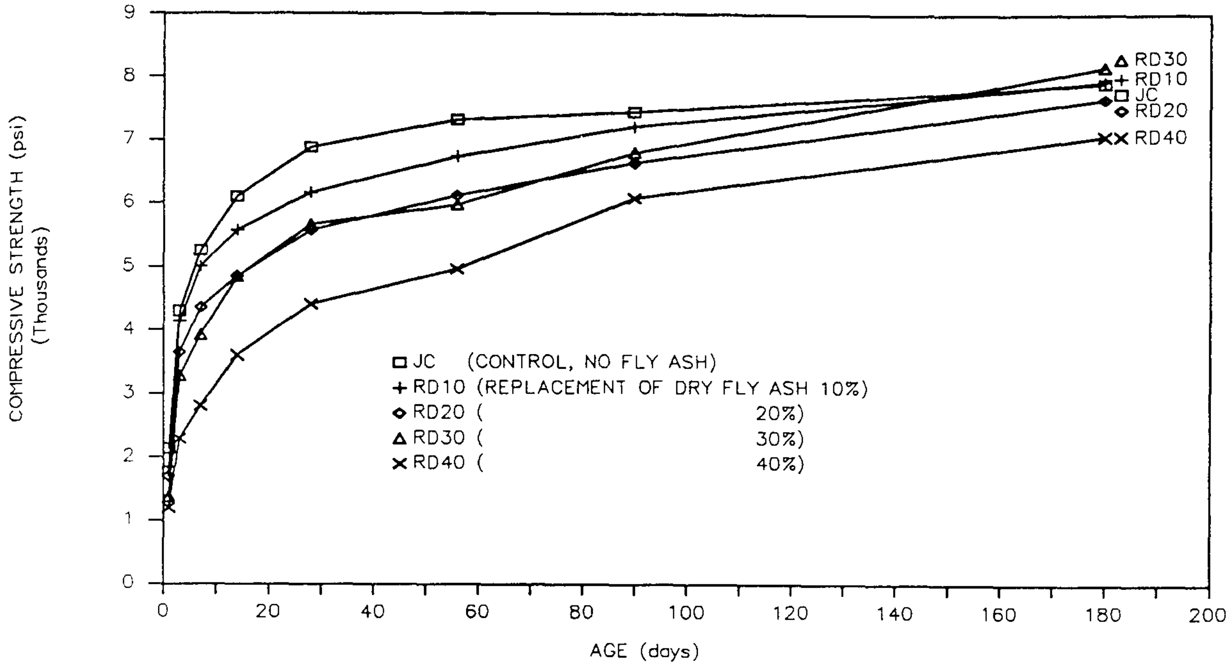

Figure 5.27 Effect of Replacement of the Dry Fly Ash on the Strength of Mortar

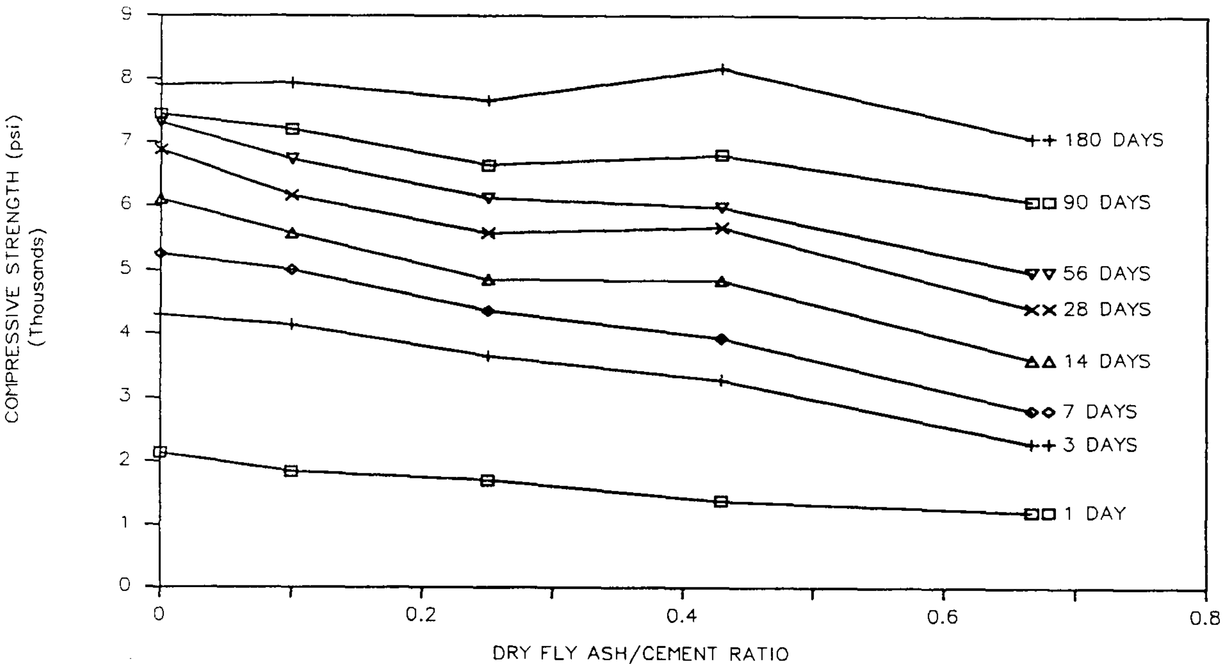

Figure 5.28 Relationship between Compressive Strength of Replacement the Dry Fly Ash Mortar and the Dry Fly Ash/Cement Ratio

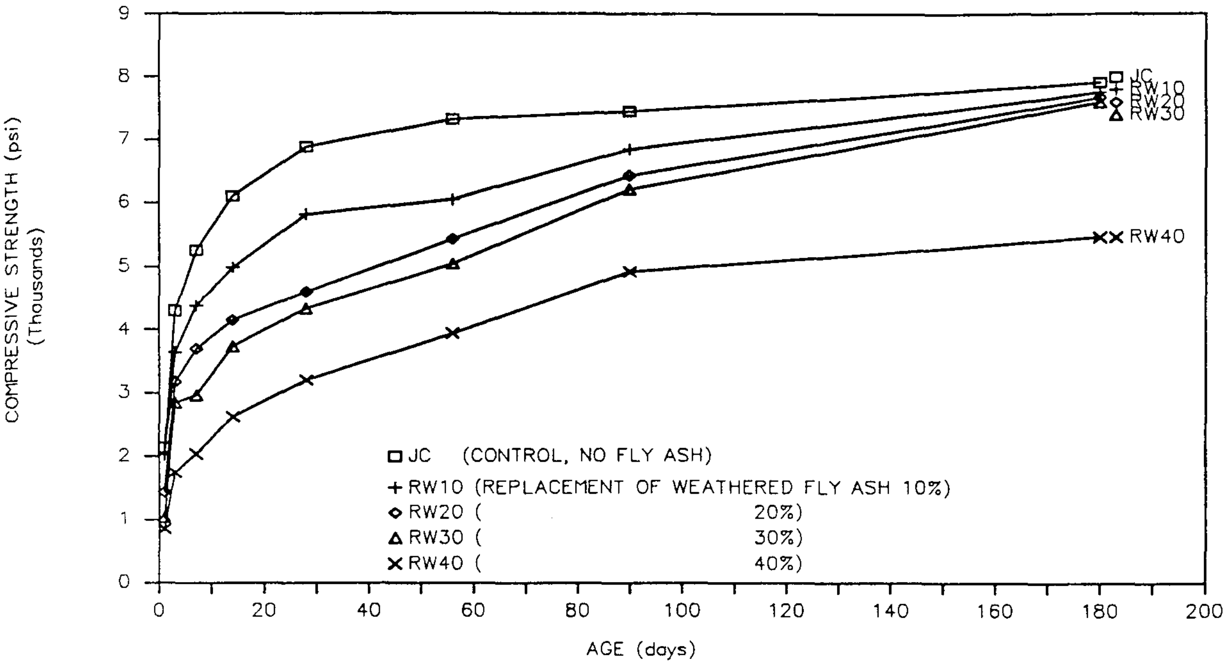

Figure 5.29 Effect of Replacement of the Weathered Fly Ash on the Strength of Mortar

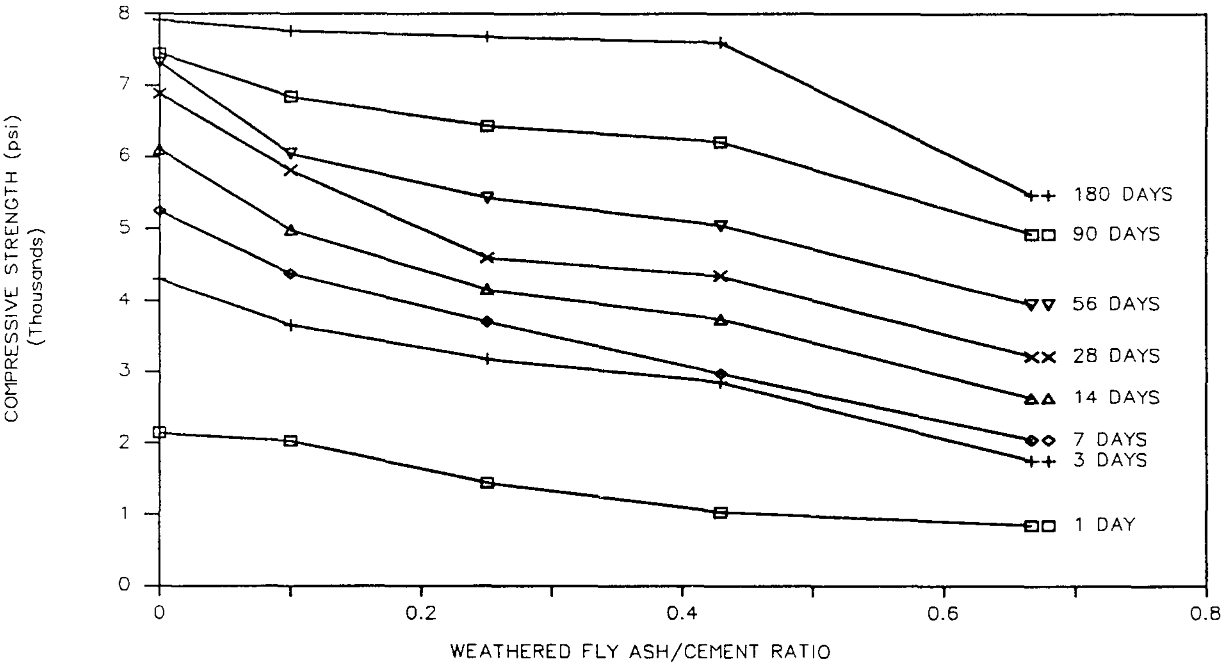

Figure 5.30 Relationship between Compressive Strength of Replacement the Weathered Fly Ash Mortar and the Weathered Fly Ash/Cement Ratio

Many investigators have concluded that fly ashes with higher percentage of finer particles gave higher strengths (Cerkanowicz et al. 1991; Ukita, Shigematsu 1989; Giergiczny and Werynska 1989; Slanicka 1991). The result here confirms this behavior since the Blaine fineness of the dry fly ash is higher than the weathered fly ash. Another reson may be due to the impurities of the weathered fly ash. An investigation was carried out by soaking both the dry and weathered fly ashes in tap water. The results indicated that the soaked water from the weathered fly ash is much darker than the one from the dry fly ash. It is believed that the weathered fly ash was contaminated by things, like clay, dust, and organic materials, while sitting in the storage pond with brackish water from the river. According to Kiattikomol and Jaturapitakkul (1989) the compressive strength of concrete can be reduced approximately by 15% with the presence of 3% of clay by weight of sand. Another reason may be that the crystalline phase in the weathered fly ash does not dissolve to a glassy phase as expected during the ponding periods. These attributed factors may be the cause of the lower compressive strength of the weathered fly ash mortar.

5.8.3 Setting Time of Fly Ash-Cement Paste When Use as a Replacement

Table 5.23 records the results of setting times of cement-fly ash paste. Sample RD and RW have the same proportion of cement and fly ash as shown in Table 4.1 Series VIII except that no sand was used. The initial setting times by Vicat or Gillmore methods are in close agreement. It seems that the setting time tested by the Gillmore needles is a slightly longer than the Vicat needle. Consider in terms of normal consistency, w/c, the normal consistency is higher with the higher content of fly ash. If considers in term of water to cementitious (cement+fly ash), it is nearly constant at 28% which is the same value for the cement paste.

The results show that the presence of fly ash in the mix increases the setting times, the higher the percentage of fly ash, the longer the setting times. Results reported by Meinlinger (1982), Ravina (1984), and Costa and Massazza (1983) also showed an increase in setting times with the increase of fly ash in cement. This is because Class F fly ash possesses very little cementitious material and the presence of fly ash will dilute the concentration of the cement while other factors such as water, temperature, humidity, etc., remain constant.

The initial and final setting times of cement paste by Vicat needle are 2 h 20 min and 5 h 30 min, respectively. With the Gillmore needles test, the initial and final setting times of cement paste are 2 h 40 min and 5 h 30 min, respectively. Both methods seem to agree closely with each other. The use of high percentage of fly ash results in longer setting time. RW20 and RW40 had initial setting time of 4 h 15 min and 5 h 35 min, respectively, by Vicat needle. These are much longer than the setting time of the cement paste. It should also be noted that the final setting time of RW40 is longer than 9 h which is 3 h 30 min longer than the cement paste. For the same amount of fly ash in the paste, the weathered fly ash prolongs setting time further than the dry fly ash. The initial and final setting times of RD40 are 3 h 35 min and 7 h 55 min by Vicat needle while for RW40 are 5 h 35 min and >9 h, respectively. This means that the weathered fly ash is less reactive than the dry fly ash.

ASTM C-150 (1990) specifies that the initial setting time of standard portland cement type I by Vicat test and Gillmore test be not less than 45 min and 60 min, respectively. For the final setting time, it must not be more than 10 h by Gillmore test. It is crucial that the mix proportion be carefully selected when introducing fly ash in the cement paste since setting time may be the major factor. With high volume use of fly ash in the cement paste, the setting time may be longer than those specified by the ASTM C-150.

Table 5.23 Setting Time of Cement-Fly Ash Paste

Sam. No.	Normal Consistency (%)		Initial Setting		Final Setting	
	W/C	W/(C+FA)	Vicat h:min	Gillmore h:min	Vicat h:min	Gillmore h:min
CEM	28:00	28:00	2:20	2:40	5:30	5:30
RD10	30:76	27:69	2:25	2:30	5:55	5:55
RD20	35:00	28:00	2:35	3:00	6:00	6:05
RD40	48:71	29:23	3:35	3:55	7:55	8:00
RW10	31:79	28:61	3:10	3:35	6:20	6:20
RW20	36:15	28:92	4:15	4:30	6:50	7:00
RW40	49:23	29:53	5:35	6:00	>9:00	>9:00

5.9 Fly Ash as a Partial Addition and Replacement of Sand

In this experiment, 10 percent of the dry or weathered fly ash by weight of cement was used as a replacement of sand. Additional quantity of fly ash was added in the mix as an addition. The addition of fly ash was varied from 10% to 40% by weight of cement. The mix proportion is shown in Table 4.1 series IX. The effect of fly ash as a partial addition and replacement of sand on the strength of mortar is shown in Fig 5.31. It is seen that most samples in this test give higher compressive strength than the control strength. The exception was ED40 which at 14 days and 28 days had strengths of 95% and 96%, respectively, of the control strength.

5.9.1 Dry Fly Ash as a Partial Addition and Replacement of Sand

Using fly ash as a partial replacement for sand, in the amount of 10% the weight of cement, and, as an additive, in the amount of 20% of the weight of cement, the compressive strength of ED20 was 2444 psi at 1 day and 10275 psi at 180 days or 114% and 130%, respectively, compared to the control strength. From Figure 5.32, the optimum ratio of the dry fly ash/cement ratio is about 0.3. At the ages up to 28 days, it is very difficult to see the optimum value but it is clear after 90 days.

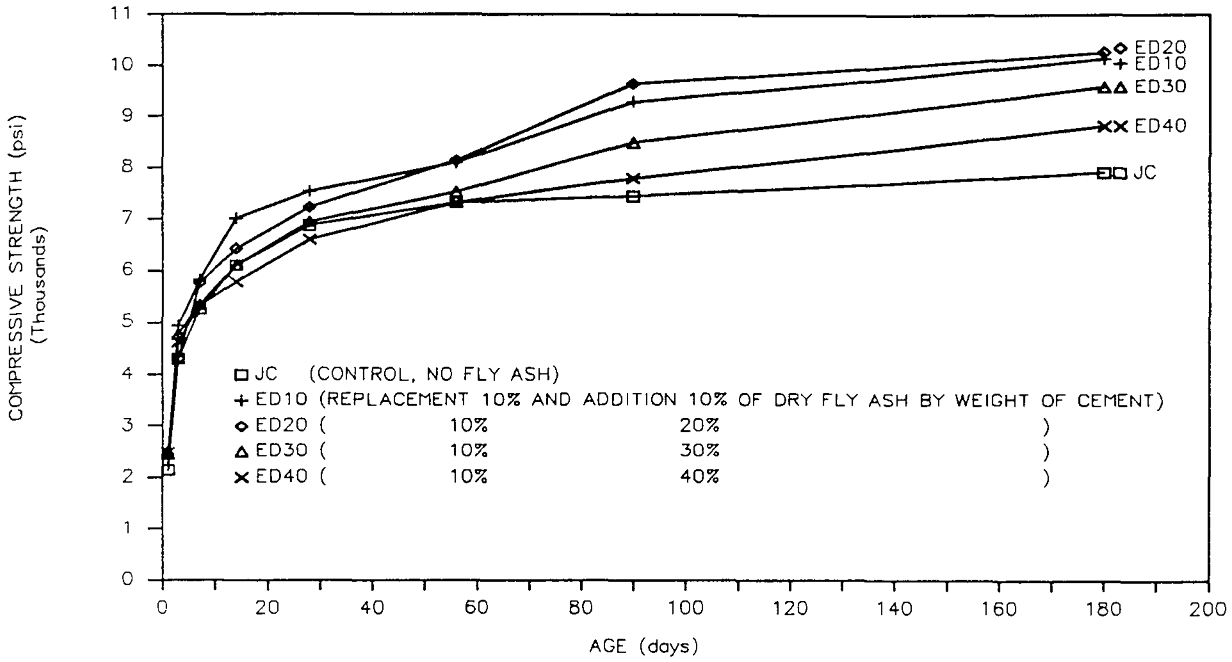

Figure 5.31 Effect of the Dry Fly Ash as a Partial Addition and Replacement of Sand on the Strength of Mortar

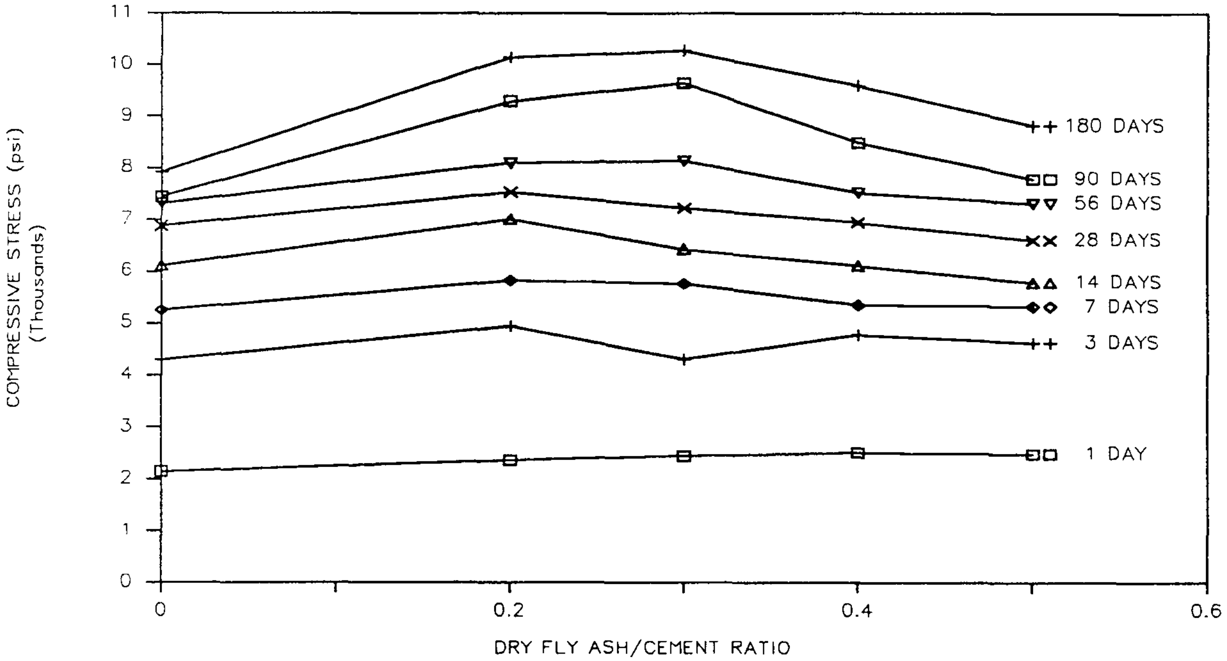

Figure 5.32 Relationship between Compressive Strength of the Dry Fly Ash as a Partial Addition and Replacement of Sand Versus the Dry Fly Ash/Cement Ratio

5.9.2 Weathered Fly Ash as a Partial Addition and Replacement of Sand

As shown in Figure 5.33, the results using the weathered fly ash are almost the same as the dry fly ash. It increases compressive strength of the sample. The optimum ratio of the weathered fly ash/cement is about 0.2 to 0.4 (See Figure 5.34). At the age of 180 days, the compressive strength of all fly ash mortar samples are higher than 10,000 psi and the highest is in EW30 which is 10949 psi or 138% of the control strength. The results of this test series suggest that the partial addition and replacement of fly ash in the mix gives superior of mortar strength than the control. Huang et al. (1991) suggested that fly ash used as 20% replacement for cement and 40% replacement for river sand is an engineering economic application.

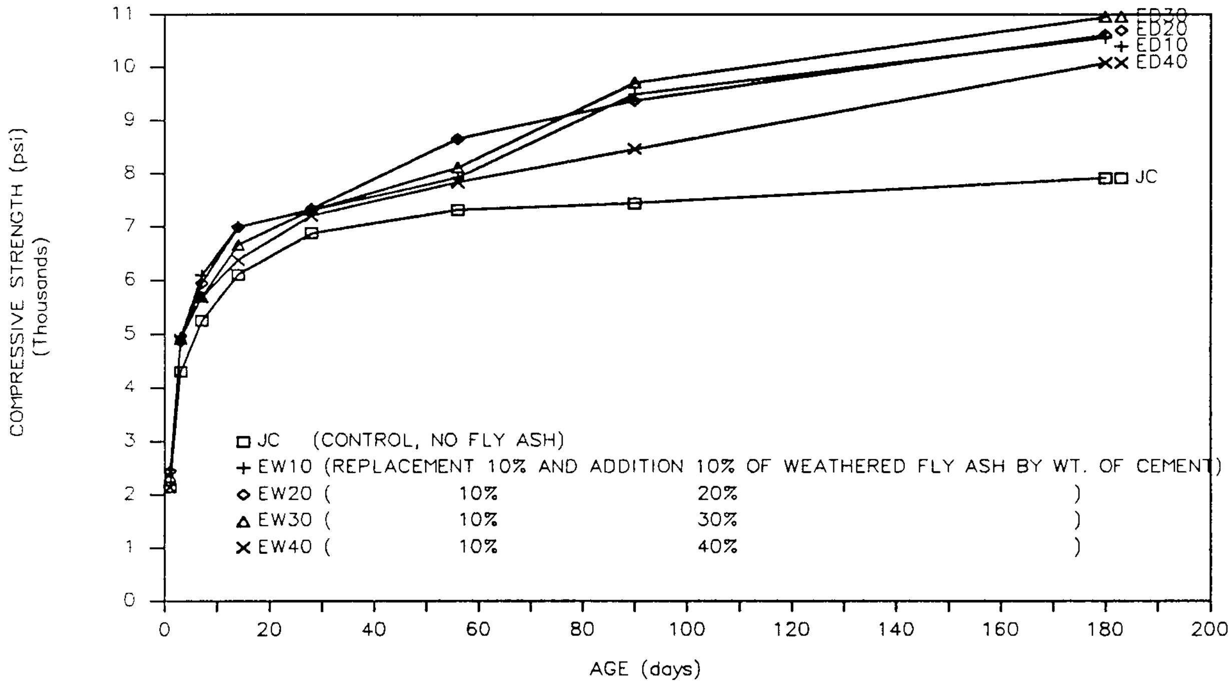

Figure 5.33 Effect of the Weathered Fly Ash as a Partial Addition and Replacement of Sand on the Strength of Mortar

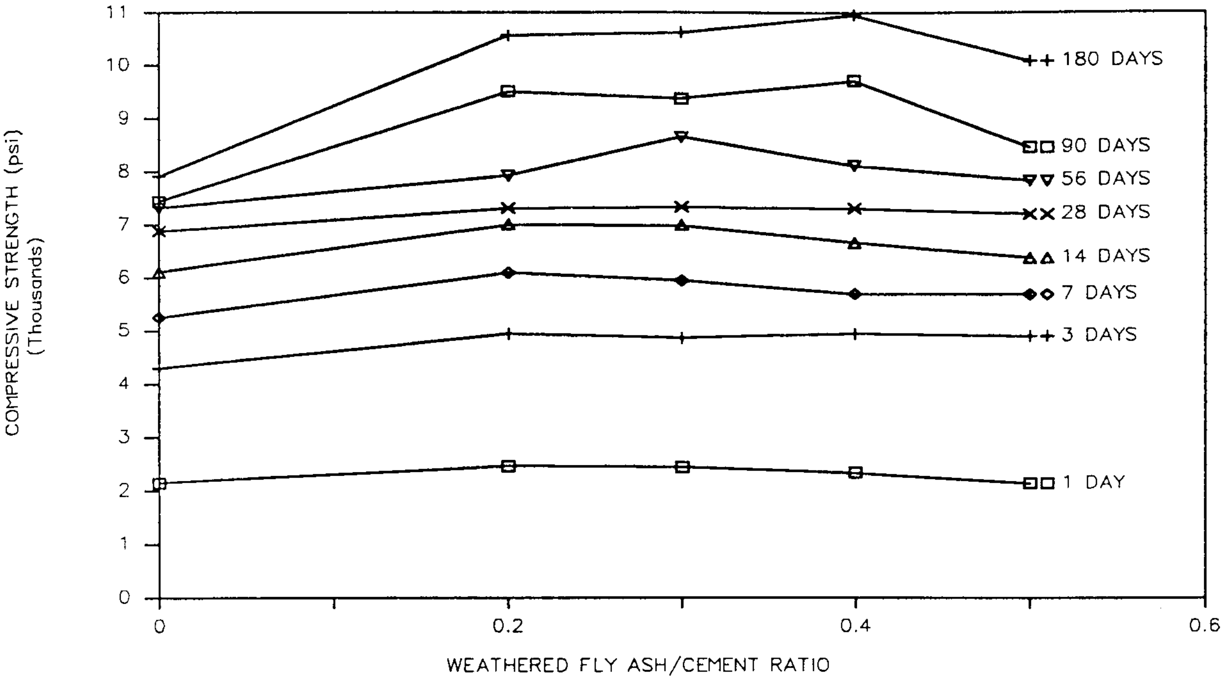

Figure 5.34 Relationship between Compressive Strength of the Weathered Fly Ash as a Partial Addition and Replacement of Sand Versus the Weathered Fly Ash/Cement Ratio

5.10 Fly Ash as an Additive

In this experiment, dry and weathered fly ashes were used as an addition in cement mortar. By keeping cement, sand, and water as constants, fly ash was added directly in the mix. The addition of fly ash was varied from 10% to 40% by weight of cement. The mix proportion is shown in Table 4.1 series X.

Generally, the addition of fly ash up to 40% by weight of cement results in a higher compressive strength of mortar at all ages. This result is in agreement with Berry and Malhotra (1980) who reported that the addition of dry fly ash generally increased the strength of concrete at all ages. The addition of very high volume of fly ash (more than 30%) causes lumps in the mix and sometimes reduces the compressive strength.

5.10.1 Addition of the Dry Fly Ash

The effect of adding additional fly ash on the strength of mortar is shown in Figure 5.35. Addition of the dry fly ash generally reduces the workability of mortar but increases the compressive strength. It can be seen that the compressive strength tends to increase with the age of fly ash mortar. The additional 10% of the dry fly ash by weight of cement increases the compressive strength from 7082 psi at 28 days to 9342 psi at 180 days or from 103% to 118% of the control strength, respectively. 20% additional fly ash produces the highest compressive strength (See Figure 5.36). For this optimum percentage, the compressive strength varied from 2444 psi at 1 day to 9768 psi at 180 days or 114% to 123% of the control strength.

Some samples such as AD30 and AD40 had lower compressive strength than control strength at the age up to 28 days. This effect is probably due to the lumps in the mix. The lumps are black spots and be easily seen after test for compression. The addition of high volume of fly ash usually caused lumps to form in cement-fly ash paste. By keeping the water constant, the addition of large volume of fly ash caused lumping and reduced compressive strength because of a non-homogeneous mix. After 28 days, all samples had higher compressive strength than the control strength.

5.10.2 Addition of the Weathered Fly Ash

In Figure 5.37, the addition of the weathered fly ash results in higher compressive strength than the control mortar. The compressive strength of AW30 varies from 2401 psi at 1 day to 10554 psi at 180 days or 112% to 133% of the control strength. The increase of compressive strength is small up to the age of 28 days but has a pronounced effect at 180 days. At early ages, the addition of fly ash does not effect the strength of mortar. Figure 5.38 shows that the fly ash-cement ratio does not have any effect on the strength of fly ash mortar until the age of 28 days. After that, an increasing trend in the strength was observed. The addition of 30% of the weathered fly ash gives the highest compressive strength.

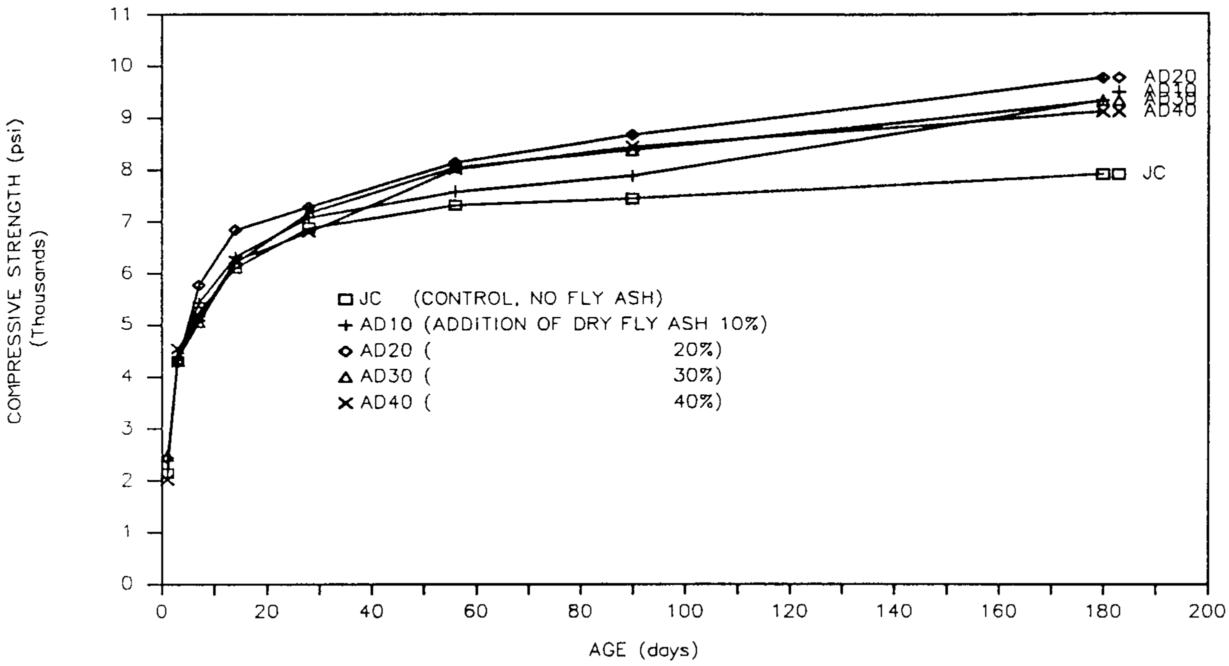

Figure 5.35 Effect of Addition the Dry Fly Ash on the Strength of Mortar

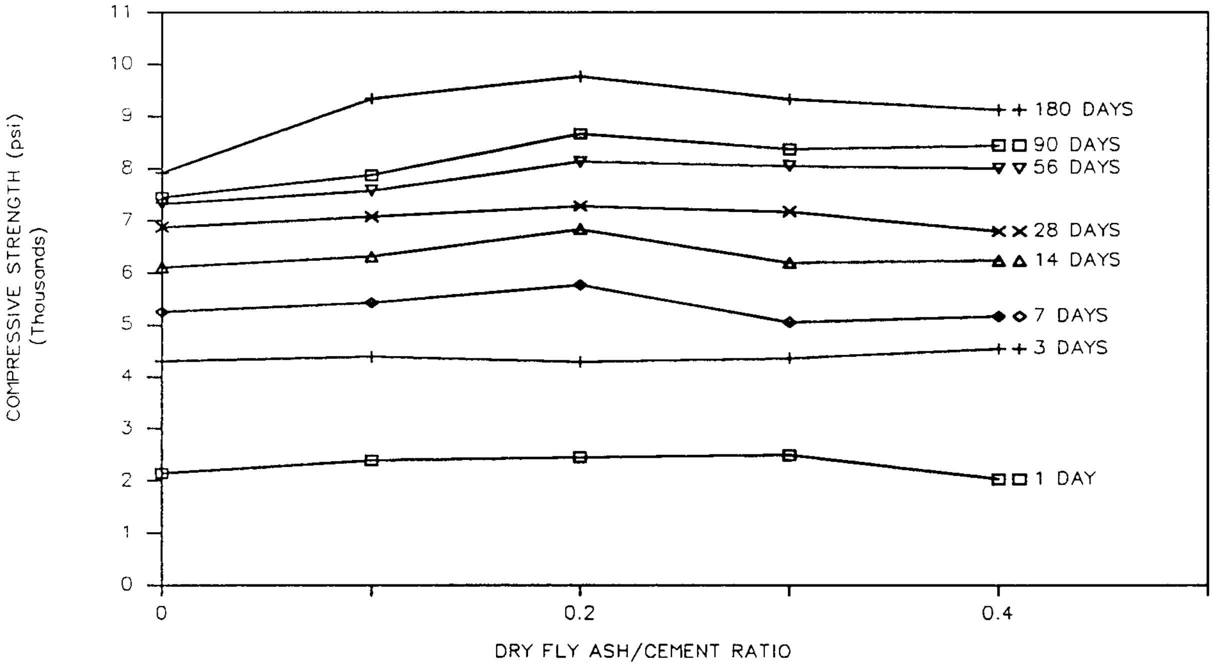

Figure 5.36 Relationship between Compressive Strength of Addition the Dry Fly Ash Mortar and the Dry Fly Ash/Cement Ratio

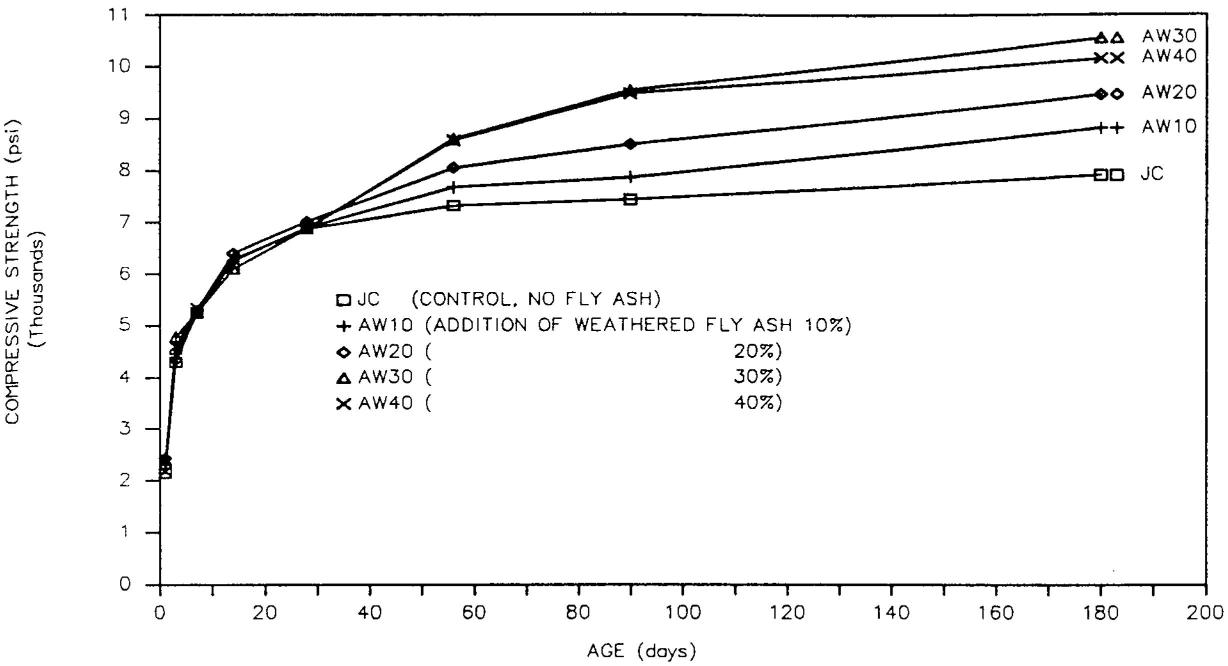

Figure 5.37 Effect of Addition the Weathered Fly Ash on the Strength of Mortar

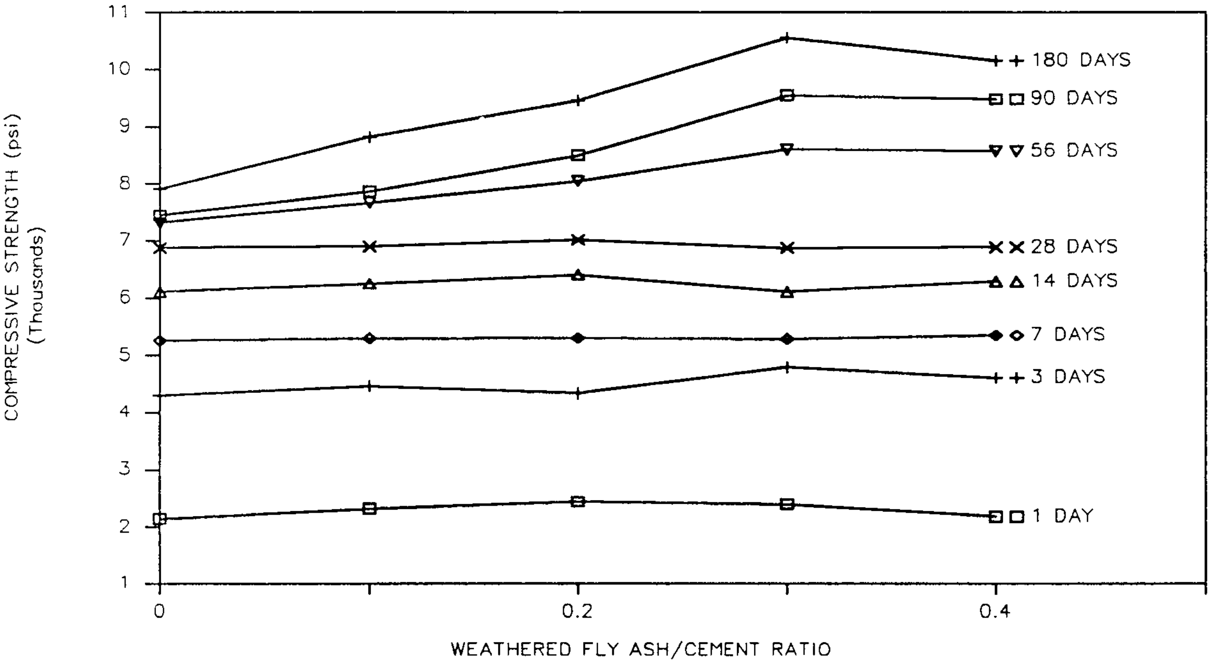

Figure 5.38 Relationship between Compressive Strength of Addition the Weathered Fly Ash Mortar and the Weathered Fly Ash/Cement Ratio

5.11 Soaked and Washed Fly Ashes

Soaked and washed fly ashes were used in this experiment. The soaked fly ash was produced by covering the dry fly ash with tap water for 1 week. Everyday the soaked fly ash was stirred to make sure that every particle of fly ash was soaked by water. After 7 days, the water of soaked fly ash and soaked fly ash were used for casting mortar specimens.

The washed fly ash was prepared by covering the dry fly ash with water, then stirred until they mixed together. The fly ash slurry was allowed to settle for one day then the water was decanted. After the water was taken out, the clean water was added into the fly ash again, then stirred and decanted again next day. Repeating this process for 1 week, the washed fly ash used for casting mortar specimens was obtained.

The washed and soaked fly ashes were used as addition to and as a replacement for cement. The 2"x2"x2" cube mortar was used to investigate the compressive strength. The compressive strengths of fly ash mortar were tested from 1 day to 180 days. The mix proportions are shown in Table 4.1 series XI. JC is the control sample. JR and JA refer to the samples with the replacement and addition, respectively, of the soaked fly ash. TR and TA refer to the samples with the replacement and addition of the washed fly ash. Numbers 15 and 25 stand for the amount of replacement or addition of fly ash in the mix.

5.11.1 Soaked and Washed Fly Ashes as a Replacement

The results of compressive strength of soaked and washed fly ash mortar are shown in Table 5.24. Table 5.25 is the results showing percentage compressive strength of the soaked and washed fly ash mortar comparing with the control strength. It is seen in Figures 5.39 and 5.40 that with the same amount of replacement of soaked or washed fly ashes, the compressive strength of fly ash mortar is almost the same. Carles-Gibergues and Aitcin (1986) also reported the same results for the behavior of the washed and unwashed fly ash concrete after 7 days. Additionally, there was no difference in the chemical composition of the extracted water and the water remaining capillarity in the wet fly ash. The replacement of soaked or washed fly ash lowers compressive strength of mortar comparing with the control strength up to 56 days. After 90 days, 15% and 25% replacement of the soaked or washed fly ash gives higher compressive strength than the control strength. At the age of 180 days, the strengths of JR15, JR25, TR15, and TR25 are 105%, 108%, 110%, and 107%, respectively, of the control strength.

Table 5.24 Compressive Strength of Soaked and Washed Fly Ash Mortar

Sam. No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
JC	2144	4303	5252	6109	6884	7320	7448	7918
JR15	1591	3812	4805	5724	6153	6651	7796	8322
JA15	2221	4658	5940	6414	7453	8458	9636	10268
TR15	1895	3500	4675	5655	6090	7307	7706	8678
TA15	2224	4454	5732	6499	7249	8903	9453	10323
JR25	1338	3197	4301	5150	5891	6806	7600	8519
JA25	2308	4436	5640	6866	7476	8468	9930	10749
TR25	1354	3089	3841	4706	5536	6367	7868	8444
TA25	2423	5001	5849	7085	7883	8891	9940	11396

Table 5.25 Percentage Compressive Strength of Soaked and Washed Fly Ash Mortar

Sam. No	Percentage Compressive Strength (%)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
JC	100	100	100	100	100	100	100	100
JR15	74	89	91	94	89	91	105	105
JA15	104	108	113	105	108	116	129	130
TR15	88	81	89	93	88	100	103	110
TA15	104	104	109	106	105	122	127	130
JR25	62	74	82	84	86	93	102	108
JA25	108	103	107	112	109	116	133	136
TR25	63	72	73	77	80	87	106	107
TA25	113	116	111	116	115	121	133	144

5.11.2 Soaked and Washed Fly Ashes as an Additive

The addition of soaked and washed fly ashes result in a higher compressive strength than the control. The addition 15% of soaked and washed fly ashes give very similar compressive strengths at the same age. The compressive strength of JA15 varies from 2221 psi at 1 day to 10268 psi at 180 days. TA15 varies from 2224 psi at 1 day to 10323 psi at 180 days. With 25% of addition, the strength of JA25 varies from 2308 psi at 1 day to 10749 psi at 180 days while the strength of TA25 varies from 2423 psi at 1 day to 11396 psi at 180 days. Generally, the addition 25% by weight of cementitious material of soaked and washed fly ashes, produce higher compressive strength than the addition only 15% of soaked and washed fly ashes at the age of 180 days.

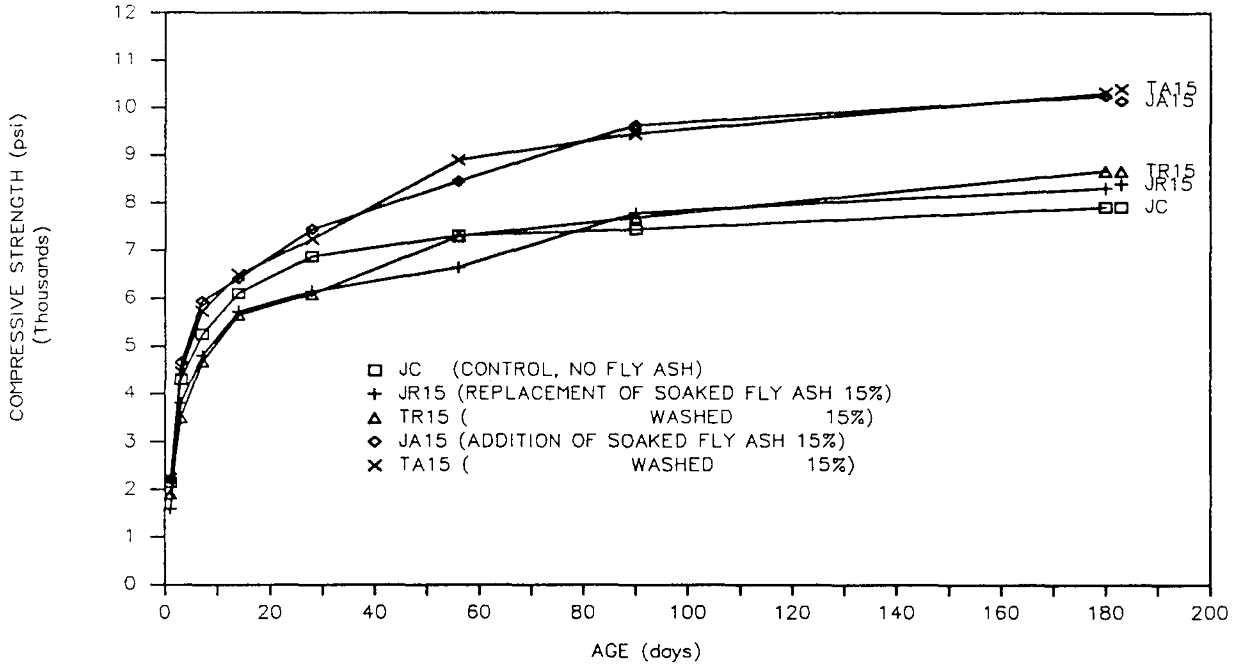

Figure 5.39 Effect of Soaked and Washed Fly Ashes on the Strength of Mortar (with 15% of Soaked and Washed Fly Ashes)

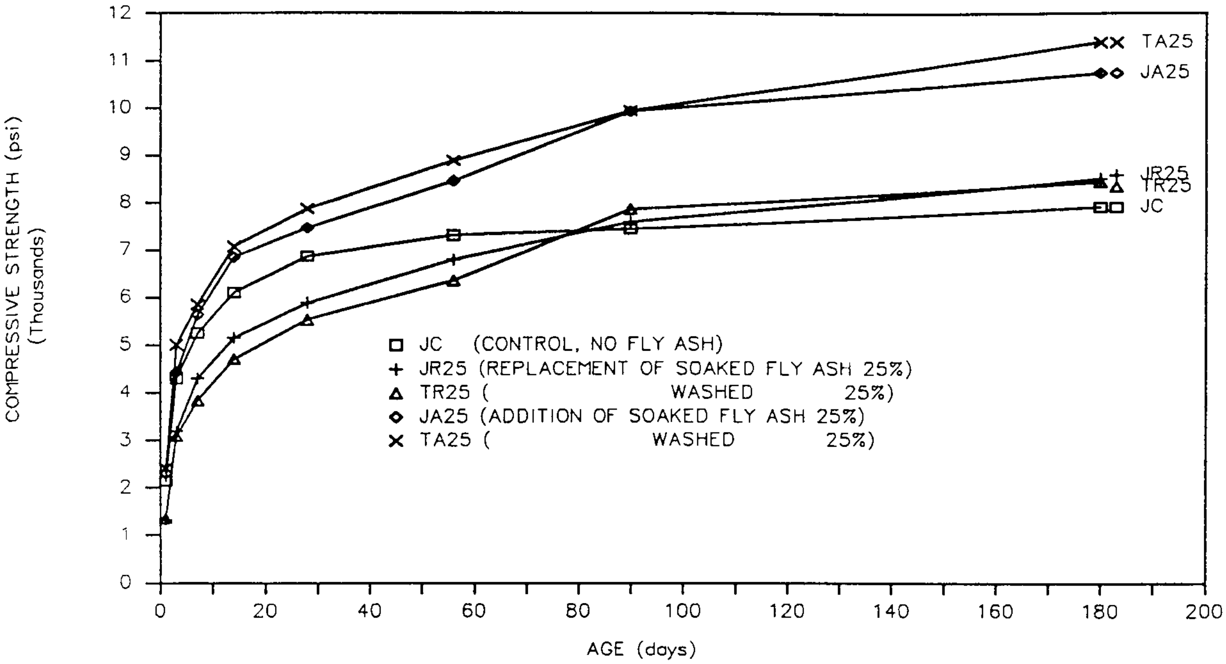

Figure 5.40 Effect of Soaked and Washed Fly Ashes on the Strength of Mortar (with 25% of Soaked and Washed Fly Ashes)

5.12 Effect of Fractionated Fly Ashes on the Strength of Concrete

This experimental series concentrates on the study of fly ash when the particle size distributions have a smaller range than the original feed fly ash, that is, fly ash as received from storage silo. Due to its narrower range of particle size distribution, each fractionated fly ashes gives a more unique indication of its pozzolanic activity than the original feed fly ashes which has a wider range of particle size distribution. The materials in this experiment consisted of cement type I, fractionated fly ashes, sand, coarse aggregate, and water. No any kind of admixture was used.

Sample CCCC is the control sample, i.e. sample without any fly ash in the mix. CDRY and CWET are the samples for concrete mixed with the original feed of dry and wet bottom fly ashes, respectively. The fractionated fly ashes used in the sample are implied by the number(s) follow by the character. The last two digits indicate the proportion of fly ash in the mix. For example, sample "3FC15" means that the concrete sample consists of 3F fly ash 15% by weight of cementitious materials. Sample "3FC25" stands for the concrete sample using 25% of 3F fly ash by weight of cementitious materials.

5.12.1 Workability of Fractionated Fly Ash Concrete

Table 5.25 shows the slump test results for fractionated fly ash concrete. The slump is usually higher when fly ash is used in agreement with Ukita, Shigematsu, and Ishii (1989). Incorporation of fly ash in concrete often improves workability and thereby reduces the water requirement with respect to conventional concretes (Lane and Best 1982; ACI 226 1987; Yamato and Sugita 1983). The results of this experiment show that only the finest fly ash reduces the workability of fresh concrete especially when high quantities of fly ash are applied. Most of the other sizes of fly ash increase slump. Since the weight of fly ash was kept constant, the finer particle fly ash has more surface area and thus needs more water to maintain the same workability as the coarser fly ash.

Table 5.26 Slump of Fractionated Fly Ash Concrete

Sam.	Slump (cm)	Sam.	Slump (cm)	Sam.	Slump (cm)	Sam.	Slump (cm)
3FC15	5.5	3FC25	5.5	3FC35	5.0	3FC50	4.5
6FC15	8.0	6FC25	7.0	6FC35	8.5	6FC50	8.5
10FC15	8.0	10FC25	9.0	10FC35	11.0	10FC50	13.0
11FC15	8.5	11FC25	9.5	11FC35	10.5	11FC50	13.5
1CC15	7.0	1CC25	8.0	1CC35	6.5	1CC50	8.0
CDRY15	7.0	CDRY25	8.0	CDRY35	7.5	CDRY50	10.0
13FC15	6.0	13FC25	5.0	13FC35	3.5	13FC50	3.0
15FC15	7.0	15FC25	6.0	15FC35	6.0	15FC50	5.0
16FC15	7.5	16FC25	8.0	16FC35	6.0	16FC50	7.0
18FC15	6.5	18FC25	8.5	18FC35	7.0	18FC50	12.0
18CC15	5.0	18CC25	6.5	18CC35	5.5	18CC50	8.0
CWET15	5.5	CWET25	7.0	CWET35	7.0	CWET50	9.5
CCCC	5.0	CCCC	5.0	CCCC	5.0	CCCC	5.0

With 50% fly ash of the finest particle size in the cementitious materials, the fly ash concrete samples of dry and wet bottom fly ashes, 3FC50 and 13FC50, are less workable than those of the control concrete which has a slump of about 5 cm. The slumps of fly ash concrete from the original feed fly ashes are slightly higher than the control mix. For the original feed fly ashes, samples from the dry bottom fly ash, CDRY, are more workable than those from the wet bottom fly ash, CWET. This may be because the particle sizes of the dry bottom fly ash is larger than those of the wet bottom fly ash. With the same amount of fly ash in the mix, the coarsest particle sizes, 1CC and 18CC, seem to give a little lower slump than the original feed fly ash concrete.

5.12.2 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete with 15% Replacement

The compressive strength of the fractionated of dry bottom fly ash concrete with 15% replacement of cement is shown in Table 5.27. The percentage variation of compressive strength compared to the control mix is listed in Table 5.28. The relationship between compressive strength of the fractionated of dry bottom fly ash concrete and its corresponding age is shown in Figure 5.41.

Table 5.27 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (15% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
3FC15	1721	5946	7189	8318	9129	9888	11100
6FC15	1718	5746	6887	7946	8949	9484	10606
10FC15	1673	5670	6477	7541	8414	9010	10339
11FC15	1667	5550	6430	7350	8139	8723	9850
1CC15	1598	5416	6411	6971	7889	8259	9269
CDRY15	1622	5525	6479	7440	8300	8943	10083

Table 5.28 Percentage Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (15% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3FC15	79.8	95.3	100.7	102.0	104.8	107.5	109.2
6FC15	79.6	92.1	96.4	97.4	102.8	103.1	104.4
10FC15	77.6	90.9	90.7	92.4	96.6	98.0	101.8
11FC15	77.3	89.0	90.0	90.1	93.5	94.9	96.9
1CC15	74.1	86.8	89.8	85.5	90.6	89.8	91.2
CDRY15	75.2	88.6	90.7	91.2	95.3	97.3	99.2

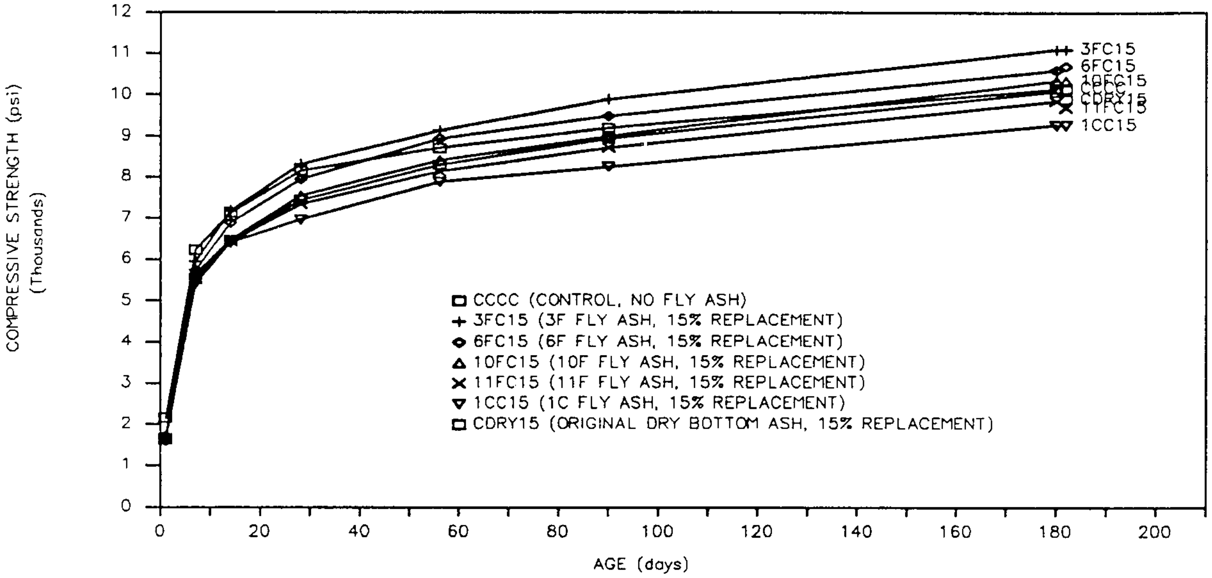

Figure 5.41 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (15% Replacement) and Age

The early strength of fractionated fly ash concrete is always lower than the control mix. With a portion of cement replaced by the Class F fly ash, the mix generally produces lower strength because fly ash acts as a relatively inert component during the early period of hydration (Carette and Malhotra 1983). This result was also reported by Plowman (1984) and Langley, Carette, and Malhotra (1989).

With 15% replacement of cement by fractionated fly ashes, the compressive strength at 1 day is reduced about 20% to 25% compared to the control strength (sample CCCC). The variation of the strength is due to the different particle sizes of fly ash. The finer particle fly ash gives a better packing effect than the coarser one. After 14 days of curing, 3FC15 concrete (15% replacement of 3F fly ash) has a compressive strength essentially equal to the control strength. This means that the pozzolanic activity of the finest particle size fly ash produces a higher strength than the strength achieved by the hydration process of cement. This result continues resulting in larger differences between the 3FC15 fly ash concrete and the control concrete. Sample 6FC15 gains the same strength as the control before the age of 56 days. It needs about 180 days of curing for the samples 10FC15 and CDRY15 (15% replacement of the original feed of dry bottom fly ash) to have the same strength as the control concrete. With the coarsest particle size of fly ash in concrete, 1CC15, the compressive strength varies from 1598 psi at 1 day to 9269 psi at 180 days or from 74.1% to 91.2% comparing with the control concrete. Considering sample 3FC15, the compressive strength varies from 1721 psi at 1 day to 11100 psi at 180 days or from 79.8% to 109.2% comparing with the control strength. Since all the chemical composition of these fractionated fly ashes are almost the same, the particle size of fly ash is the major factor affecting the compressive strength of fly ash concrete.

5.12.3 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete with 25% Replacement

Table 5.29 shows the compressive strength of the fractionated of dry bottom fly ash concrete with 25% replacement of cement. Table 5.30 presents the percentage compressive strength of the fractionated of dry bottom fly ash concrete compared to the control concrete. The relationship between the compressive strength of the fractionated of dry bottom fly ash concrete and its corresponding age is shown in Figure 5.42.

Table 5.29 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (25% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
3FC25	1510	5280	6494	7686	8567	9502	10731
6FC25	1485	4816	5842	7058	8122	8785	9974
10FC25	1447	4735	5620	6691	7719	8367	9315
11FC25	1390	4633	5566	6582	7389	8111	9109
1CC25	1369	4542	5400	6360	7001	7521	8348
CDRY25	1390	4593	5492	6598	7390	8044	9070

Table 5.30 Percentage Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (25% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3FC25	70.0	84.7	90.9	94.2	98.4	103.3	105.6
6FC25	68.8	77.2	81.8	86.5	93.3	95.5	98.2
10FC25	67.1	75.9	78.7	82.0	88.7	91.0	91.7
11FC25	64.4	74.3	77.9	80.7	84.9	88.2	89.6
1CC25	63.5	72.8	75.6	78.0	80.4	81.8	82.2
CDRY25	64.4	73.6	76.9	80.9	84.9	87.5	89.3

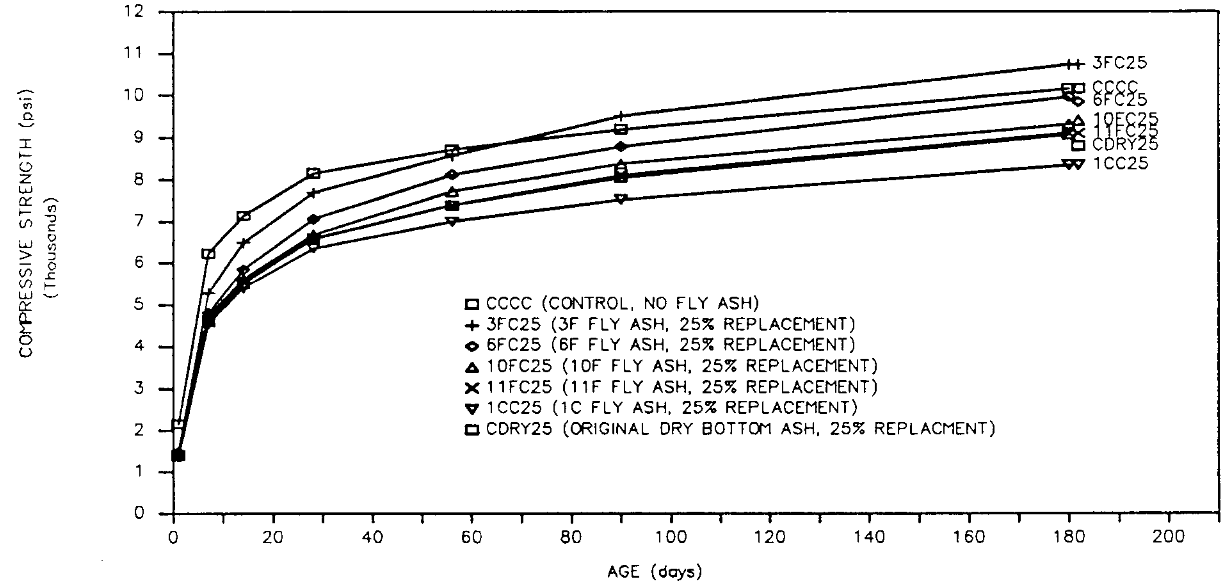

Figure 5.42 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (25% Replacement) and Age

With 25% replacement of cement by the fractionated of dry bottom fly ashes, the early strengths of the concrete, with the same kind of fly ash, are lower than with a 15% replacement. To gain the same strength as the control, takes at least 56 days for the sample 3FC25 (25% replacement of 3F fly ash). The percentage compressive strength of the fractionated of dry bottom fly ash concrete varies form 63.5% in 1CC25 to 70.0% in 3FC25 at 1 day. The strength gain of 3FC25 sample from 70% (1 day) to 105.6% (180 days) is about 35.2% which is much higher than that of 1CC25 concrete which is from 63.5% to 82.2% or 18.7%. The strength gain from 1 day to 180 days of the original feed of dry bottom fly ash sample (CDRY25) is about 25%. The results indicate that the finer fly ash particles gains higher strength than the coarser particles. The results of this study also indicate that for compressive strength the quality of fly ash can be improved by reducing the particle size of fly ash.

5.12.4 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete with 35% Replacement

The compressive strength of the fractionated of dry bottom fly ash concrete with 35% replacement of cement is shown in Table 5.31. The percentage variation of compressive strength compared to the control mix is shown in Table 5.32. The relationship between compressive strength of the fractionated of dry bottom fly ash concrete and its age is shown in Figure 5.43.

With the replacement of fly ash up to 35% by weight of cementitious materials, the percentage compressive strength for fractionated fly ash concrete at 1 day varies from 39.9% to 52.7% of the control strength, depending on the fineness of the fly ash. In general, the compressive strength of the finer particle mixes is higher than that for the coarser ones. The finer particles react with cement faster than the coarser ones since they have more surface area. The early strengths of all fly ash concretes are lower than the control concrete. This behavior is normal in fly ash concrete, especially when a high volume of cement is replaced by fly ash. After 180 days of curing, the compressive strength of fly ash concrete made from the original feed of dry bottom fly ash is 8389 psi or 82.6% of the control concrete. With the finest particle size of fly ash, 3F, it takes about 180 days for the fly ash concrete to have the same strength as the control when used fly ash 35% by weight of cementitious materials. The compressive strength of 3FC35 varies from 1136 psi at 1 day to 10080 psi at 180 days. That is an increase of about 8.8 times from 1 day to 180 days. It is interesting to note that the strength of the coarsest sample, i.e. 1CC35, at the age of 180 days is only 71.3% of the control strength.

Table 5.31 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (35% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
3FC35	1136	4606	5531	6602	7483	8406	10080
6FC35	988	4222	5324	6378	7246	8001	9451
10FC35	888	3913	4838	5766	6466	7137	8401
11FC35	882	3739	4768	5613	6217	6859	8031
1CC35	860	3567	4501	5240	5691	6200	7242
CDRY35	906	3895	4696	5798	6440	7189	8389

Table 5.32 Percentage Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (35% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3FC35	52.7	73.8	77.5	80.9	85.9	91.4	99.2
6FC35	45.8	67.7	74.6	78.2	83.2	87.0	93.0
10FC35	41.2	62.7	67.7	70.7	74.3	77.6	82.7
11FC35	40.9	59.9	66.8	68.8	71.4	74.6	79.0
1CC35	39.9	57.2	63.0	64.2	65.4	67.4	71.3
CDRY35	42.0	62.4	65.8	71.1	74.0	78.2	82.6

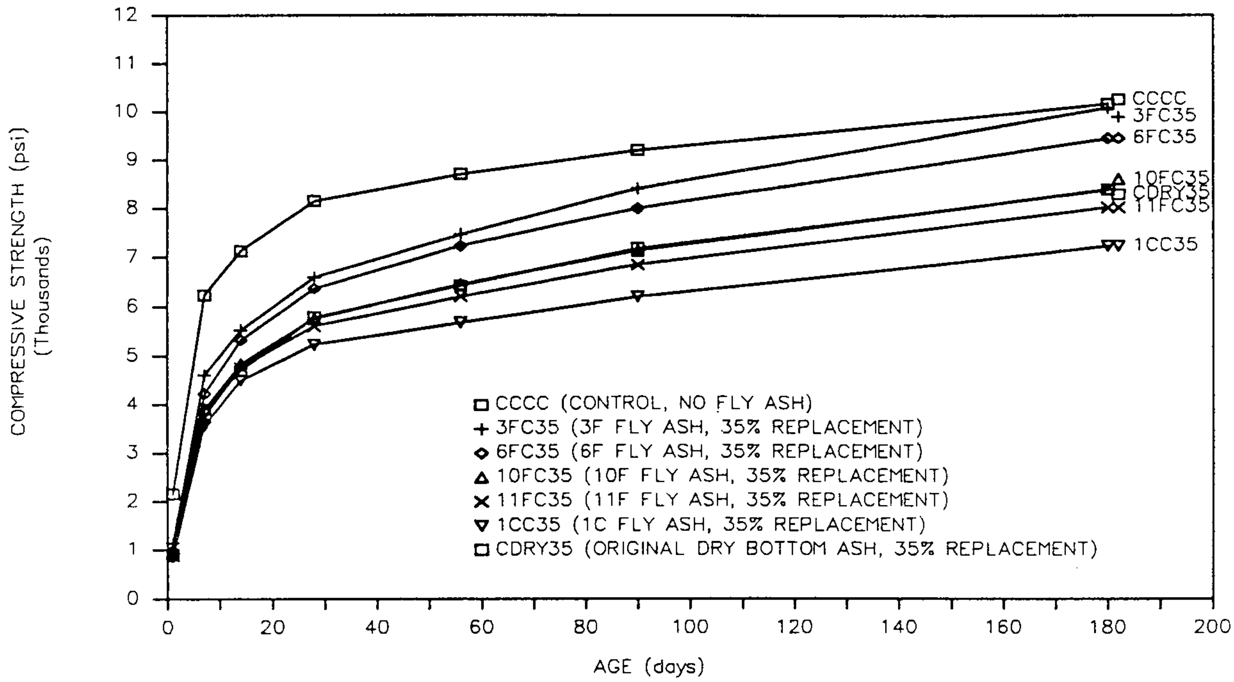

Figure 5.43 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (35% Replacement) and Age

5.12.5 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete with 50% Replacement

The compressive strength of the fractionated of dry bottom fly ash concrete with 50% replacement of cement is shown in Table 5.33. The percentage variation of compressive strength compared to the control mix is listed in Table 5.34. The relationship between compressive strength of the fractionated of dry bottom fly ash concrete and its age is presented in Figure 5.44.

With 50% fly ash of the cementitious materials, all strengths of fractionated fly ash concrete are lower than the control strength. The compressive strength at 1 day varies from 407 psi to 567 psi (from the coarse to the fine particle size of fly ash) or 18.9% to 26.3% of the control strength. This strength is much lower than the control strength which is 2157 psi. The compressive strength of fly ash concrete gradually increases with time due to the pozzolanic activity of fly ash. The strength of 3FC50 varies from 567 psi at 1 day to 8639 psi at 180 days or 26.3% to 85.0% comparing with the control strength. Considering Figure 5.44, it is seen that after 28 days the slope of 3FC50 concrete is higher than the slope of CCCC (control sample). This means that after 28 days the pozzolanic activity of the fly ash contributes more strength than the strength produced by the hydration of cement.

Table 5.33 Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (50% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
3FC50	567	3026	4142	5073	6400	7246	8639
6FC50	434	2682	3521	4397	5155	5839	7823
10FC50	425	2649	3140	3857	4527	5271	7069
11FC50	411	2382	2991	3748	4442	5044	6666
1CC50	407	2110	2692	3334	3976	4340	5578
CDRY50	410	2405	3041	3782	4466	5054	6857

Table 5.34 Percentage Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (50% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3FC50	26.3	48.5	58.0	62.2	73.5	78.8	85.0
6FC50	20.1	43.0	49.3	53.9	59.2	63.5	77.0
10FC50	19.7	42.5	44.0	47.3	52.0	57.3	69.6
11FC50	19.1	38.2	41.9	45.9	51.0	54.9	65.6
1CC50	18.9	33.8	37.7	40.9	45.7	47.2	54.9
CDRY50	19.0	38.6	42.6	46.4	51.3	55.0	67.5

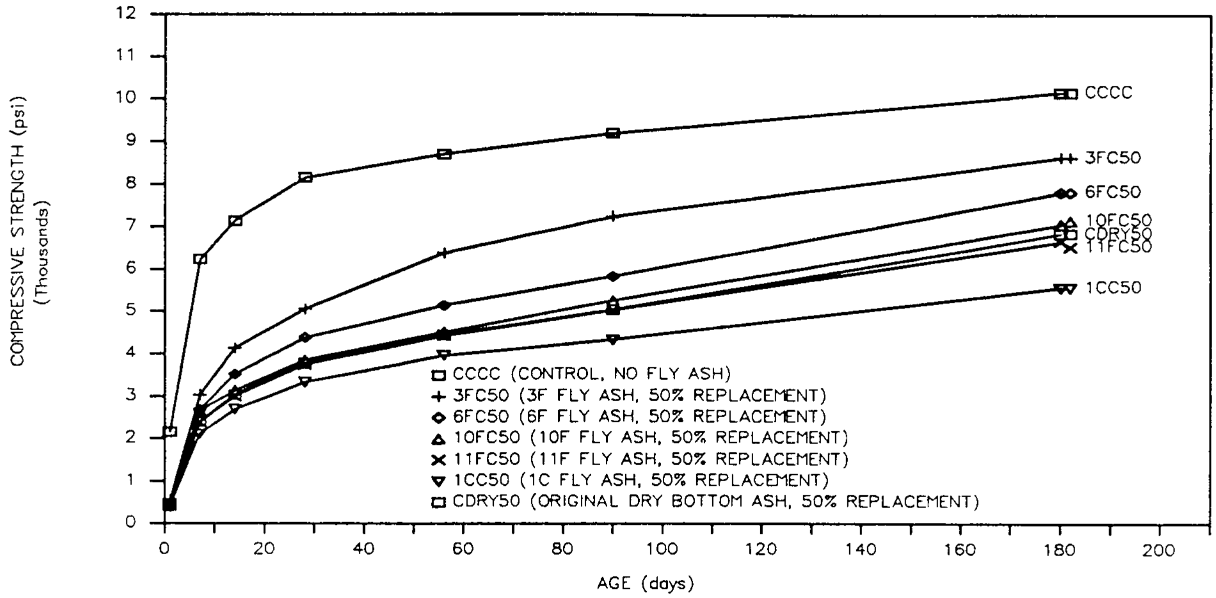

Figure 5.44 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete (50% Replacement) and Age

5.12.6 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete with 15% Replacement

The compressive strength of the fractionated of wet bottom fly ash concrete with 15% replacement of cement is shown in Table 5.35. The percentage variation of compressive strength compared to the control mix is presented in Table 5.36. The relationship between compressive strength of the wet fractionated fly ash concrete and its corresponding age is shown in Figure 5.45.

The compressive strength of the original feed of wet bottom fly ash is higher than that from the dry bottom fly ash at the same age and for the same mix proportions. This is primarily due to the finer particle size of the wet bottom fly ash. With 15% replacement of cement by fly ash, all the early strengths of fractionated fly ash concrete are lower than the control. At 14 days, the compressive strength of 13FC15 is a little higher than the control strength. After 56 days, sample 15FC15 gives the same strength as the control concrete. It takes 90 days for samples 16FC15 and 18FC15 to achieve the same strength as the control concrete. After 180 days, all of the fractionated fly ash concretes have higher strength than the control concrete except sample 18CC15 which has 95.3% of the control strength. Sample 18CC15 uses 18CC fly ash which has the residue retained on sieve No. 325 (45 microns) 29% which is lower than the limit given by ASTM C-618 (1990) which is 34%. This indicates that the active particle size of fly ash is smaller than this size of sieve opening. It is also noted that it takes 180 days for the original feed of wet bottom fly ash concrete to gain strength of the same order as the control concrete.

5.12.7 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete with 25% Replacement

The compressive strength of the fractionated of wet bottom fly ash concrete with 25% replacement of cement is shown in Table 5.37. The percentage variation of compressive strength compared to the control mix is listed in Table 5.38. The relationship between compressive strength of the fractionated of wet bottom fly ash concrete and its corresponding age is shown in Figure 5.46.

The results of this test are the same as 15% replacement of the fractionated of wet bottom fly ash concrete except that the strengths are lower. The early strengths of fractionated fly ash concrete are lower than the control concrete up to 14 days. At the age of 28 days, sample 13FC25 produces a higher strength than the control strength and continue higher after this age. At the age of 180 days, the compressive strength of 13FC25 is 11162 psi or 109.9% comparing with the control concrete. Sample 15FC25 reaches the same strength as the control concrete before the age of 56 days. Before 90 days of curing, sample 16FC25 also gives the same strength as the control. The strength of concrete using the coarsest particle, 18CC25, is only 84.4% of the control concrete at 180 days. The results show that the strength of fractionated fly ash concrete depends on the particle size of the fly ash. The smaller the particle size of fly ash in concrete, the higher is the compressive strength.

Table 5.35 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (15% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
13FC15	1998	6012	7216	8329	9233	9868	11201
15FC15	1977	5905	6943	7922	8800	9433	10815
16FC15	1898	5739	6641	7652	8609	9320	10715
18FC15	1848	5737	6575	7501	8205	9133	10509
18CC15	1821	5464	6284	7228	7827	8389	9681
CWET15	1844	5468	6345	7345	8102	8888	10158

Table 5.36 Percentage Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (15% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
13FC15	92.6	96.4	101.1	102.1	106.0	107.3	110.2
15FC15	91.7	94.7	97.2	97.1	101.1	102.6	106.4
16FC15	88.0	92.0	93.0	93.8	98.9	101.4	105.5
18FC15	85.7	92.0	92.1	92.0	94.2	99.3	103.4
18CC15	84.4	87.6	88.0	88.6	89.9	91.2	95.3
CWET15	85.5	87.7	88.9	90.0	93.1	96.7	100.0

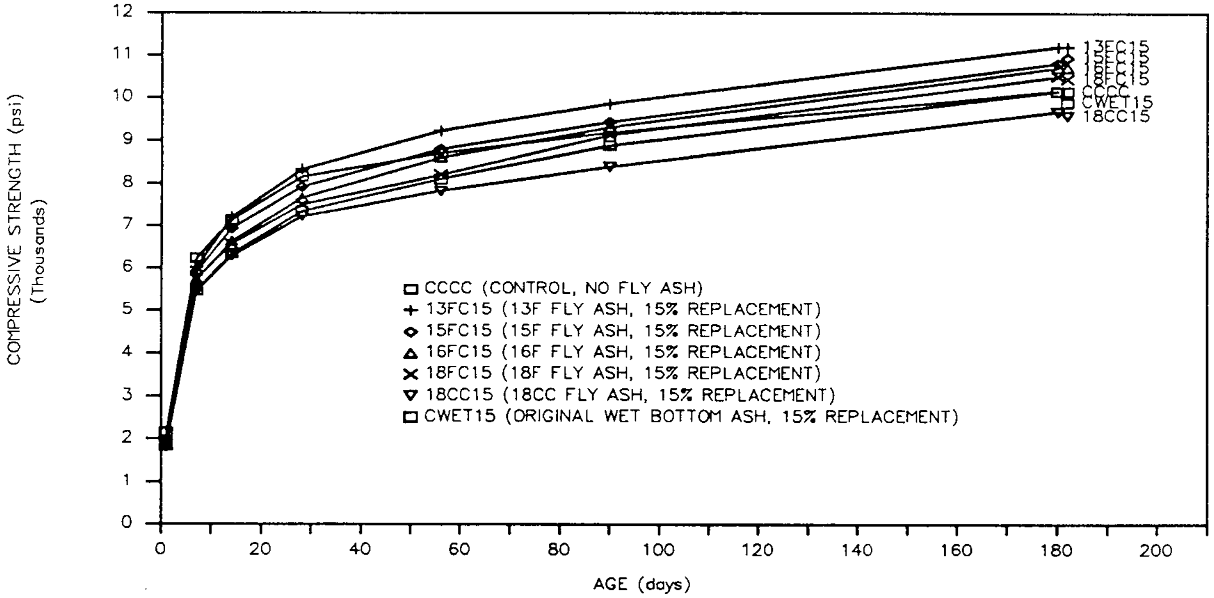

Figure 5.45 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (15% Replacement) and Age

Table 5.37 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (25% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
13FC25	1600	5491	6899	8267	9127	9861	11162
15FC25	1548	5371	6667	7854	8783	9645	10794
16FC25	1480	5165	6341	7522	8488	9434	10524
18FC25	1389	4880	6025	7141	7910	8626	9778
18CC25	1367	4638	5671	6348	7215	7765	8571
CWET25	1405	4923	6017	7210	8112	8601	9467

Table 5.38 Percentage Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (25% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
13FC25	74.2	88.0	96.6	101.3	104.8	107.2	109.9
15FC25	71.8	86.1	93.4	96.3	100.9	104.9	106.2
16FC25	68.6	82.8	88.8	92.2	97.5	102.6	103.6
18FC25	64.4	78.2	84.4	87.5	90.8	93.8	96.2
18CC25	63.4	74.4	79.4	77.8	82.9	84.4	84.4
CWET25	65.1	78.9	84.3	88.4	93.2	93.5	93.2

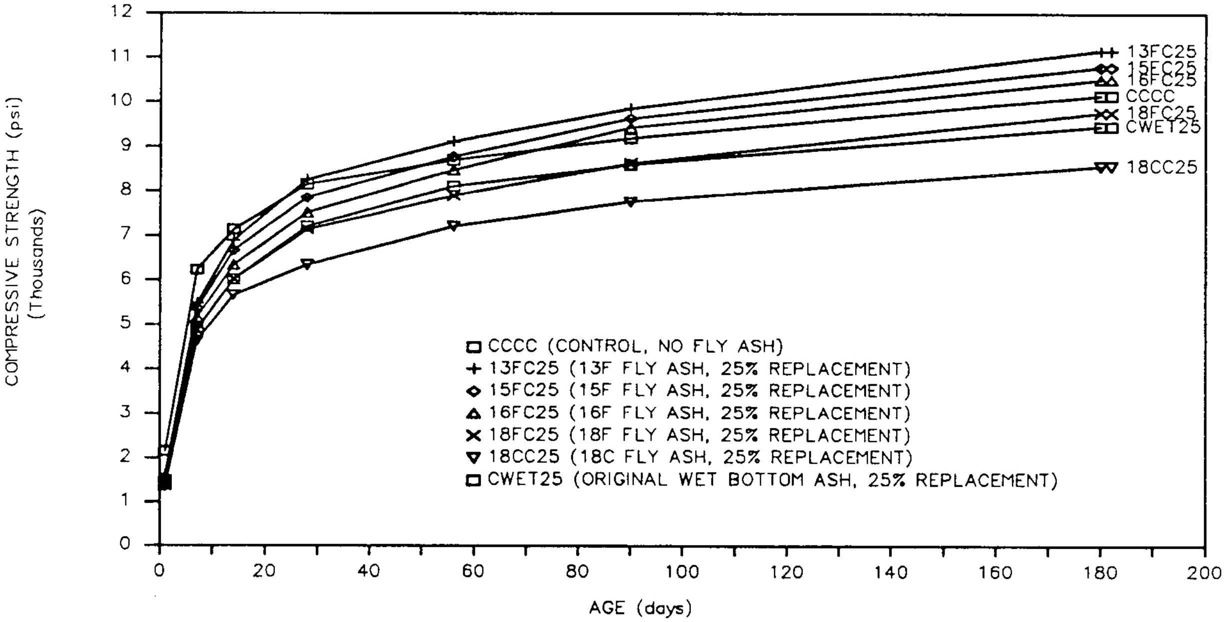

Figure 5.46 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (25% Replacement) and Age

5.12.8 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete with 35% Replacement

The compressive strength of the fractionated of wet bottom fly ash concrete with 35% replacement of cement is shown in Table 5.39. The percentage variation of compressive strength compared to the control mix is listed in Table 5.40. The relationship between compressive strength of the fractionated of wet bottom fly ash concrete and its corresponding age is shown in Figure 5.47.

With 35% replacement of cement by fly ash in concrete, the compressive strengths are lower than those for 15% and 25% replacement, especially at the early ages. The compressive strength of fractionated fly ash concrete at 1 day varies from 851 psi to 1460 psi, moving from coarse to fine particle sizes. Most strengths of fractionated fly ash concrete are lower than the control concrete at all ages except the sample with the finest particle size of fly ash, 13FC35. The strength of sample 13FC35 varies from 1460 psi at 1 day to 10788 psi at 180 days or 67.6% to 106.2% of the control strength. The strength of fly ash concrete with 35% replacement can be as high as the control strength within 90 days by using 13F fly ash. With the original feed of wet bottom fly ash, CWET35, had a compressive strength at 180 days about 90% of the control strength.

Table 5.39 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (35% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
13FC35	1460	4944	5945	7314	8410	9188	10788
15FC35	1187	4754	5639	6838	7927	8740	9983
16FC35	942	4616	5409	6609	7532	8215	9578
18FC35	899	4243	5068	6057	6859	7546	9008
18CC35	851	3920	4660	5466	6047	6649	7875
CWET35	926	4438	5144	6144	6940	7721	9135

Table 5.40 Percentage Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (35% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
13FC35	67.7	79.3	83.3	89.7	96.6	99.9	106.2
15FC35	55.0	76.2	79.0	83.8	91.0	95.1	98.3
16FC35	43.7	74.0	75.7	81.0	86.5	89.3	94.3
18FC35	41.7	68.0	71.0	74.3	78.8	82.1	88.7
18CC35	39.5	62.9	65.3	67.0	69.4	72.3	77.5
CWET35	42.9	71.2	72.0	75.3	79.7	84.0	89.9

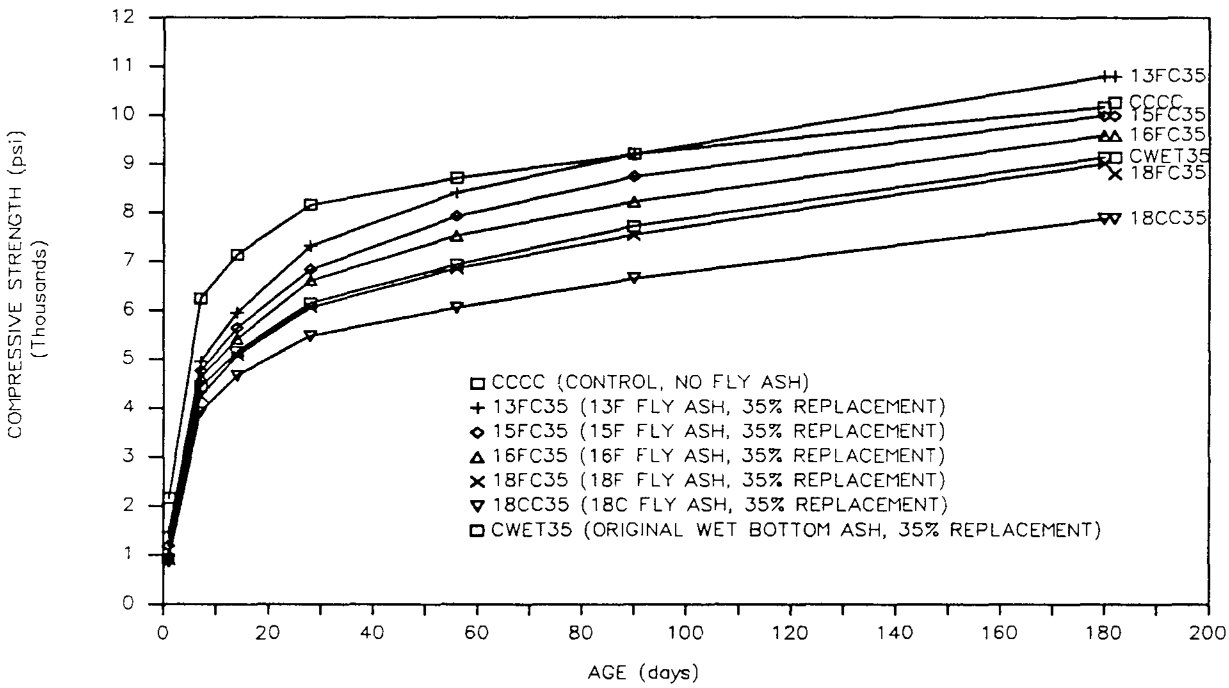

Figure 5.47 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (35% Replacement) and Age

5.12.9 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete with 50% Replacement

The compressive strength of the fractionated of wet bottom fly ash concrete with 50% replacement of cement is listed in Table 5.41. The percentage variation of compressive strength compared to the control mix is listed in Table 5.42. The relationship between compressive strength of the fractionated of wet bottom fly ash concrete and its corresponding age is shown in Figure 5.48.

The replacement of cement with fly ash 50% by weight of cementitious materials gives very low strength at 1 day. The compressive strength at 1 day varies form 484 psi to 733 psi or 22.4% to 34.0% compared to the control strength. After 180 days of curing, all strengths of the fractionated fly ash concrete are lower than the control concrete. Although the cement in each fly ash concrete is only half of the control sample, some of fly ash concretes still give a good strength results. Sample 13FC50 has compressive strength 9672 psi or 95.2% of the control strength at 180 days. The strengths of samples 15FC50 and 16FC50 are 88.2% and 80.8% of the control concrete, respectively. The development of strength for 13FC50 with 50% is very good compared to the control. It varies from 34.0% at 1 day to 95.2% at 180 days. Unlike the 18CC50 sample, which varies from 22.4% at 1 day to only 60.5% at 180 days.

Table 5.41 Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (50% Replacement)

Sample No.	Compressive Strength (psi)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	2157	6237	7141	8157	8707	9195	10161
13FC50	733	3443	4292	5462	6943	7850	9672
15FC50	629	3379	4239	5038	5894	6731	8964
16FC50	547	3088	3872	4751	5438	6275	8212
18FC50	520	2754	3370	4185	5132	5769	7377
18CC50	484	2513	3067	3613	4330	4771	6147
CWET50	517	2886	3730	4528	5235	5890	7711

Table 5.42 Percentage Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (50% Replacement)

Sample No.	Percentage Compressive Strength (%)						
	1-d	7-d	14-d	28-d	56-d	90-d	180-d
CCCC	100.0	100.0	100.0	100.0	100.0	100.0	100.0
13FC50	34.0	55.2	60.1	67.0	79.7	85.4	95.2
15FC50	29.2	54.2	59.4	61.8	67.7	73.2	88.2
16FC50	25.4	49.5	54.2	58.2	62.5	68.2	80.8
18FC50	24.1	44.2	47.2	51.3	58.9	62.7	72.6
18CC50	22.4	40.3	42.9	44.3	49.7	51.9	60.5
CWET50	24.0	46.3	52.2	55.5	60.1	64.1	75.9

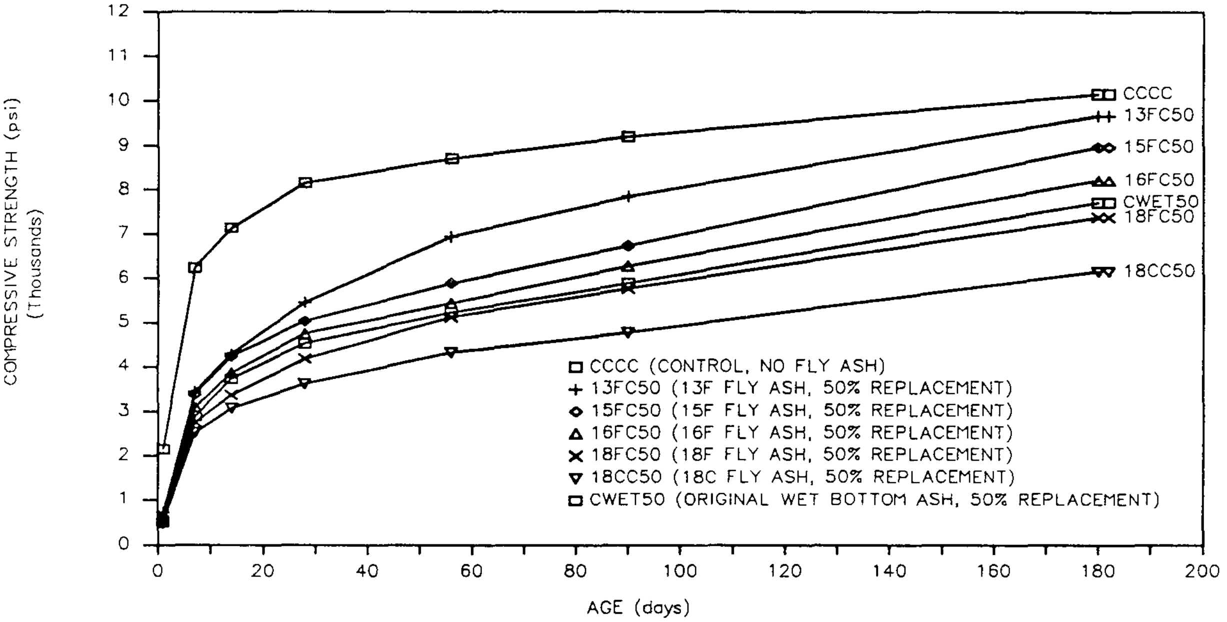

Figure 5.48 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete (50% Replacement) and Age

5.12.10 Relationship Between Compressive Strength and Mean Diameter of Fractionated Fly Ashes

The relationships between compressive strength and mean diameter of the fractionated of dry bottom fly ashes is shown in Figures 5.49, 5.50, 5.51, and 5.52. It is seen that the relationship is well defined as a straight when the coarsest particle fraction, 1C (mean diameter 39.45 microns), is not considered. At early ages (1 day to 7 days), there is almost no relationship between the compressive strength and mean diameter of fly ash. But, at 180 days the slope of the curve shows clearly that the smaller mean diameters (finer particles) of fly ash produce higher strengths than the larger mean diameters.

The same relationships are also occurred for the fractionated of wet bottom fly ash concrete. Figures 5.53, 5.54, 5.55, and 5.56 show the relationships between compressive strength and mean diameter of the fractionated of wet bottom fly ashes. The point for the original feed of wet bottom fly ash (mean diameter of 6.41 microns) drops dramatically compared with the other points in the same region. Since the particle size distribution of the original feed of wet bottom fly ash ranges from 1 to 300 microns, the mean diameter does not represent the particle size mix of the fly ash as well as it does for the fractionated fly ashes which have a narrower particle size distribution. This causes the strength of fly ash concrete made from the original feed fly ash to drop at that point because the coarse particles of fly ash do not react completely with $Ca(OH)_2$ to form C-S-H resulting in a lower compressive strength at that point.

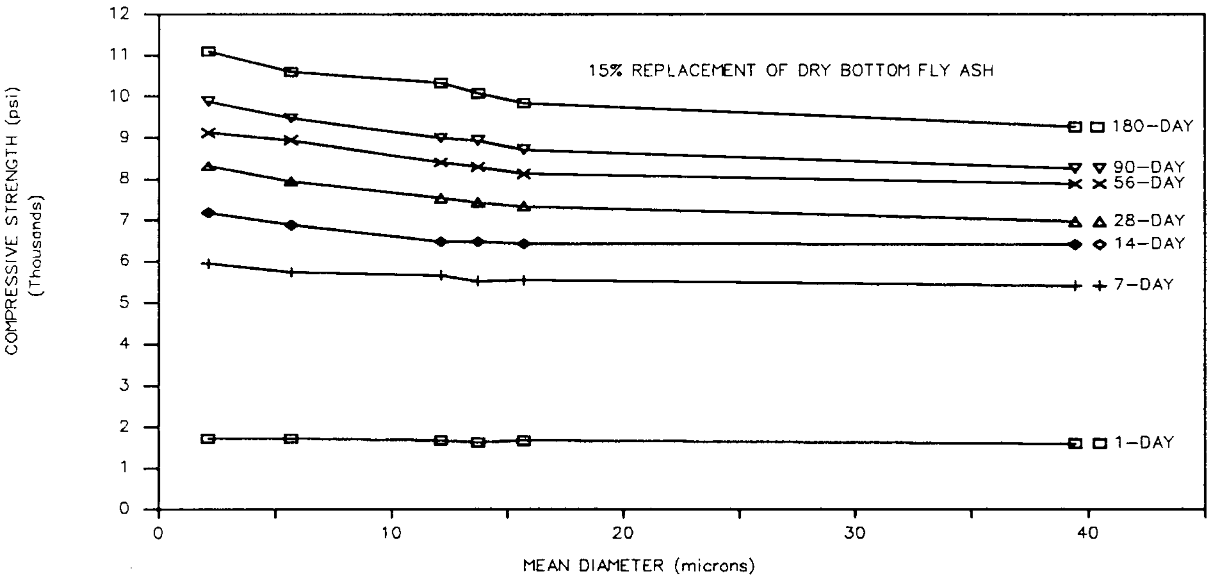

Figure 5.49 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (15% Replacement)

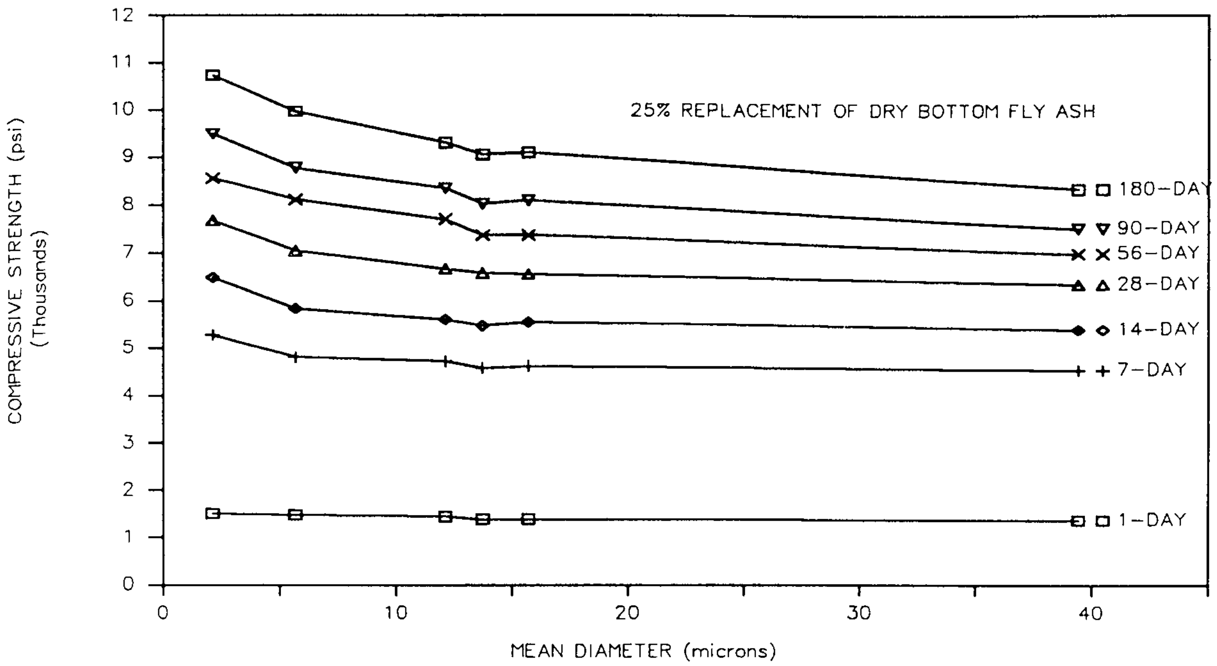

Figure 5.50 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (25% Replacement)

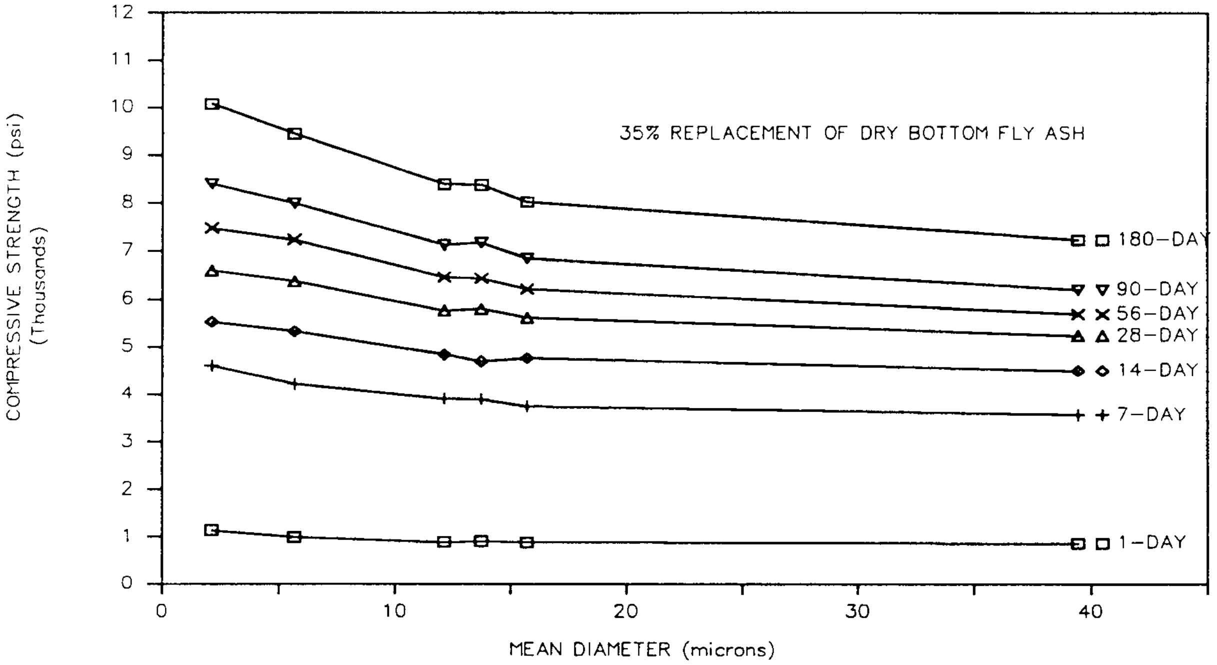

Figure 5.51 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (35% Replacement)

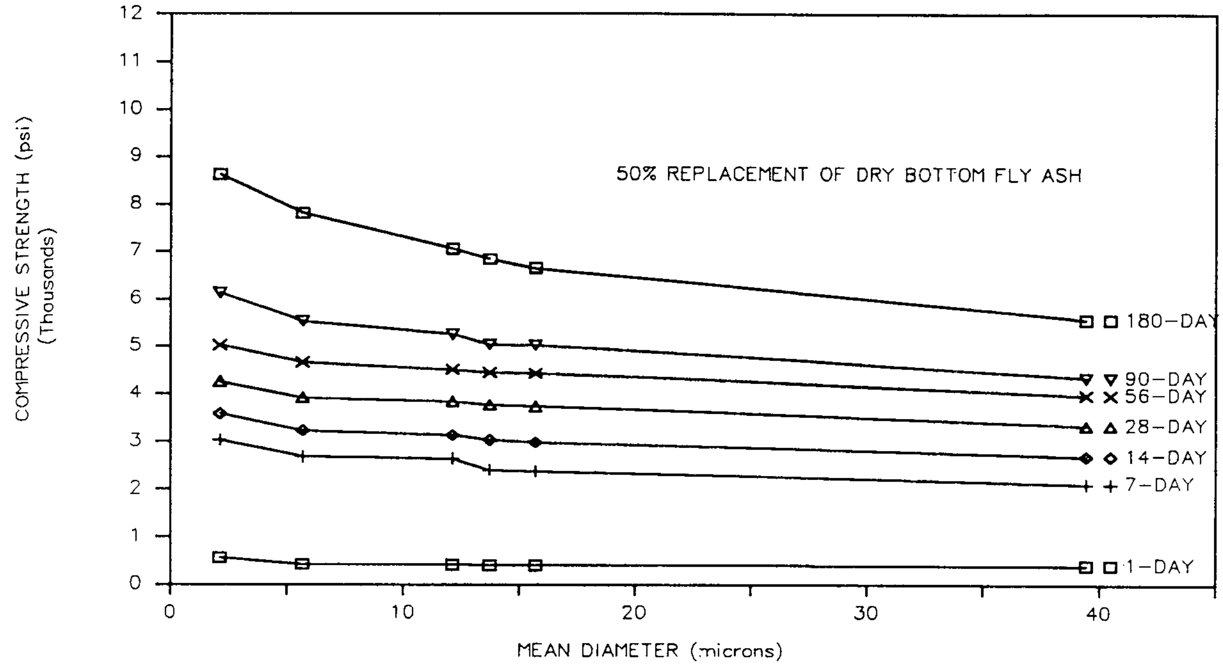

Figure 5.52 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (50% Replacement)

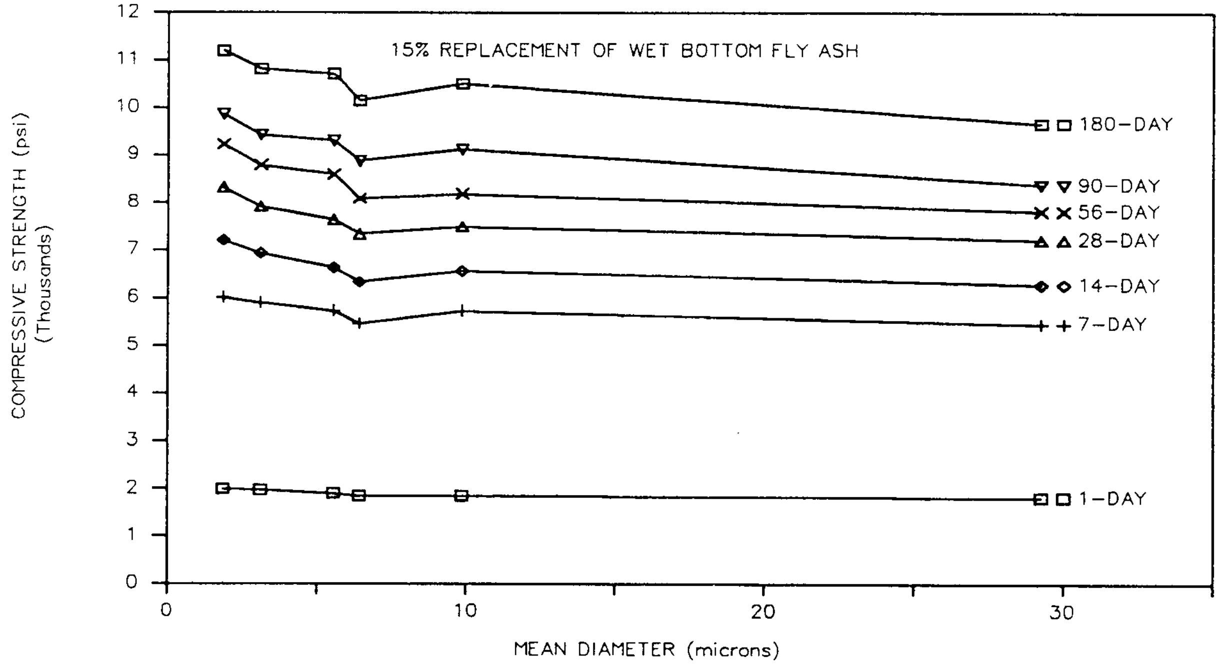

Figure 5.53 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (15% Replacement)

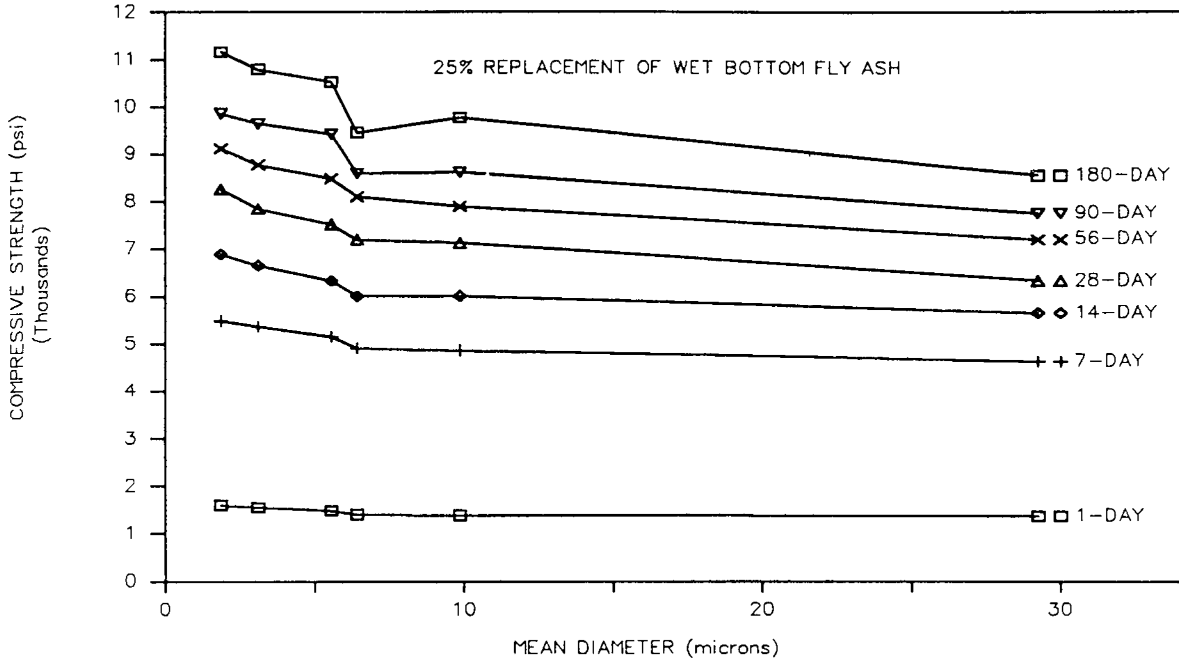

Figure 5.54 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (25% Replacement)

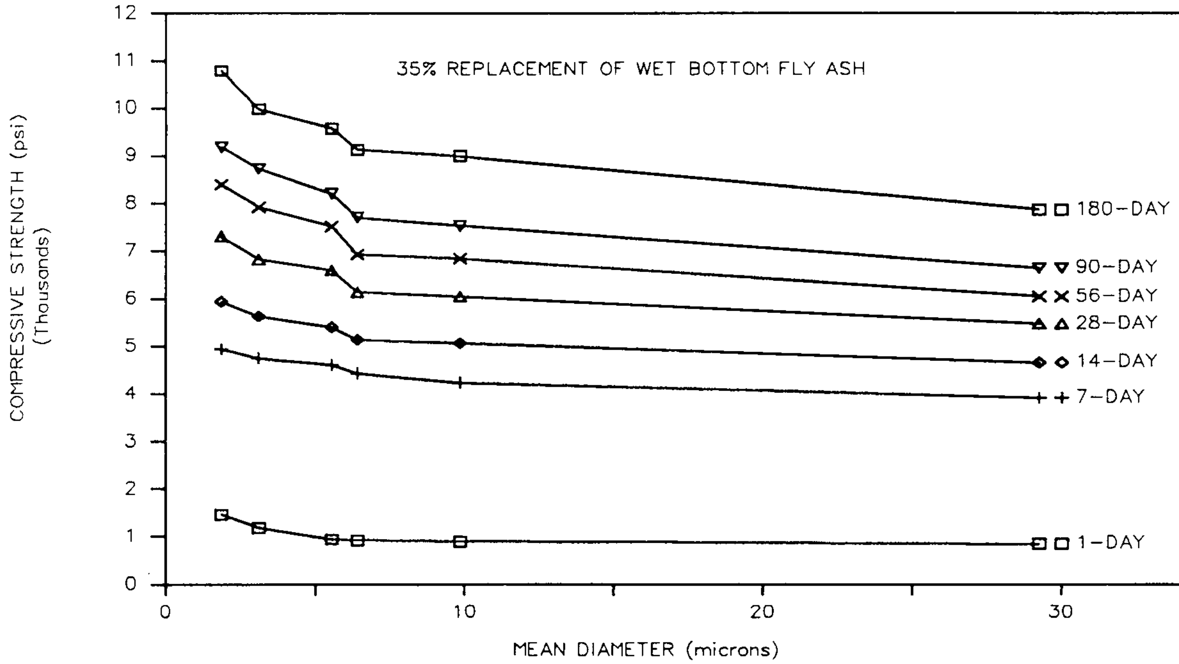

Figure 5.55 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (35% Replacement)

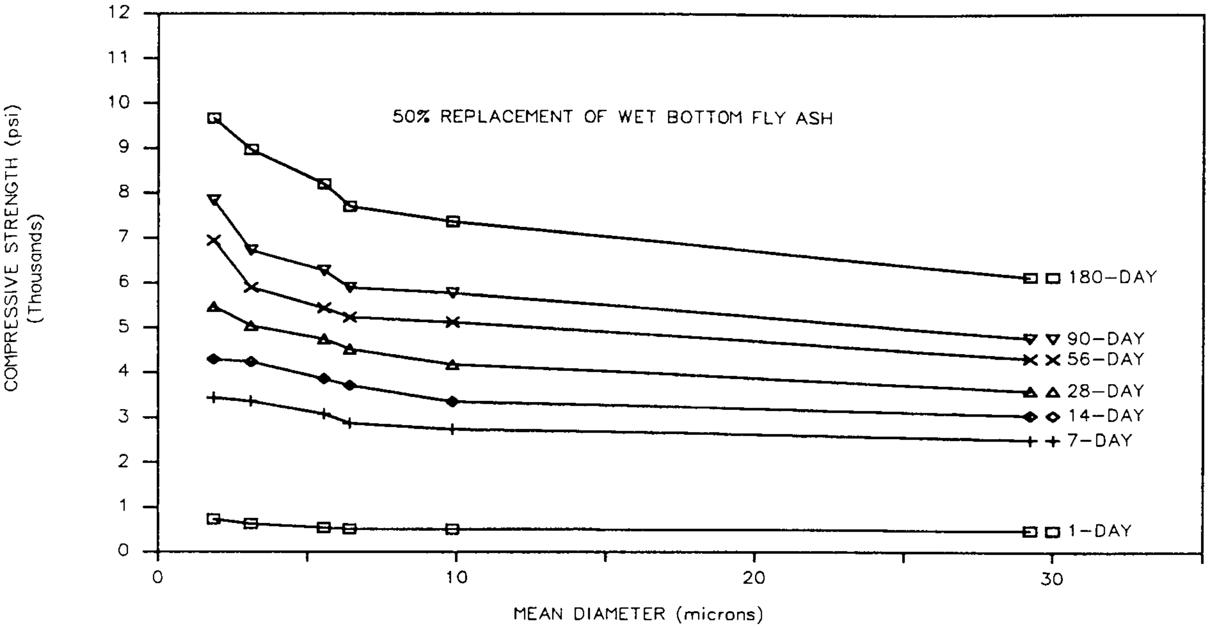

Figure 5.56 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete and Mean Diameter of Fly Ash (50% Replacement)

5.13 Effect of Fractionated Fly Ashes on the Strength of Mortar

In addition to the study of fractionated fly ash concrete, cement fly ash mortar was also used to verify the effect of fractionated fly ashes on the strength of mortar. The fractionated fly ashes from the dry and wet bottom boilers were used as a replacement for cement at 15%, 25%, and 50% by weight of cementitious (cement + fly ash) materials. The water to cementitious materials ratio was kept as a constant 0.5. Control mortar, without any fly ash replacement, using the same mix proportion and the same water cementitious materials ratio was also mixed and cast. No any kind of admixture. The mix proportion is shown in Table 4.3. After casting 24 hours, the 2"x2"x2" cube samples were removed from the mold and cured in saturated lime water prior to test. The compressive strength of samples were tested at the age of 1, 3, 7, 14, 28, 56, 90, and 180 days.

CF is the control sample. Samples "DRY" and "WET" are the mortars with the original feed of dry and wet bottom fly ashes, respectively. The numbers "15", "25", and "50" stand for the percentage of cement replaced by fly ash. The 3F15 sample is fly ash mortar using 3F fly ash as a replacement for cement 15 percent by weight of cementitious materials. Likewise, 6F15 is the fly ash mortar using 6F fly ash as a 15 percent replacement for cement by weight of cementitious materials.

5.13.1 Compressive Strength of Fractionated Fly Ash Mortar with 15% Replacement

The compressive strength of fractionated fly ash mortar with 15% replacement of cement is shown in Table 5.43. The percentage compressive strength of fractionated fly ash mortar compared to the control mortar strength are listed in Table 5.44. The relationship between the compressive strength of fractionated fly ash mortar and age is shown in Figure 5.57 (dry bottom fly ash) and Figure 5.58 (wet bottom fly ash).

As expected, the early age strengths of fly ash mortar are lower than the control mortar since no kind of modification of the mix was applied. This phenomenon is the same as that for the concrete. Because of the fact that less cement is presented in the fly ash mortar, it would seem to be inevitable that there would be less strength developed at early ages (Plowman 1984). With 15% replacement of fractionated fly ashes, the compressive strength is more than 80% of the control mortar strength at 1 day. The percentage compressive strengths of fractionated fly ash mortars gradually increase with age. The strengths of fractionated fly ash mortar also depend on the average size of fly ash particles. Consider the fractionated of dry bottom fly ash mortar at 1 day, the results show that the strengths increase with the decrease in particle sizes of fly ash. They vary from 2290 psi for coarse particles to 2666 psi for fine particles. At all curing ages, the lowest compressive strengths occur in the samples with the coarsest particles of fly ash (1C15 and 18C15). Up to 14 days, the compressive strengths of all fly ash mortars are lower than the control strength, except the samples with the fine fly ashes (3F15 and 13F15). The compressive strengths of samples 3F15 and 13F15 at

14 days are 7968 psi and 7925 psi, respectively. These strengths represent 101.1% and 100.5% of the control strength. After 180 days of curing, all samples of fractionated fly ash mortar give higher strength than the control sample, except samples 1C15 and 18C15. Since 1C15 and 18C15 samples use the coarsest particles of each type of fly ash to replace cement, it seems that the pozzolanic activity between fly ash and $Ca(OH)_2$ is not great enough to make up for the strength given by the cement hydration process.

The compressive strengths of 1C15 and 18C15 are 93.6% and 92.7% of the control mortar at 180 days, respectively. At the same age and for the same type of fly ash, the finer the particle size of fly ash in the mortar, the higher is the compressive strength. It is noted that the strength of mortar made from the original feed of wet bottom fly ash (WET15) is slightly higher than that from the dry bottom fly ash. This may be due to the fact that the particle sizes of the wet bottom fly ash are much finer than the dry ones.

Table 5.43 Compressive Strength of the Fractionated Fly Ash (Dry and Wet Bottom) Mortar with 15% Replacement

Sample No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
CF	2851	5216	7006	7883	9094	9872	10356	11057
3F15	2666	5002	6771	7968	9415	11112	12072	13108
5F15	2486	4972	6635	7789	9089	10503	11485	12511
6F15	2383	4962	6576	7709	8756	10202	11147	11927
10F15	2402	4922	6506	7655	8551	9807	10609	11815
11F15	2363	4977	6420	7574	8515	9654	10362	11502
1C15	2290	4837	6376	7254	8142	9102	9715	10353
DRY15	2416	4801	6493	7416	8537	9752	10606	11591
13F15	2764	5146	6807	7925	9402	11209	12137	13218
14F15	2608	5059	6760	7767	9235	10578	11415	12307
15F15	2533	4981	6707	7750	9111	10290	11082	12002
16F15	2361	4622	6613	7727	8867	10017	10807	11705
18F15	2330	4554	6293	7217	8242	9234	9922	11291
18C15	2322	4275	6007	6911	7724	8871	9413	10254
WET15	2525	4946	6683	7603	8671	9914	10637	11715

Table 5.44 Percentage Compressive Strength of the Fractionated Fly Ash (Dry and Wet Bottom) Mortar with 15% Replacement

Sample No.	Percentage Compressive Strength (%)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
CF	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3F15	93.5	95.9	96.6	101.1	103.5	112.6	116.6	118.5
5F15	87.2	95.3	94.7	98.8	99.9	106.4	110.9	113.2
6F15	83.6	95.1	93.9	97.8	96.3	103.3	107.6	107.9
10F15	84.3	94.4	92.9	97.1	94.0	99.3	102.4	106.9
11F15	82.9	95.4	91.6	96.1	93.6	97.8	100.1	104.0
1C15	80.4	92.7	91.0	92.0	89.5	92.2	93.8	93.6
DRY15	84.8	92.0	92.7	94.1	93.9	98.8	102.4	104.8
13F15	97.0	98.7	97.2	100.5	103.4	113.5	117.2	119.5
14F15	91.5	97.0	96.5	98.5	101.5	107.2	110.2	111.3
15F15	88.9	95.5	95.7	98.3	100.2	104.2	107.0	108.5
16F15	82.8	88.6	94.4	98.0	97.5	101.5	104.4	105.9
18F15	81.8	87.3	89.8	91.6	90.6	93.5	95.8	102.1
18C15	81.5	82.0	85.7	87.7	84.9	89.9	90.9	92.7
WET15	88.6	94.8	95.4	96.4	95.3	100.4	102.7	106.0

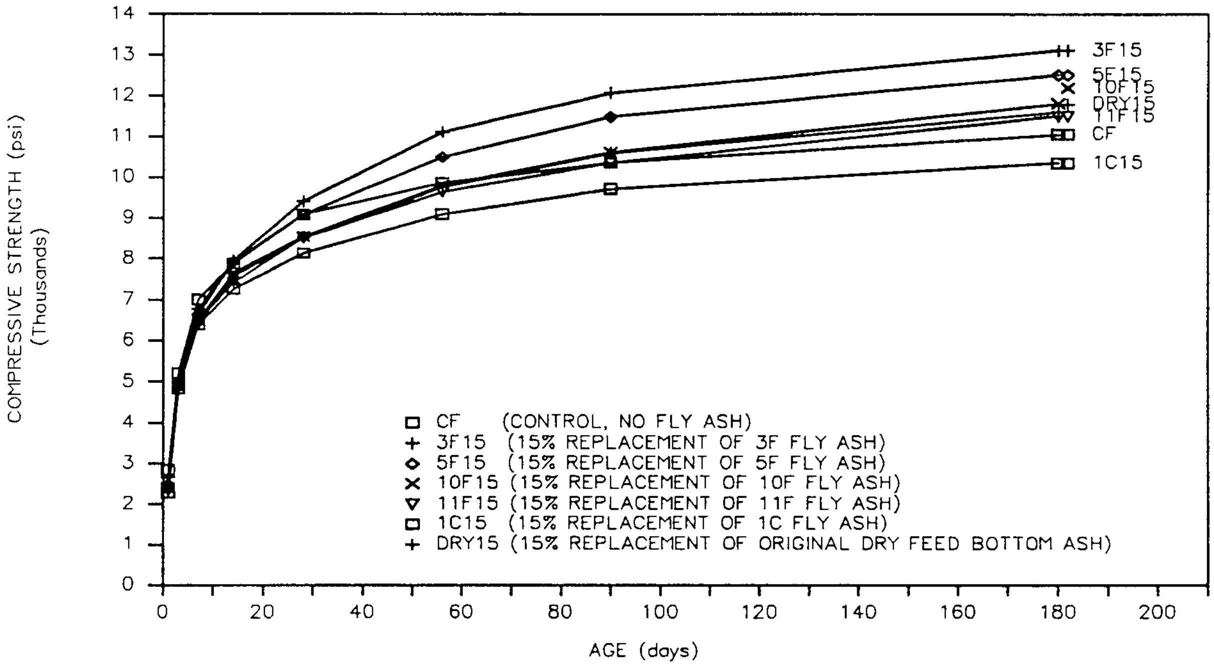

Figure 5.57 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Mortar and Age with 15% Replacement of Fly Ash

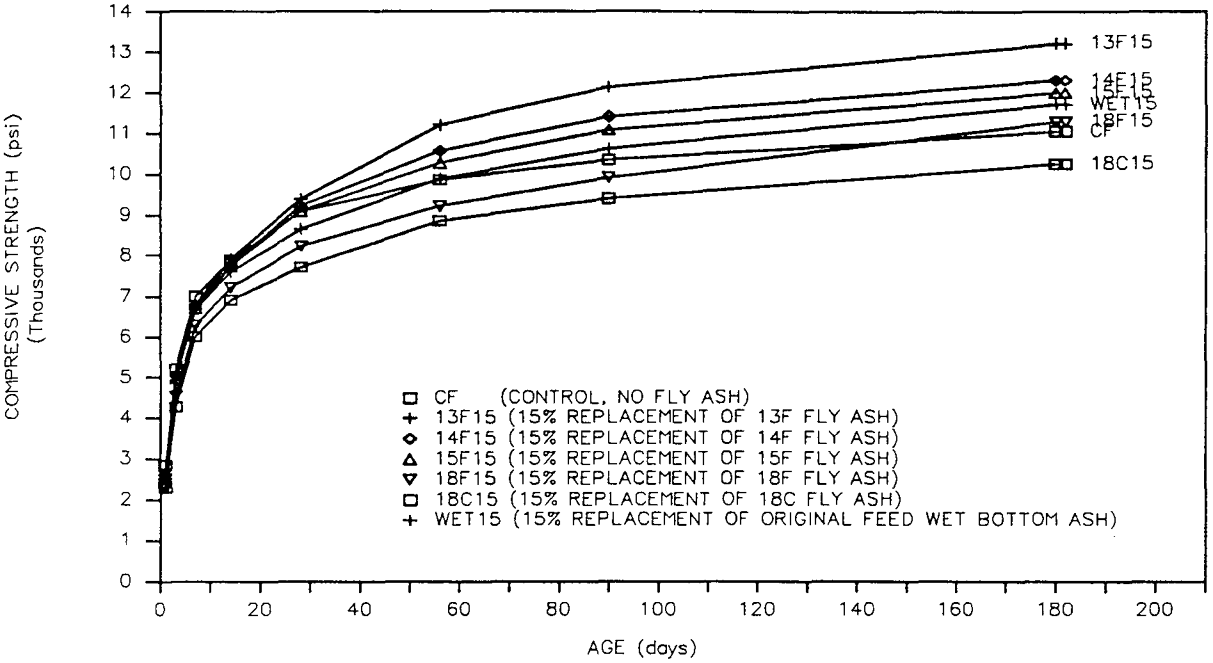

Figure 5.58 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Mortar and Age with 15% Replacement of Fly Ash

5.13.2 Compressive Strength of Fractionated Fly Ash Mortar with 25% Replacement

The compressive strength of fractionated fly ash mortar with 25% replacement of cement is shown in Table 5.45. The percentage compressive strength of fractionated fly ash mortar compared to the control mortar is shown in Table 5.46. The relationship between compressive strength of the fractionated of dry bottom fly ash mortar and age is shown in Figure 5.59. Figure 5.60 is the relationship between compressive strength of fractionated of wet bottom fly ashes and age.

The compressive strength of fractionated fly ash mortar with 25% replacement is somewhat lower than that with 15% replacement. The trend is the same as the 15% replacement. All of the early strengths of the fractionated of dry bottom fly ash mortars are lower than the control mortar up to 28 days. With 25% replacement, the strengths of mortar from the original feed (dry or wet bottom fly ash) is only about 30% of the control strength at 1 day. For the replacement with the fractionated of wet bottom fly ashes, most of fly ash mortars give lower compressive strength than the control strength at the age of 28 days except sample 13F25. The compressive strength of 13F25 is 9112 psi or 100.2% of the control strength at the age of 28 days. With the replacement using the original feed of dry and wet bottom fly ashes, the compressive strengths are 7821 psi and 8031 psi, respectively or 86% and 88.3% compared to the control mortar at 28 days. Usually, the strength of mortar from the original feed of wet bottom fly ash is slightly higher than the mortar made from the original feed of dry bottom fly ash.

Table 5.45 Compressive Strength of the Fractionated Fly Ash (Dry and Wet Bottom) Mortar with 25% Replacement

Sample No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
CF	2850	5216	7006	7883	9095	9872	10356	11057
3F25	2106	4248	5988	7336	8882	10146	10951	12237
5F25	1863	4002	5632	7001	8417	9514	10452	11797
6F25	1897	3915	5378	6754	8278	9315	10323	11412
10F25	1725	3795	5287	6710	7988	8789	9591	11020
11F25	1755	3640	5049	6521	7721	8545	9282	10145
1C25	1723	3639	4976	5671	6710	7575	8110	9219
DRY25	1922	3971	5476	6736	7821	8878	9758	11164
13F25	2427	4617	6501	7493	9112	10323	11125	12343
14F25	2330	4387	6091	7186	8601	9762	10712	11875
15F25	2355	4253	5834	6887	8398	9354	10397	11511
16F25	2337	4232	5820	6530	8086	9211	10321	11459
18F25	1995	4212	5674	6439	8001	8957	10001	10942
18C25	1992	3964	5239	5951	7356	8543	9216	10068
WET25	1981	4125	5833	6570	8031	8987	9831	11245

Table 5.46 Percentage Compressive Strength of the Fractionated Fly Ash (Dry and Wet Bottom) Mortar with 25% Replacement

Sample No.	Percentage Compressive Strength (%)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
CF	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3F25	73.9	81.4	85.5	93.1	97.7	102.8	105.7	110.7
5F25	65.4	76.7	80.4	88.8	92.5	96.4	100.9	106.7
6F25	66.6	75.1	76.8	85.7	91.0	94.4	99.7	103.2
10F25	60.5	72.8	75.5	85.1	87.8	89.0	92.6	99.7
11F25	61.6	69.8	72.1	82.7	84.9	86.6	89.6	91.8
1C25	60.5	69.8	71.0	71.9	73.8	76.7	78.3	83.4
DRY25	67.4	76.1	78.2	85.4	86.0	89.9	94.2	101.0
13F25	85.2	88.5	92.8	95.1	100.2	104.6	107.4	111.6
14F25	81.8	84.1	86.9	91.2	94.6	98.9	103.4	107.4
15F25	82.6	81.5	83.3	87.4	92.3	94.8	100.4	104.1
16F25	82.0	81.1	83.1	82.8	88.9	93.3	99.7	103.6
18F25	70.0	80.8	81.0	81.7	88.0	90.7	96.6	99.0
18C25	69.9	76.0	74.8	75.5	80.9	86.5	89.0	91.1
WET25	69.5	79.1	83.3	83.3	88.3	91.0	94.9	101.7

The compressive strength of fly ash mortar with the very coarse fly ashes, i.e. 1C25 and 18C25, are 83.4% and 91.1%, respectively at the age of 180 days compared with the control strength. For both types of fly ash, the compressive strength of fractionated fly ash mortar increases with the decrease of fly ash particle size. After the age of 180 days, most of fly ash mortars have strength at the same level or higher than the control, except the mortars made with the coarse particle sizes (11F, 1C, and 18C) of fly ash. The original feed of fly ash needs 180 days of curing to gain the strength at the same level as the control strength. The results indicates that the use of fine particles of the fractionated fly ashes increase the rate of pozzolanic activity. The finer the particle size of fly ash, the greater the rate of pozzolanic activity resulting in the faster rate of the strength development.

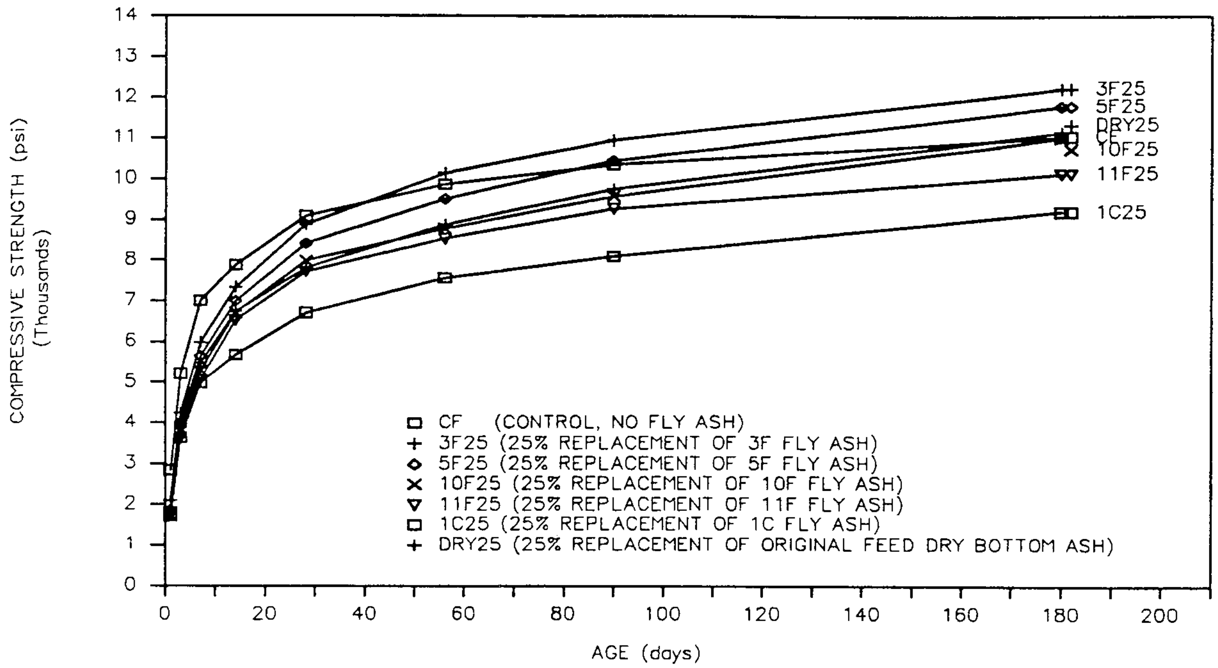

Figure 5.59 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Mortar and Age with 25% Replacement of Fly Ash

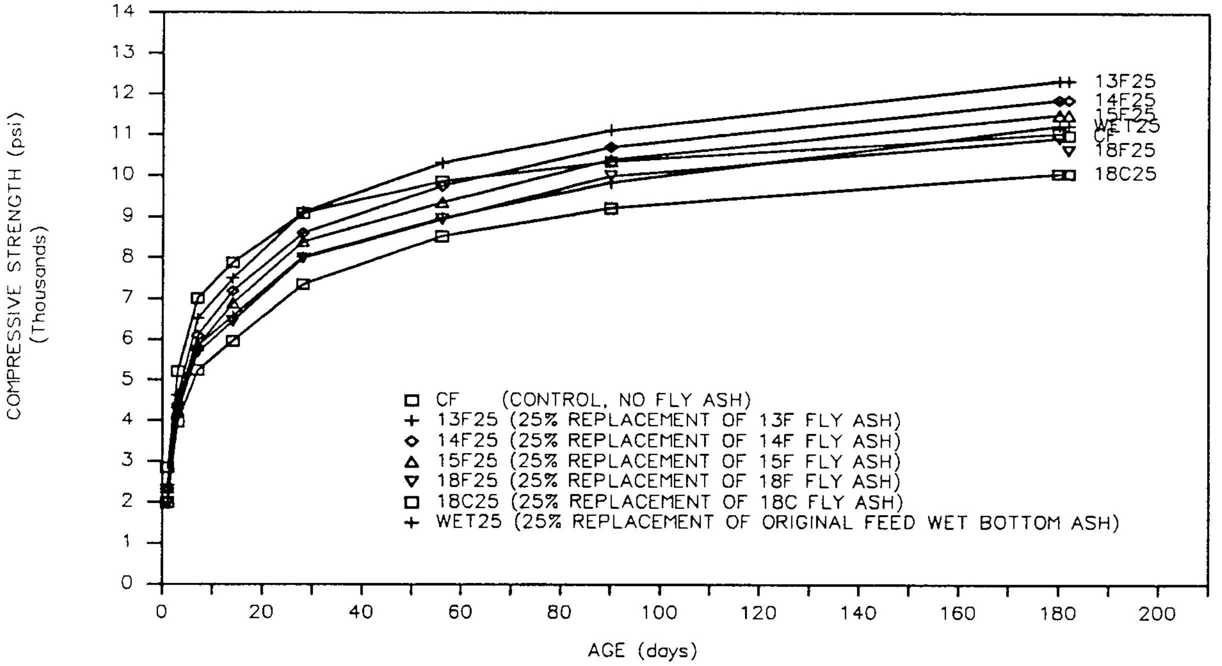

Figure 5.60 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Mortar and Age with 25% Replacement of Fly Ash

5.13.3 Compressive Strength of Fractionated Fly Ash Mortar with 50% Replacement

Table 5.47 show the results of compressive strength of fractionated fly ash mortar with 50% replacement of cement. Table 5.48 lists the percentage compressive strength of fractionated fly ash mortar compared to the control mortar. Figures 5.61 and 5.62 are the relationships between the compressive strength of the fractionated fly ash (dry and wet bottom) mortar and age.

With a high percentage of fly ash in the mix, the early strengths of fly ash mortar are very low. All strengths of fractionated fly ash mortars at 1 day are less than 50% of the control strength. The compressive strengths of fractionated fly ash mortars at 1 day vary from 711 psi to 1322 psi, depending on the particle size of fly ash. The percentage compressive strength of sample 3F50 varies from 46.4% at 1 day to 81.6% at 180 days. With the original feed fly ashes, the strengths of the dry and wet bottom fly ash mortar are 26.2% and 30.2%, of the control mortar respectively. For the original feed of dry bottom fly ash sample, DRY50, the compressive strength is 747 psi at 1 day and increases to 7642 psi at 180 days. In general, the compressive strength of the original feed of wet bottom fly ash is higher than that of the dry one. The reason is that the average particle size of the wet bottom fly ash is finer than that of the dry one. After 180 days, all strengths of fractionated fly ash mortar still lower than the control mortar. Considering the graphs of Figures 5.61 and 5.62, it is believed that the samples from fine fly ashes, i.e. 3F50, 6F50, 13F50, 14F50, and 15F50 are still gaining strength after 180 days. According to Hensen (1990), the pozzolanic activity of fly ash will proceed until 3 years after casting concrete.

Table 5.47 Compressive Strength of the Fractionated Fly Ash (Dry and Wet Bottom) Mortar with 50% Replacement

Sample No.	Compressive Strength (psi)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
CF	2850	5216	7006	7883	9095	9872	10356	11057
3F50	1322	2552	3545	4062	5127	6062	7211	9017
5F50	1012	2527	3350	3890	4784	5932	6948	8860
6F50	836	2182	3097	3647	4551	5460	6412	8421
10F50	711	1982	2745	3249	4150	5014	5862	7407
11F50	726	1909	2654	3158	3858	4543	5521	6879
1C50	769	1817	2385	3035	3603	4180	4425	5377
DRY50	747	1930	2876	3449	4496	5345	6022	7642
13F50	1314	2655	3851	4802	5692	6754	7816	9742
14F50	1020	2541	3709	4632	5552	6512	7492	9387
15F50	853	2498	3631	4522	5384	6503	7299	9120
16F50	718	2618	3543	4238	5405	6387	7230	8607
18F50	991	2373	3078	3858	4732	5855	6506	8106
18C50	784	2104	2836	3325	4068	4934	5491	6839
WET50	861	2513	3407	4144	5313	6435	7063	8519

Table 5.48 Percentage Compressive Strength of the Fractionated Fly Ash (Dry and Wet Bottom) Mortar with 50% Replacement

Sample No.	Percentage Compressive Strength (%)							
	1-d	3-d	7-d	14-d	28-d	56-d	90-d	180-d
CF	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3F50	46.4	48.9	50.6	51.5	56.4	61.4	69.6	81.6
5F50	35.5	48.4	47.8	49.3	52.6	60.1	67.1	80.1
6F50	29.3	41.8	44.2	46.3	50.0	55.3	61.9	76.2
10F50	24.9	38.0	39.2	41.2	45.6	50.8	56.6	67.0
11F50	25.5	36.6	37.9	40.1	42.4	46.0	53.3	62.2
1C50	27.0	34.8	34.0	38.5	39.6	42.3	42.7	48.6
DRY50	26.2	37.0	41.1	43.8	49.4	54.1	58.1	69.1
13F50	46.1	50.9	55.0	60.9	62.6	68.4	75.5	88.1
14F50	35.8	48.7	52.9	58.8	61.0	66.0	72.3	84.9
15F50	29.9	47.9	51.8	57.4	59.2	65.9	70.5	82.5
16F50	25.2	50.2	50.6	53.8	59.4	64.7	69.8	77.8
18F50	34.8	45.5	43.9	48.9	52.0	59.3	62.8	73.3
18C50	27.5	40.3	40.5	42.2	44.7	50.0	53.0	61.9
WET50	30.2	48.2	48.6	52.6	58.4	65.2	68.2	77.0

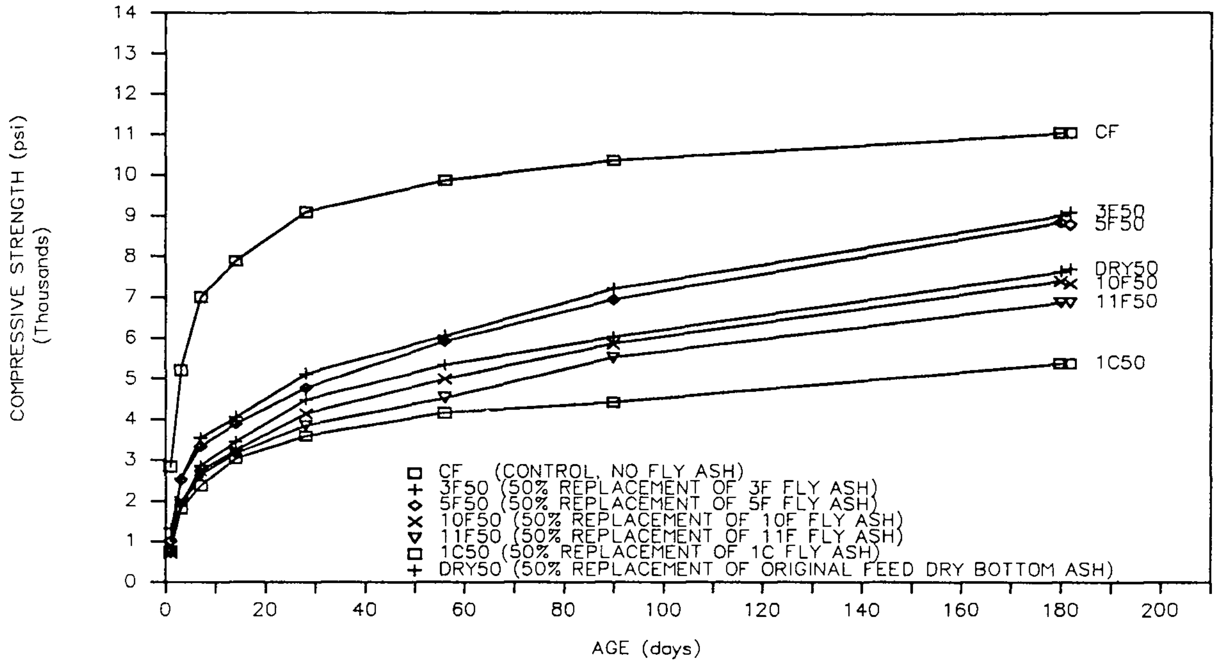

Figure 5.61 Relationship between Compressive Strength of the Fractionated of Dry Bottom Fly Ash Mortar and Age with 50% Replacement of Fly Ash

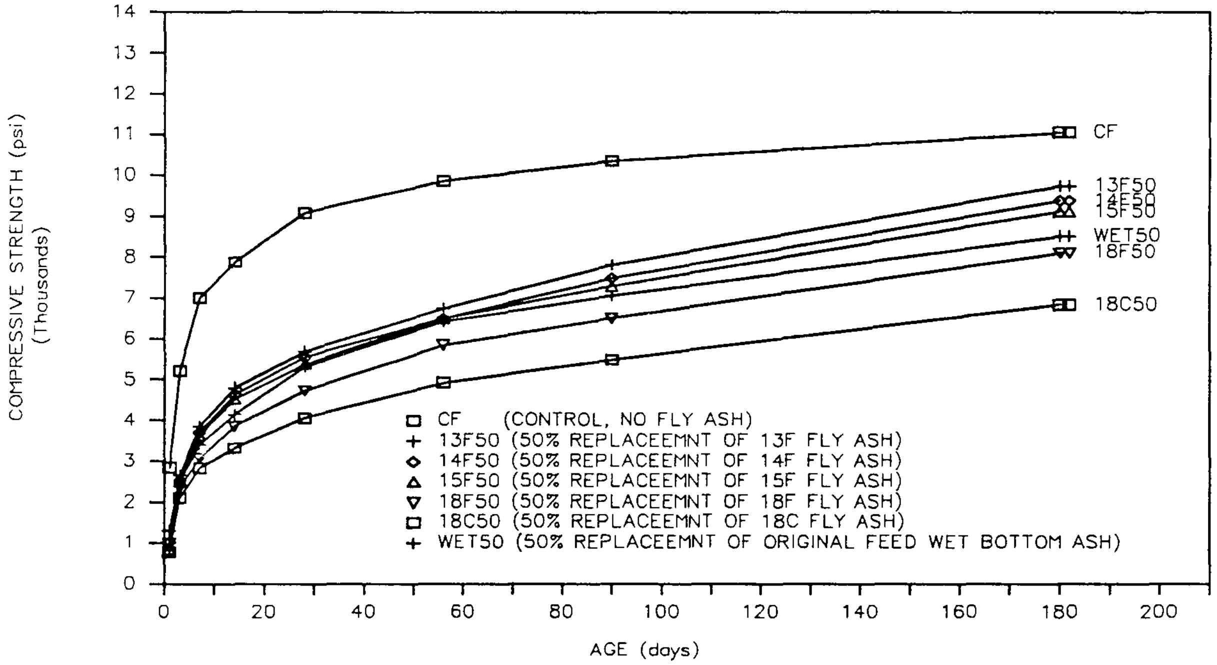

Figure 5.62 Relationship between Compressive Strength of the Fractionated of Wet Bottom Fly Ash Mortar and Age with 50% Replacement of Fly Ash

5.14 Setting Time of Fractionated Fly Ash-Cement Paste

Table 5.49 shows the results of setting time of fractionated fly ash-cement paste by Vicat needle method. Sample CEM is the cement paste without any fly ash. Sample 3F is the fly ash-cement paste with replacement of cement by 3F fly ash. DRY and WET are the samples with the replacement of the original feed of dry and wet bottom fly ashes, respectively.

Table 5.49 Setting Time of Fractionated Fly Ash-Cement Paste

Sam. No.	15% Repl.		25% Repl.		35% Repl.		50% Repl.	
	Ini.	Final	Ini.	Final	Ini.	Final	Ini.	Final
	(h:min)		(h:min)		(h:min)		(h:min)	
CEM	2:40	5:20	2:40	5:20	2:40	5:20	2:40	5:20
3F	2:50	5:45	3:00	6:00	3:25	6:15	3:35	6:50
6F	2:55	5:45	3:05	6:05	3:25	6:20	3:40	6:55
1C	2:55	5:45	3:15	6:10	3:30	6:30	3:50	6:55
DRY	2:55	5:45	3:10	6:10	3:20	6:15	3:50	6:50
13F	2:50	5:30	2:55	5:40	3:00	5:40	3:10	6:30
16F	2:55	5:40	3:05	5:45	3:05	5:40	3:15	6:35
18C	2:50	5:40	3:15	5:50	3:20	5:55	3:20	6:40
WET	2:50	5:35	3:05	5:45	3:10	5:55	3:15	6:30

It is seen that the setting times of fly ash-cement paste increase with the increase the amount of fly ash in the paste. The same results were also reported by Ravina (1984), Meinlinger (1982), and Lane and Best (1982). The initial and final setting times are slightly changed with the 15% replacement of the fractionated of dry and wet bottom fly ashes. The initial setting time of fractionated fly ash-cement paste is about 2 h and 55 min while the setting of the cement paste is 2 h 40 min. The final setting times of fly ash-cement paste with 15% replacement (dry or wet bottom fly ash) are about 25 minutes longer than the setting time of the cement paste.

With 25% replacement, the initial setting times increase 20 to 35 minutes from the initial setting time of cement paste depending on the particle size of fly ash. The fine particle size of fly ash-cement paste seems to set faster than the paste using the coarse fly ash. For the dry bottom fly ash, the initial and final setting times of sample 3F are 3 h and 6 h, respectively while the initial and final sets of the sample 1C are 3 h 10 min and 6 h 10 min, respectively. The setting time of the sample using the original feed of wet bottom fly ash is slightly shorter than that of the dry one.

When the replacement of fly ash increases to 35% by weight of cementitious materials, the setting times are longer than those with 15% and 25% replacement. The initial sets of fractionated fly ash-cement paste are usually about 3 h 20 min. The final setting times of samples from the fractionated of dry bottom fly ashes are longer than those for the fractionated of wet bottom fly ashes by about 20 to 30 minutes. With 35% replacement of the fractionated of dry bottom fly ashes, the final setting times are about 1 hour longer than the setting time of the cement paste. With the same replacement of the fractionated of wet bottom fly ashes, the final setting times are about 40 minutes longer than the cement paste.

With 50% of fly ash in the fly ash-cement paste, the initial setting times of the fractionated of dry bottom fly ashes are about 1 hour longer than the setting time of the cement paste. In general, the initial and final setting times of the fractionated of wet bottom fly ashes are shorter than those of the dry bottom fly ash. This is due to the fact that the fractionated of wet bottom fly ashes have higher CaO content than those of the dry bottom fly ashes. The CaO content of the original feed of wet and dry bottom fly ashes is 6.89% and 2.41%, respectively. Since CaO can react with water and set like cement, the fractionated of wet bottom fly ash pastes set faster than that of the dry bottom fly ash paste.

5.15 Effect of Calcium Oxide (CaO) on the Strength of Fractionated Fly Ash Mortar

In this experiment, the objective is to accelerate the early strength of fly ash mortar by using calcium oxide (CaO). Calcium oxide in the powder form with purity more than 98% was used to increase the calcium oxide content in the fly ash. The percentage of fly ash plus calcium oxide in the mix is kept constant as 35% by weight of the cementitious (cement+fly ash+calcium oxide) materials.

CA0 is the cement mortar sample without any fly ash or calcium oxide and designed as a control sample. DCA0 and WCA0 are the samples of fly ash mortar mixed with the original feed of dry and wet bottom fly ashes, respectively. The numbers at the end of the samples, i.e "0", "10", "20", and "30", are the percentage of calcium oxide in the mix by weight of fly ash + calcium oxide. Samples CA10, CA20, and CA30 are the samples at which the cement was replaced by the calcium oxide as 3.5%, 7.0%, and 10.5%, respectively by weight of cement+calcium oxide. The amounts of calcium oxide replaced by the cement for CA10, CA20, and CA30 are the same weight as in the fly ash mortar with the calcium oxide content of 10%, 20%, and 30%, respectively.

Table 5.50 is the compressive strength of the fractionated fly ash mortar mixed with calcium oxide. Table 5.51 is the percentage compressive strength of the fractionated fly ash mortar mixed with calcium oxide compared to the control strength. With a constant of water to cementitious materials ratio, a higher content of calcium oxide in the mix made the sample less workable than the cement-mortar mix. All the early strengths of the fractionated fly ash mortar is lower than the control strength up to 28 days. The use of calcium oxide increases the early strength of fractionated fly ash mortar. For the original feed of dry bottom fly ash, the strength at 1 day of DCA0 (fly ash mortar without calcium oxide) is 970 psi and increases to 1993 psi for sample DCA30 (fly ash mortar with calcium oxide 30%) or increases from 43.6% to 89.6% of the control strength. For the original feed of wet bottom fly ash, the 1 day strength increases from 1033 psi for 0% of the addition of calcium oxide to 2294 psi for the 30% of calcium oxide. The increase in the compressive strength at 1 day by the use of calcium oxide is about 2 times of the sample without the addition of calcium oxide. This behavior is also occurred in the samples with the fractionated 6F, 16F, 1C, and 18C fly ashes. The increase in the strength by the use of calcium oxide may be due to the added calcium oxide which is an active form. During the mixing period of calcium oxide and water, the chemical reaction between calcium oxide and water released energy in the form of heat. This heat will accelerate the hydration process of the cement thus gives a higher strength at the early ages than the sample without added calcium oxide. The increase in strength by using calcium oxide appreciates at the early ages, i.e. up to 14 days. At 28 days, the differences of the strengths between the samples with and without the addition of calcium oxide are not prominent. The compressive strengths at 28 days of DCA0 and DCA30 are 6813 psi and 7506 psi, respectively or 73.9% and 81.4% of the control strength. For the other fractionated fly ash mortars, 6F, 16F, 1C, and 18C, the strength of fly ash mortar with calcium oxide from 10% to 30% by weight of fly ash+calcium oxide are slightly higher than that of the mortar without calcium oxide.

Sample CA10 (replacement of cement by calcium oxide 3.5% by weight of cement + calcium oxide) gives strength at 1 day 2485 psi or 111.7% of the control mortar. The other two samples, CA20 and CA30, also produce higher strengths than the control strength and in a higher magnitude. They are 134.4% and 153.8%, respectively compared to the control mortar. The gain of the strength of these samples is slow after 3 days. The use of calcium oxide does not give any benefit after 7 days since the compressive strengths at 7 days of samples CA10, CA20, and CA30 are 91.7%, 95.1%, and 96.0%, respectively of the control strength. At 28 days, the strengths of the samples with the replacement of cement by calcium oxide are about 90% of the control strength mortar. With the results above, it can conclude that the use of calcium oxide to replace cement will accelerate the strength at 1 day but gives a lower strength after 7 days compared to the control mortar.

Table 5.50 Compressive Strength of the Fractionated Fly Ash Mortar Mixed with Calcium Oxide

Sam No.	Compressive Strength (psi)				
	1-day	3-day	7-day	14-day	28-day
CAO	2224	5565	7586	8487	9216
DCA0	970	2932	4416	5236	6813
DCA10	1213	3386	4693	5546	6955
DCA20	1696	3725	5063	6201	7245
DCA30	1993	4250	5466	6270	7506
WCA0	1033	3538	4751	5938	7678
WCA10	1337	3887	5218	6075	7768
WCA20	2074	4215	5331	6367	7843
WCA30	2294	4596	5808	6471	7996
6CA0	1013	3097	4481	5492	7325
6CA10	1496	3501	4851	6003	7455
6CA20	1506	3692	5057	6183	7482
6CA30	1813	3996	5241	6266	7575
16CA0	1162	3636	4953	6052	7530
16CA10	1611	3805	5235	6157	7687
16CA20	2023	4186	5373	6458	7675
16CA30	2342	4697	5918	6733	8096
1CA0	811	2661	3935	4845	5680
1CA10	1318	3130	4277	5121	6035
1CA20	1321	3221	4406	5193	6071
1CA30	2029	3832	5181	5728	6378
18CA0	841	3137	4336	5192	6052
18CA10	1216	3190	4472	5361	6135
18CA20	1474	3276	4366	5322	6122
18CA30	2172	4132	5196	5915	6562
CA10	2485	5157	6953	7938	8292
CA20	2990	5698	7218	8087	8491
CA30	3420	5883	7286	7947	8453

Table 5.51 Percentage Compressive Strength of the Fractionated Fly Ash Mortar Mixed with Calcium Oxide Compared to the Control Strength

Sam No.	Percentage Compressive Strength (%)				
	1-day	3-day	7-day	14-day	28-day
CAO	100.0	100.0	100.0	100.0	100.0
DCAO	43.6	52.7	58.2	61.7	73.9
DCA10	54.5	60.8	61.9	65.3	75.5
DCA20	76.3	66.9	66.7	73.1	78.6
DCA30	89.6	76.4	72.1	73.9	81.4
WCAO	46.4	63.6	62.6	70.0	83.3
WCA10	60.1	69.8	68.8	71.6	84.3
WCA20	93.3	75.7	70.3	75.0	85.1
WCA30	103.1	82.6	76.6	76.2	86.8
6CAO	45.5	55.7	59.1	64.7	79.5
6CA10	67.3	62.9	63.9	70.7	80.9
6CA20	67.7	66.3	66.7	72.9	81.2
6CA30	81.5	71.8	69.1	73.8	82.2
16CAO	52.2	65.3	65.3	71.3	81.7
16CA10	72.4	68.4	69.0	72.5	83.4
16CA20	91.0	75.2	70.8	76.1	83.3
16CA30	105.3	84.4	78.0	79.3	87.8
1CAO	36.5	47.8	51.9	57.1	61.6
1CA10	59.3	56.2	56.4	60.3	65.5
1CA20	59.4	57.9	58.1	61.2	65.9
1CA30	91.2	68.9	68.3	67.5	69.2
18CAO	37.8	56.4	57.2	61.2	65.7
18CA10	54.7	57.3	59.0	63.2	66.6
18CA20	66.3	58.9	57.6	62.7	66.4
18CA30	97.7	74.2	68.5	69.7	71.2
CA10	111.7	92.7	91.7	93.5	90.0
CA20	134.4	102.4	95.1	95.3	92.1
CA30	153.8	105.7	96.0	93.6	91.7

5.16 High Strength Fly Ash and Silica Fume Concrete

In this section, testing is made to evaluate the effect of silica fume and fly ash when used as a cement based matrix in concrete. Silica fume in the powder form and the finest fly ash from the dry and wet bottom ashes (3F and 13F) are mixed with concrete as 15% and 25% cement replacements. Superplasticizer is added to lower the water content in the mix. With a high portion of silica fume in the mix, the superplasticizer is used at 10 ml per pound of the cementitious (cement + fly ash or silica fume) materials.

Sample CSF is the control sample, without any fly ash or silica fume. Samples CSF15 and CSF25 are the concrete with 15% and 25% of the weight of cementitious materials replaced by silica fume. Sample C3F15 and C3F25 are the concrete with 15% and 25% replaced by 3F fly ash. Finally, samples C13F15 and C13F25 are the concrete with 15% and 25% replacement of 13F fly ash. Table 5.52 shows the compressive strength of high strength fly ash and silica fume concrete. Table 5.53 is the percentage compressive strength of high strength fly ash and silica fume concrete compared with the CSF sample. Figures 5.63 and 5.64 are the relationship between the compressive strength of high strength concrete and age when using 15% and 25% replacement of cement by fly ash or silica fume in the mix.

Table 5.52 Compressive Strength of High Strength Fly Ash and Silica Fume Concrete

Sample No.	Compressive Strength (psi)						Slump (cm)
	1-day	7-day	14-day	28-day	56-day	90-day	
CSF	1912	6352	7346	7881	8645	9322	23
CSF15	2335	7176	7768	8009	8715	9286	1
CSF25	2675	6664	7479	8032	8500	9122	0
C3F15	1216	5855	7056	7820	9031	10023	21
C3F25	1212	5968	7248	8648	9775	10521	20
C13F15	1945	6787	7805	8740	9853	10487	16
C13F25	1782	6091	7240	8561	9814	10748	12

Table 5.53 Percentage Compressive Strength of High Strength Fly Ash and Silica Fume Concrete Compared with the CSF Sample

Sample No.	Percentage Compressive Strength (%)					
	1-day	7-day	14-day	28-day	56-day	90-day
CSF	100.0	100.0	100.0	100.0	100.0	100.0
CSF15	122.1	113.0	105.7	101.6	109.9	99.6
CSF25	139.9	104.9	101.8	101.9	98.4	97.9
C3F15	63.6	92.2	96.1	99.2	104.5	107.5
C3F25	63.4	94.0	98.7	109.7	113.1	112.9
C13F15	101.7	106.8	106.2	110.9	114.0	112.5
C13F25	93.2	95.9	98.6	108.6	113.6	115.3

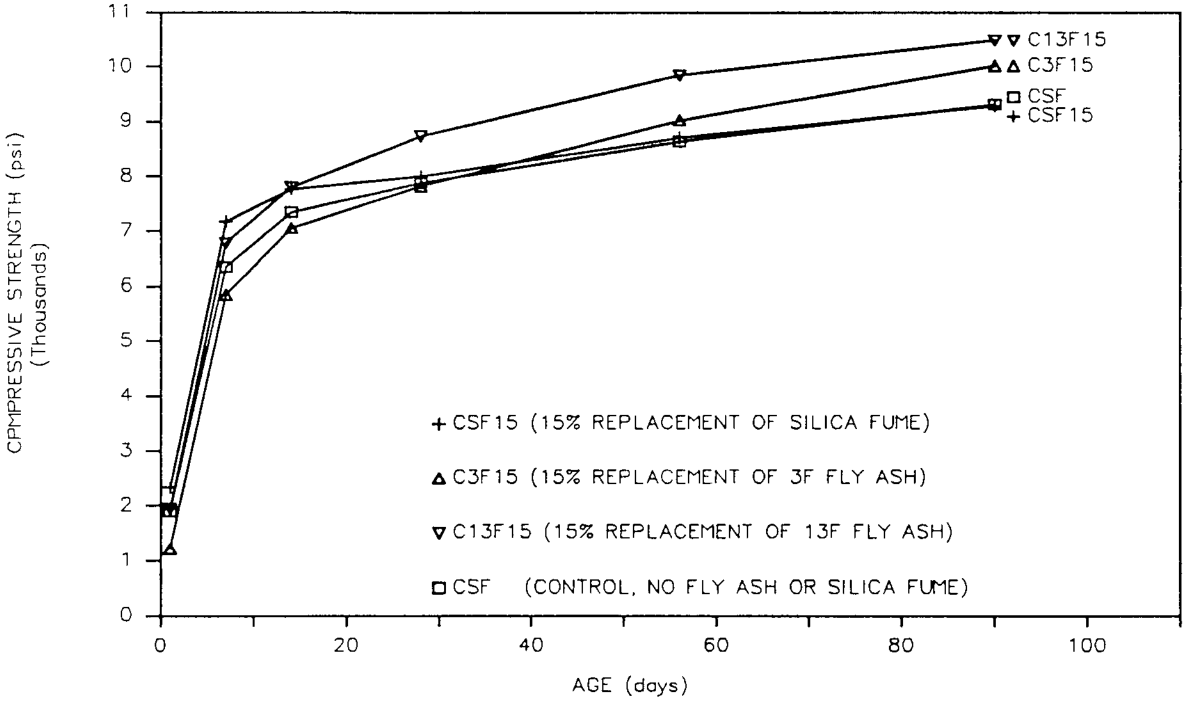

Figure 5.63 Relationship between Compressive Strength of High Strength Concrete and Age with 15% Replacement of Fly Ash or Silica Fume

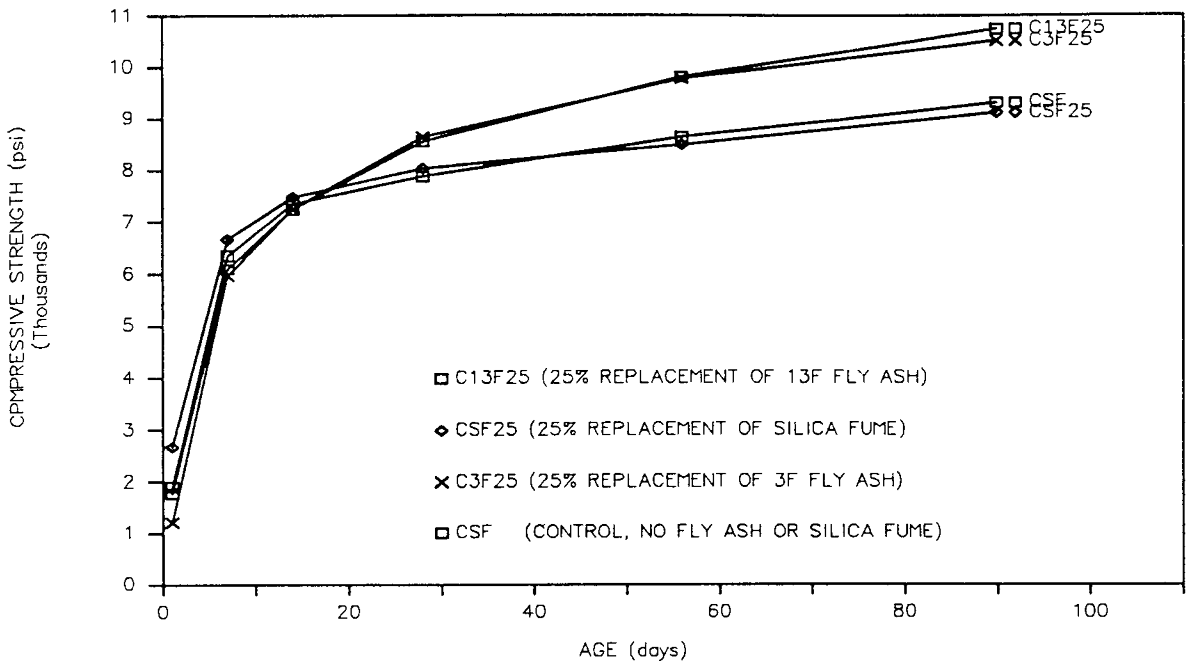

Figure 5.64 Relationship between Compressive Strength of High Strength Concrete and Age with 25% Replacement of Fly Ash or Silica Fume

Since the cementitious materials, sand, coarse aggregate, water, and superplasticizer are constants, the consistency of the fresh concrete depends on the characteristics of the cementitious materials. Fresh concrete with 25% replacement of cement by silica fume had zero slump while the control concrete (CSF) had a 23 cm slump (see Table 5.52). Because silica fume is very fine particle material, it has more surface area than cement on an equal weight basis. In general, when the mix proportion of concrete is constant, the mix with silica fume (in powder form) needs more water to maintain the same slump. The slump of concrete with fly ash replacement is lower than that of the control sample. Usually, fly ash will increase the slump of concrete but, this behavior does not apply to this type of fly ash. 3F and 13F are very fine particle fly ashes, their surface areas measured by the Blaine method are much higher than that of the cement. The results of this testing confirms the previous result, that very fine particle fly ash will reduce the workability of fresh concrete.

The compressive strength of the control concrete (CSF) varies from 1912 psi at 1 day to 9322 psi at 180 days. Within 7 days, the compressive strength of CSF is 6352 psi, which can be considered as high strength concrete (ACI 363 1990). The compressive strengths at 1 day of CSF15 and CSF25 are 2335 psi and 2675 psi, respectively or 22.1% and 39.9%, stronger than the control concrete. Concrete with silica fume gains strength very fast at early age. This behavior can be attributed to both packing and pozzolanic effects. Because the particle sizes of silica fume are very small, they fill the voids of the concrete matrix and make concrete denser and more compact after casting. During the curing period, the pozzolanic reaction by silica fume will take place with a faster rate than the fly ashes because of its higher fineness. After 28 days, the strength gain of silica fume concrete slows and the strength falls below that of the control. The percentage of control strength of high strength silica fume concrete with 25% replacement reduces from 139.9% at 1 day to 97.9% at 180 days.

High strength concrete made from fly ash behaves in different way. The early strengths of high strength fly ash concrete are usually lower than the control concrete. With 15% replacement of 3F fly ash, the compressive strength of fly ash concrete varies from 1216 psi at 1 day to 10023 psi at 180 days or 63.4% to 107.5% of the control strength. With 15% replacement of 3F fly ash, the compressive strength at 1 day is expected to be on the order of 80% of the control strength. The lower value obtained here may be due to the high dose of superplasticizer. The superplasticizer used in this experiment is about 3 times higher than the recommended by the manufacture. High dosage of this admixture will retard the setting of cement which results in the lower compressive strength at early age. The effect is not pronounced in the wet bottom fly ash, 13F fly ash. After 7 days, the rate of strength gain of high strength fly ash concrete returns to what would normally be expected. The compressive strength of fly ash concrete is considered to be high strength after 7 days since the compressive strength is over 6000 psi. The strength variation of high strength fly ash concrete with 25% replacement of 13F fly ash varies from 1782 psi at 1 day to 10748 psi at 180 days. The greater use of fly ash gives lower compressive strength at the early ages up to 14 days. After 90 days, concrete with higher fly ash content produces higher strength than the concrete with a lower fly ash content. In general, the strength of fly ash concrete using 13F fly ash is higher than the concrete utilizing 3F fly ash.

Before 7 days, the highest strength is found in the samples with silica fume in the mix. After 14 days, sample CSF15 and C13F15 almost have the same strength about 7800 psi. At 28 days of curing, high strength concretes using fly ash as a replacement produced a stronger concrete than for either the control or the silica fume concrete. The strength of samples C13F15, C13F25, and C3F25 are 8740 psi, 8561 psi, and 8648 psi, respectively or 110.8%, 108.6%, and 109.7% compared with the control strength. As the age increases, the strengths of fly ash concrete also increase. At 90 days, the compressive strengths of fly ash concrete are 107% to 115% of the control concrete.

It is interesting to note that the compressive strength of concrete made with silica fume (both 15% and 25% replacement) have almost the same strength as the control strength at the age of 90 days. These strengths range from 9100 psi to 9300 psi. It is obvious that the silica fume in concrete reacts faster than fly ash and control concrete but the rate becomes slow after 7 days. Figures 5.63 and 5.64 confirm the behavior of high strength silica fume concrete.

5.17 Bending Strength (Modulus of Rupture) of Fly Ash Concrete

In this experiment, the objective is to find the relationship between the bending strength of fly ash concrete and its compressive strength. Fly ash concrete with 25%

replacement of cement was mixed and cast to make concrete beam. Control mix, BCON, is the concrete without any fly ash was also mixed and cast at the same days and cured in the same environment of the fly ash concrete beams. Samples BHUD and BMER are the concrete with 25% replacement of the original feed of dry and wet bottom fly ashes, respectively by weight of cementitious materials. Each sample consists of 4 beams and 12 cylinders. At each test date, 2 beams and 6 cylinders are used. The beams were used for testing the bending strengths. Three cylinders are used for evaluating the compressive strength and the other 3 cylinders are for determining the splitting tensile strength.

Table 5.54 shows the bending strength of fly ash concrete beam together with the splitting and compressive strength. In general, the bending strength increases with the increase in compressive strength. This result is also reported by Ravindrarajah and Tam (1989). The bending strengths of fly ash and plain concrete beams are in the range of 8.7% to 10.1% compared to their compressive strengths.

Table 5.54 Bending, Splitting, and Compressive Strength of Fly Ash Concrete

Sam No.	Age (Day)	Comp (psi)	Splitting (psi)	Bending (psi)	Percentage of Comp. (Splitting)	(Bending)
BCON	28	7051	860	709	12.2	10.1
BHUD	28	6318	787	614	12.5	9.7
BMER	28	6017	742	591	12.3	9.8
BCON	90	7759	912	734	11.8	9.5
BHUD	90	7427	852	643	11.5	8.7
BMER	90	7602	867	678	11.4	8.9

The splitting tensile strengths of fly ash concrete beams depend on the compressive strength. The splitting strength is slightly higher than that of the bending strength. It varies from 11.4% to 12.5% of the compressive strength. These values of splitting strength are very close to the results that reported by Giaccio and

Malhotra (1988). They concluded that the tensile strengths of fly ash concrete measured by the splitting test are about 10% of the 28-day compressive strength. At the age of 90 days, the percentage of splitting and bending strengths are slightly lower than those at 28 days. It can be concluded that the bending and splitting strength of fly ash concrete can be estimated in the same way of the plain concrete.

5.18 Relationship between Compressive Strength and Tensile Strength of Fractionated Fly Ash Concrete

In addition to compressive strength of fractionated fly ash concrete, tensile strengths by splitting test are also determined. The fractionated fly ash concrete with 15%, 25%, 35%, and 50% replacement of cement by weight of cementitious materials are tested for their tensile strength at the age of 180 days. Two hundred cylinder samples are tested for both compression and splitting. The results are shown in Figure 5.65. It is seen that the splitting tensile strength of fractionated fly ash concrete increases with the increase of the compressive strength. A suitable way to express the splitting tensile strength of concrete is as a percentage of its compressive strength. Figure 5.66 is the relationship between the compressive strength and the percentage of splitting tensile strength as compare with the compressive strength. The results yield an average value for the splitting strength of 11.8% of the compressive strength. The maximum and minimum values are 14.13% and 8.61% respectively, with standard deviation of 1.18%. In general, the tensile strength of concrete by splitting test is about 10% of the compressive strength (Giaccio and Malhotra 1988). So, it can be concluded that the use of fly ash in concrete does not change the tensile characteristics.

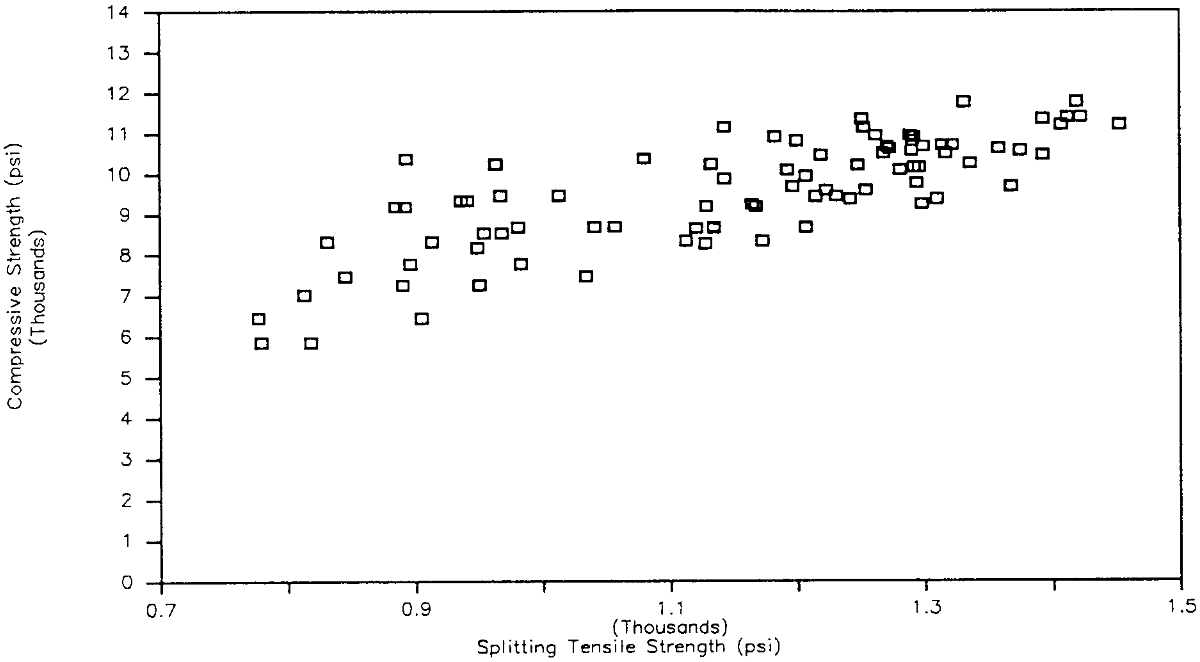

Figure 5.65 Relationship between Compressive Strength and Splitting Tensile Strength

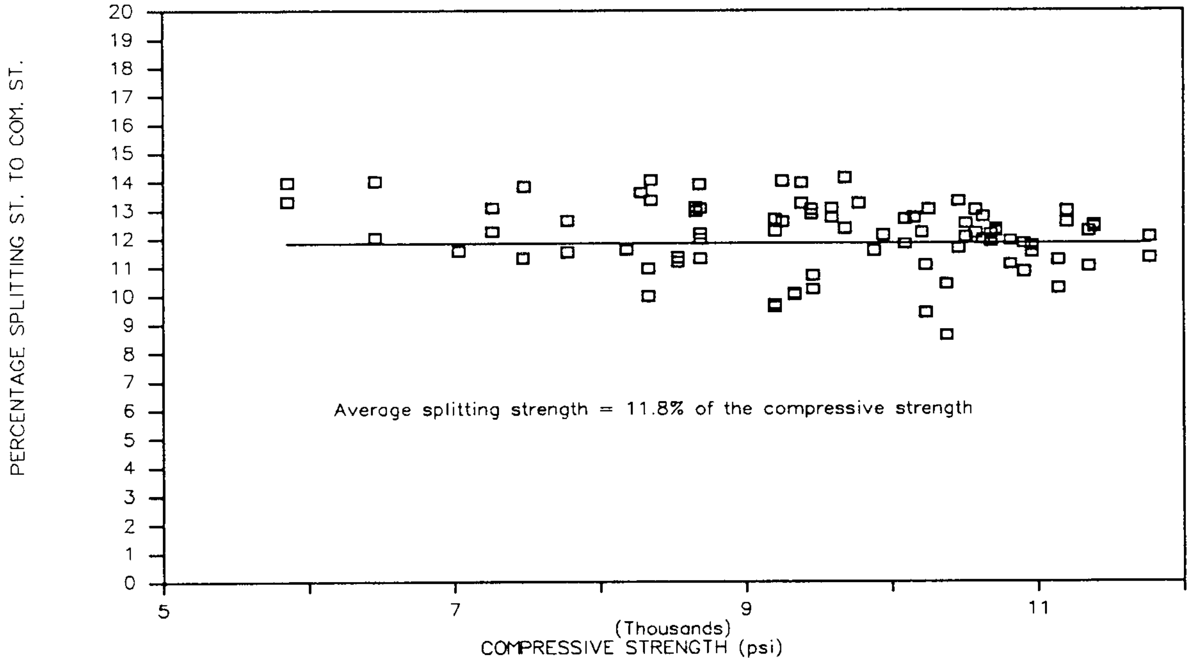

Figure 5.66 Relationship between Compressive Strength and Percentage Splitting Tensile Strength as Compared with the Compressive Strength

5.19 Modulus of Elasticity of Fractionated Fly ash Concrete

The modulus of elasticity (E_C) in this experiment is the slope of the stress-strain curve of fractionated fly ash concrete. The E_C values are obtained at 40% of f'_C since at that point the curve is still the straight line. The typical stress-strain curve is presented in Figure 5.67. More than 660 samples testing of modulus of elasticity of fractionated fly ash and control concrete were collected. The lowest strength was 2079 psi in 1CC50 at 7 days and the highest strength was 11201 psi in 13FC15 at 180 days.

Figure 5.68 shows that the modulus of elasticity of fractionated fly ash concrete lowers than the suggested formula given by ACI 318-89 (1990). The relation of square root of maximum compressive strength and modulus of elasticity of fractionated fly ash concrete by linear regression can be expressed as:

E_C (psi) = $45000 \sqrt{f'_C}$

The formula given by ACI 318-89 (1990) is:

E_C (psi) = $57000 \sqrt{f'_C}$

where f'_C in psi

The modulus of elasticity of fly ash concrete is the same (Ghosh and Timusk 1981; Ravindrarajah and Tam 1989) or slightly lower (Lane and Best 1982; Ukita and Ishii 1991) than the concrete without fly ash. The results here suggest that the modulus of elasticity of high strength fly ash concrete is not changed with the replacement of fly ash but rather changed with the maximum compressive strength. The lower values may be due to the test set up and the test specimens. For the suggested value by ACI 318-89 (1990), the 6x12 cylinder is used to determine the E_C. The tests here use the 3x6 cylinder as a test specimen. Another reason for low values of E_C is that the cover plates of the test set up may tilt during testing and gives a higher value of strain which results in the lower value of E_C.

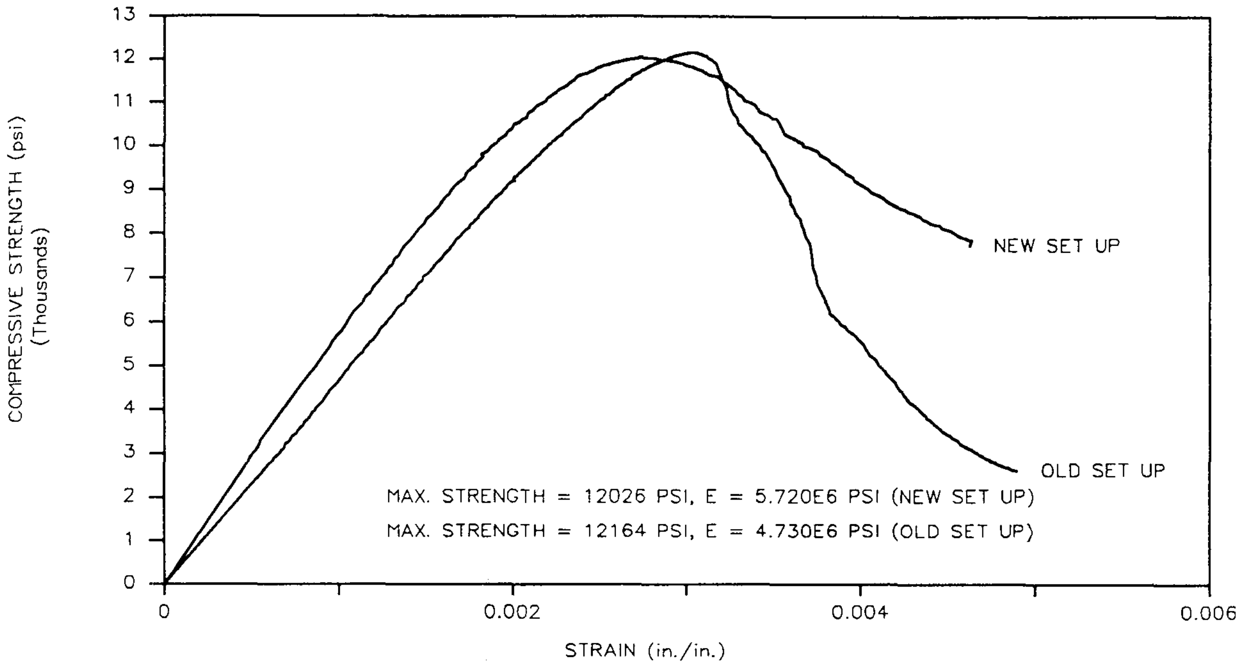

Figure 5.67 Typical Stress-Strain Curve of Fractionated Fly Ash Concrete

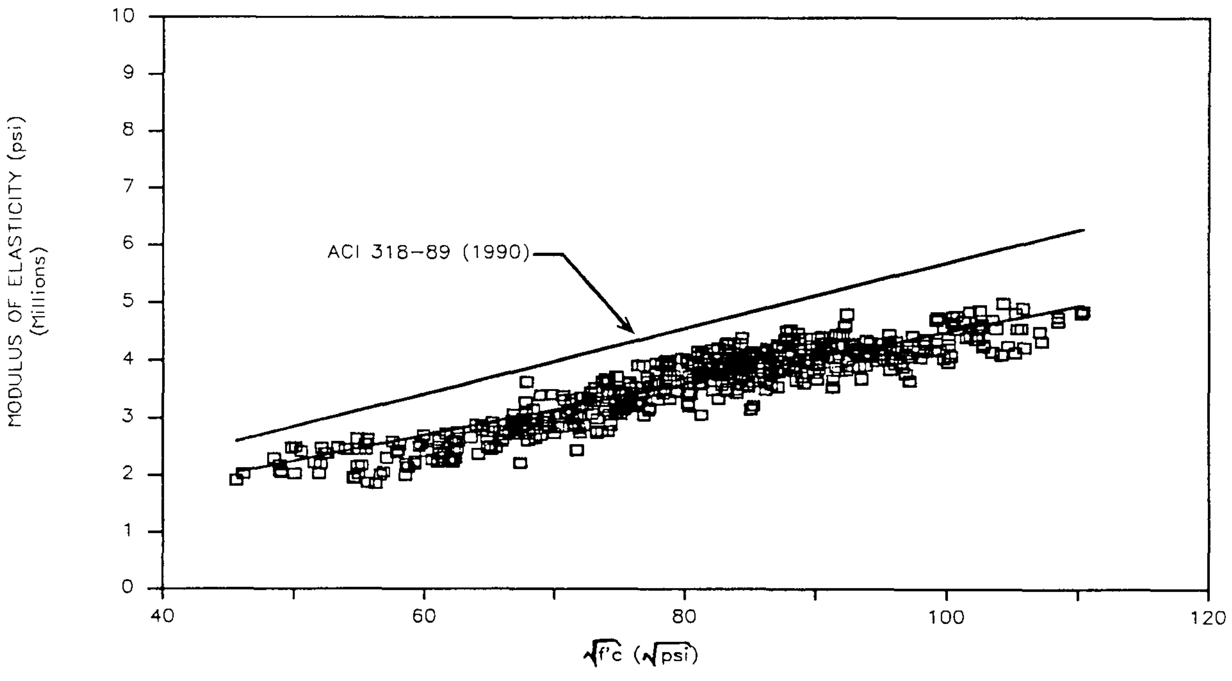

Figure 5.68 Relation between Modulus of Elasticity and Square Root of Maximum Compressive Strength of Fractionated Fly Ash Concrete

To get rid of this error, a new set up is used to determined the modulus of elasticity of fly ash concrete. With this set up, the deformation of fly ash concrete is measured based on the point which is attacked on the surface of the concrete. The result obtained by this set up is also presented in Figure 5.67. With the maximum compressive strength of 12060 psi, the modulus of elasticity is 5.72×10^6 psi or increases 17.3% compared to the value obtained by the old set up. This value is comparable to the modulus of elasticity suggested by ACI 363 (1990) which is about $40000\sqrt{f'_c} + 1.0 \times 10^6$ psi or 5.39×10^6 psi.

The deviation from predicting of modulus of elasticity is highly dependent on the properties and proportions of the coarse aggregates (ACI 363 1990). Sivasundaram, Carette, and Malhotra (1989) reported that the modulus value of fly ash concretes were 15 to 20% higher than that of a conventional limestone concrete of comparable strength.

5.20 Corrosion Resistance of Fly Ash Mortar

Fractionated fly ashes, 6F, 16F, the original feed of dry bottom fly ash (DRY), and wet bottom fly ash (WET) are mixed with cement to form the fly ash cement mortar. Standard 2-inch cubes were cast and cured in saturated lime water about 60 days before being put into the acid pond. The mix proportions used are tabulated in Table 4.5. The percentage of fly ash used in the mixes was 25 and 50 percent by weight of cementitious materials. The water to cementitious materials ratio of all mixes was kept constant at 0.5. No other admixtures were used in this program. Fly ash cement-mortar samples and the control samples (no fly ash) were then immersed in the H_2SO_4 acid solution with a concentration of 100 ml/l. All samples were kept under the same corrosive environment until the day of testing. To evaluate the extent of the damage caused by acid attack, the samples were removed from the acid pond and washed with tap water. The samples were then weighed at the saturated surface dry condition. The weight loss will then be determined as compared to the weight of original sample recorded earlier. Sample designated "CF" is the control mix which contains no fly ash in the mix. The number "25" and "50" stand for the percentage of cement replaced by fly ash.

The weights of sample at different age after being submerged in the concentrated 100 ml/l of H_2SO_4 solution are tabulated in Table 5.55 The compressive strengths of fly ash mortars prior to being immersed in H_2SO_4 solution are also presented in this table. For the normal cement samples, the corrosion due to acid attack is rather obvious. The weight losses of this control sample is 30% at 7 days and 67% at 21 days. This rate of decay on the integrity of cement mortar is rather alarming. It seems that the free lime or calcium hydroxide in the cement control sample is rather vulnerable to the acid attack. Can fly ash tie up these calcium hydroxide compounds and prevent them from being attacked from the sulfuric acid? The results presented in Table 5.55 indicate that the 25% fly ash mortar samples sustained similar damage as the control cement sample, but with a little lesser extent regardless of the type of fly ash or its particle size. However, for high volume fly ash samples, the extent of weight loss was significantly reduced to practically 0% at 7 days and only 6% at the age of 21 days. Once again, the type of fly ash and its particle size play no significant role on the corrosion resistance of fly ash mortar. Figures 5.69 and 5.70 are the relationship between the weight loss of the samples and immersed time for the 25% and 50% replacement fly ash mortar. At the age of 30 days, Figure 5.70 shows the influence of particle size of fly ash on the corrosion resistance. The original feed of fly ash seems to sustain more damage than the fractionated 15-micron ash samples (6FC50 and 16FC50). Figure 5.71 shows the remains of the fly ash mortar samples after being immersed in the H_2SO_4 for 30 days. Control and fly ash mortar samples which have 25% of fly ash in the mix show severe loss of weight due to acid attack by the 100 ml/l H_2SO_4 solution. With 50 percent fly ash in the mix, the attack is much less effective than on the control and the 25 percent fly ash cement samples. Consider in terms of compressive strength, the samples with 25% cement replacement gives a higher compressive strength than the 50% one. Based on the compressive strength, we can divide the samples into 2 groups. The first is the control and the 25% fly ash samples which have the compressive strength more than 9000 psi and the second group of the 50% fly ash mortar samples which have strength below 6500 psi. It can be seen that the compressive strength of the sample is not the correct measured parameter which can indicate the ability of the cement-based composites in resisting acid attack. But rather, it is the amount of fly ash in the mix that governs the resistance. From our investigation, it seems that the limit of fly ash content to provide a reasonable corrosion resistance against acid attack is about 35%. This is believed that the resistance was a result of $Ca(OH)_2$ being tied up by the pozzolanic content in the fly ash which reacts to form a more stable C-S-H.

Table 5.55 Effect of Fly Ash Cement Mortar in H_2SO_4 100 ml/l

Sample No.	Weight at Different Ages (g)							Comp.
	0-day	1-day	3-day	7-day	14-day	21-day	30-day	(psi)
CF	301.7	289.3	262.2	206.5	139.5	100.1	69.9	9972
DRY25	297.1	287.0	263.0	212.7	166.5	125.5	92.7	9121
WET25	297.8	286.8	260.7	212.3	164.6	122.1	89.3	9250
6F25	299.6	287.6	260.3	208.6	153.4	110.6	79.2	9415
16F25	297.0	284.6	255.5	197.7	135.4	90.6	60.9	9311
DRY50	295.8	295.4	293.6	289.5	280.1	276.8	257.8	5435
WET50	291.9	291.8	291.3	291.1	291.3	276.8	233.5	6535
6F50	294.8	294.7	294.8	293.6	294.3	292.6	287.2	5560
16F50	298.3	298.2	298.0	298.2	298.5	290.8	269.3	6487

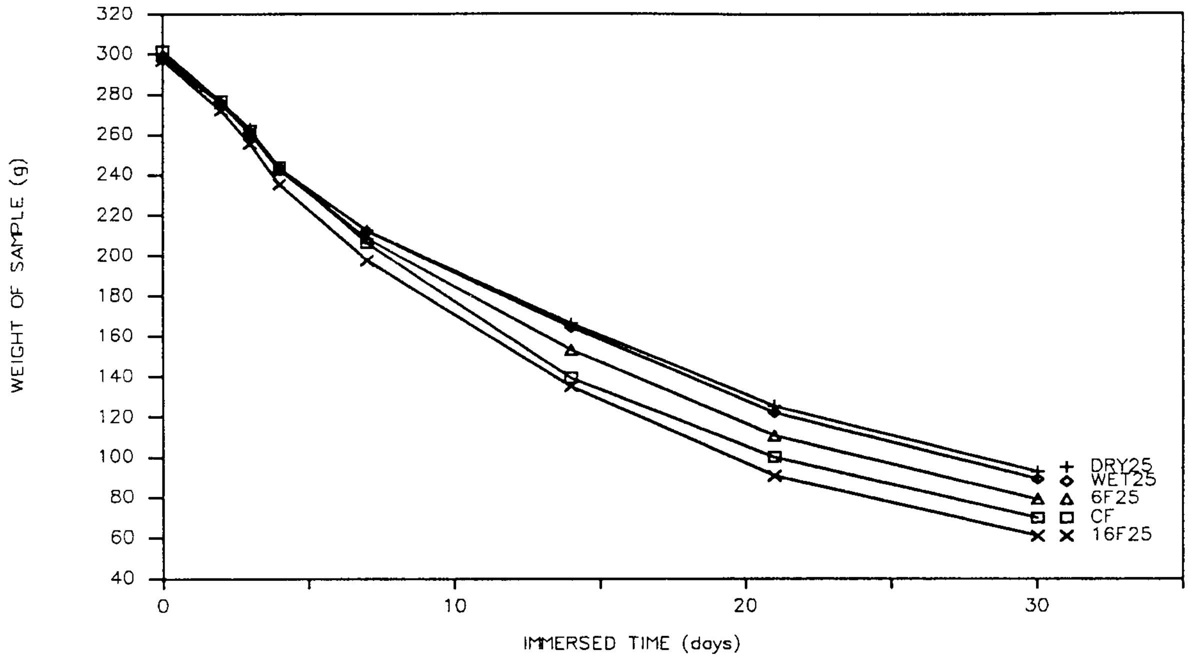

Figure 5.69 Relationship between the Weight of Fly Ash Mortar Samples and Immersed Time When Using Fly Ash 25% as Cement Replacement

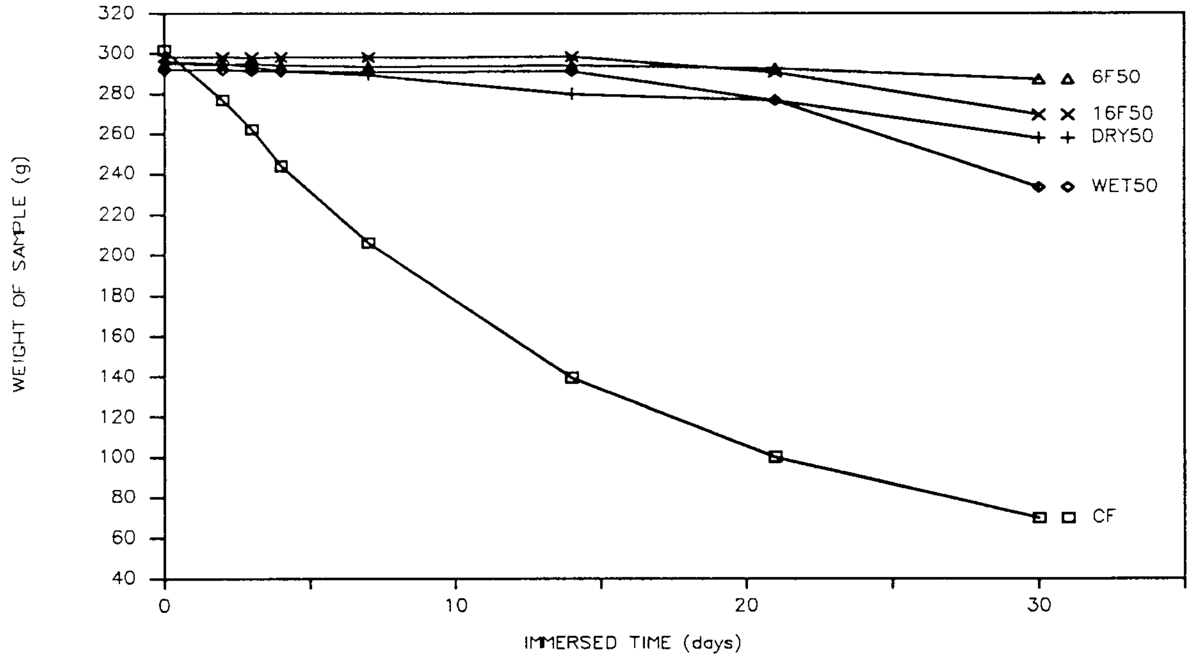

Figure 5.70 Relationship between the Weight of Fly Ash Mortar Samples and Immersed Time When Using Fly Ash 50% as Cement Replacement

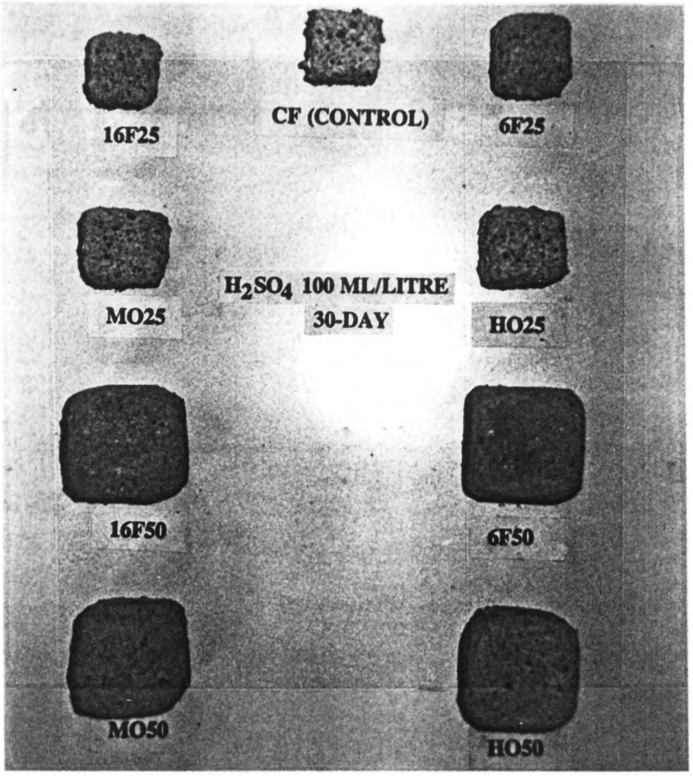

Figure 5.71 Fly Ash Mortar After Immersed in H_2SO_4 for 30 Days

5.21 Fly Ash Concrete Strength Model

In this study, fly ash concrete strength model is proposed. To avoid the influence of water, cement, fine and coarse aggregate, ect, which affect the strength, the compressive strength of fly ash concrete is predicted based on the control strength. The control strength concrete is obtained from the concrete that has the same conditions as fly ash concrete, i.e., water to cementitious materials ratio, curing condition, type of aggregates. The only difference in the control and fly ash concrete mix is the cement in the control concrete being replaced by the fly ash. The parameters needed for this model consist of the fineness modulus of fly ash, age of concrete, the amount of cement being replaced by fly ash, and the strength of the control concrete.

5.21.1 Fineness Modulus of Fly Ash (FM)

Fineness modulus of fly ash (FM) is defined as the summation of the percentage of fly ash that retains on the following sieve sizes; 0, 1, 1.5, 2, 3, 5, 10, 20, 45, 75, 150, 300, and 600 microns. In general, a little fly ash retains on the sieve with the opening size larger than 600 microns. The fineness modulus of fly ash has no unit. The number of fineness modulus indicates how fine of the fly ash compared to other fly ashes. The fineness modulus of fractionated of dry and wet bottom fly ashes are presented in Tables 5.56 and 5.57, respectively. The fineness modulus of fractionated fly ashes is between 300 to 900. Fly ash 13F has the lowest fineness modulus (the finest fly ash) and 1C has the highest fineness modulus (the coarsest fly ash).

Table 5.56 Fineness Modulus of the Fractionated of Dry Bottom Fly Ashes

Opening	Percent Retained (%)					
(Micron)	3F	6F	10F	11F	1C	DRY
300	0	0	0	0	1	0
150	0	0	0	0	4	1
75	0	0	0	0	17	8
45	0	0	0	1	44	20
20	0	0	5	20	80	40
10	0	5	60	82	99	55
5	10	53	94	96	100	70
3	35	78	96	97	100	80
2	55	83	97	98	100	87
1.5	75	90	97	100	100	92
1	93	94	98	100	100	95
0	100	100	100	100	100	100
FM	368	503	647	694	845	648

When fly ash is used as a replacement of cement with the same quantity: the lower of the fineness modulus of fly ash, the higher the compressive strength. Fineness modulus of fly ash gives more consistent results on compressive strength of concrete than the Blaine fineness and the residue on sieve No. 325. Concrete with 10F fly ash (Blaine 2028 cm^2/g) gives higher strength than concrete with the original feed of dry bottom fly ash (Blaine 3235 cm^2/g). Fly ashes 3F, 6F, and 10F have zero value retained on sieve on sieve No. 325. Thus these two methods are not suitable to measure the fineness of fractionated fly ash. By using the fineness modulus of fly ash, it gives more reliable results on the compressive strength of fly ash concrete..

Table 5.57 Fineness Modulus of the Fractionated of Wet Bottom Fly Ashes

Opening	Percent Retained (%)					
(Micron)	13F	15F	16F	18F	18C	WET
300	0	0	0	0	0	0
150	0	0	0	0	3	2
75	0	0	0	0	10	5
45	0	0	0	0	30	10
20	0	0	0	6	70	20
10	0	3	10	39	96	35
5	6	30	49	80	100	55
3	35	56	73	86	100	70
2	49	69	82	89	100	80
1.5	68	82	88	93	100	88
1	82	90	92	94	100	97
0	100	100	100	100	100	100
FM	340	430	494	587	809	562

5.21.2 Fly Ash Concrete Strength Model

The proposed of fly ash concrete strength model is in the form of:

$$\sigma(\%) = \sigma_C + \sigma_{FA} \tag{5.1}$$

$\sigma(\%)$ is the percentage compressive strength of fly ash concrete compared to control concrete.

σ_C is the percentage compressive strength of concrete contributed by cement in the concrete mix which equals to:

$$\sigma_C = 0.010C^2 \qquad (5.2)$$

where C is the percentage of cement in the cementitious materials

σ_{FA} is the contribution strength by the pozzolanic reaction between fly ash and cement at any age and

$$\sigma_{FA} = A + (B/FM) \ln (T) \qquad (5.3)$$

where A is a constant for the contribution of fineness of fly ash to the strength of concrete. For dry and wet bottom fly ashes, this constant is expressed as:

$$A = 6.74 - 0.00528FM \qquad (5.4)$$

FM is the fineness modulus of fly ash

B is the constant for the pozzolanic activity rate between fly ash and cement for any mix proportion. Constant B depends on the fly ash content in the mix. With higher fly ash content, this constant is higher than the lower content of fly ash in the mix. The constant B can be obtained from Figure 5.72. For fly ash content between 10% to 50% by weight of cementitious materials, the constant B can be expressed by

$$B = [1685 + 126C - 1.324C^2] \qquad (5.5)$$

T is the age of concrete (day)

The final form of the fly ash concrete strength model is

$$\sigma(\%) = 0.010C^2+[6.74-0.00528FM]+\{B/FM[\ln(T)]\} \qquad (5.6)$$

For fly ash content in concrete mix between 10% to 50%, equation (5.6) can also expressed as

$$\sigma(\%) = 0.010C^2+[6.74-0.00528FM]+\{(1685+126C-1.324C^2)/(FM)[\ln(T)]\} \quad (5.7)$$

After the percentage compressive strength of fly ash concrete is determined, the compressive strength of fly ash concrete is converted by multiply the control strength at that age with the percent compressive strength of fly ash concrete obtained from the model. Age of concrete, T, is varied from 1 day to 1000 days since after 1100 days (3 years), the strength of fly ash concrete incrases a little (Hensen 1990).

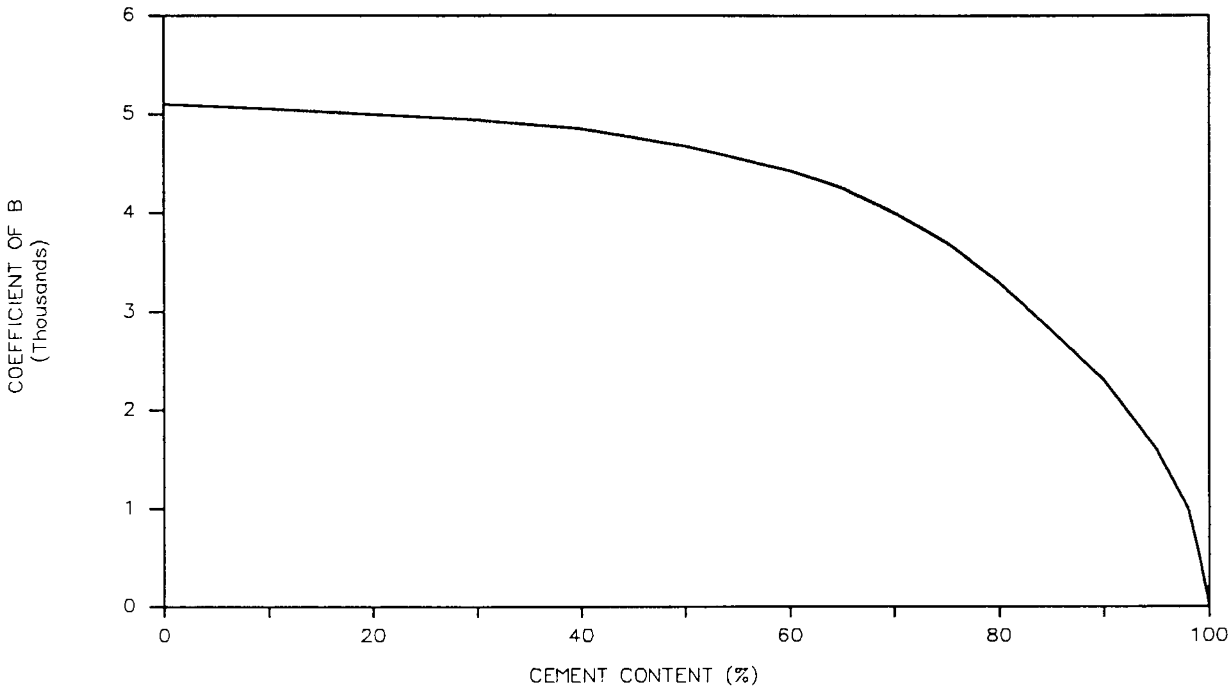

Figure 5.72 Relationship between Cement Content and Constant B

5.21.3 Prediction of Compressive Strength of the Fractionated of Dry Bottom Fly Ash Concrete

Tables 5.58 to 5.63 show the results of compressive strength of the fractionated of dry bottom fly ash concrete from experiment and from the prediction of the proposed model. Figures 5.73 to 5.76 show the results that predicted by model of the original feed of dry bottom fly ash when uses fly ash 15%, 25%, 35%, and 50% as a cement replacement. The prediction of compressive strengths of the fractionated 6F fly ash are shown in Figures 5.77 to 5.80. The other predictions of the fractionated of dry bottom fly ash concrete are shown in Figures A 1 to A 24 in Appendix A. The results here give a very good prediction of the fractionated fly ash concrete strength.

Table 5.58 Compressive Strength of Fly Ash Concrete from Experiment and from the Proposed Model for 3F Fly Ash

AGE	3F FLY ASH, FINENESS MODULUS = 368							
	3FC15	MODEL	3FC25	MODEL	3F35C	MODEL	3FC50	MODEL
1	1721	1647	1510	1304	1136	1003	567	634
7	5946	5696	5280	4986	4606	4313	3026	3374
14	7189	6902	6494	6205	5531	5514	4142	4492
28	8318	8319	7686	7654	6602	6957	5074	5850
56	9129	9344	8567	8775	7483	8128	6400	7011
90	9888	10203	9502	9704	8406	9091	7246	7958
180	11100	11816	10731	11429	10080	10865	8639	9689

Table 5.59 Compressive Strength of Fly Ash Concrete from Experiment and from the Proposed Model for 6F Fly Ash

AGE	6F FLY ASH, FINENESS MODULUS = 503							
	6FC15	MODEL	6FC25	MODEL	6F35C	MODEL	6FC50	MODEL
1	1718	1632	1485	1288	988	988	434	618
7	5746	5401	4816	4615	4222	3890	2682	2916
14	6887	6463	5842	5647	5324	4875	3521	3799
28	7946	7700	7058	6865	6378	6050	4397	4865
56	8949	8559	8122	7770	7246	6971	5155	5754
90	9484	9284	8785	8526	8001	7733	5839	6482
180	10606	10655	9974	9938	9451	9145	7823	7817

Table 5.60 Compressive Strength of Fly Ash Concrete from Experiment and from the Proposed Model for 10F Fly Ash

AGE	10F FLY ASH, FINENESS MODULUS = 647							
	10FC15	MODEL	10FC25	MODEL	10FC35	MODEL	10FC50	MODEL
1	1673	1616	1447	1272	888	972	425	602
7	5670	5202	4735	4370	3913	3613	2649	2618
14	6477	6172	5620	5285	4838	4464	3140	3355
28	7541	7298	6691	6359	5766	5473	3857	4241
56	8414	8054	7719	7132	6466	6241	4527	4963
90	9010	8696	8367	7781	7137	6880	5271	5556
180	10339	9917	9315	8999	8401	8069	7069	6648

Table 5.61 Compressive Strength of Fly Ash Concrete from Experiment and from the Proposed Model for 11F Fly Ash

AGE	11F FLY ASH, FINENESS MODULUS = 694							
	11FC15	MODEL	11FC25	MODEL	11FC35	MODEL	11FC50	MODEL
1	1667	1610	1390	1266	882	966	411	596
7	5550	5147	4633	4304	3739	3539	2382	2538
14	6430	6094	5566	5189	4768	4355	2991	3238
28	7350	7191	6582	6227	5613	5322	3748	4078
56	8139	7921	7389	6966	6217	6052	4442	4758
90	8723	8542	8111	7587	6859	6659	5044	5317
180	9850	9725	9109	8757	8031	7791	6666	6348

Table 5.62 Compressive Strength of Fly Ash Concrete from Experiment and from the Proposed Model for 1C Fly Ash

AGE	1CC FLY ASH, FINENESS MODULUS = 845							
	1CC15	MODEL	1CC25	MODEL	1CC35	MODEL	1CC50	MODEL
1	1598	1593	1369	1249	860	949	407	579
7	5416	5012	4542	4142	3567	3359	2110	2347
14	6411	5905	5400	4959	4501	4097	2692	2961
28	6971	6934	6360	5911	5240	4966	3334	3695
56	7889	7604	7001	6573	5691	5607	3976	4278
90	8259	8176	7521	7132	6200	6142	4340	4759
180	9269	9271	8348	8188	7242	7144	5578	5649

Table 5.63 Compressive Strength of Fly Ash Concrete from Experiment and from the Proposed Model for the Original Feed of Dry Bottom Fly Ash

AGE	ORIGINAL FEED FLY ASH, FINENESS MODULUS = 648							
	CDRY15	MODEL	CDRY25	MODEL	CDRY35	MODEL	CDRY50	MODEL
1	1622	1615	1390	1272	906	972	410	602
7	5525	5201	4593	4368	3895	3611	2405	2616
14	6479	6171	5492	5283	4696	4461	3041	3352
28	7440	7296	6598	6357	5798	5470	3782	4237
56	8300	8051	7390	7129	6440	6237	4466	4958
90	8943	8693	8044	7776	7189	6875	5054	5551
180	10083	9913	9070	8994	8389	8063	6857	6642

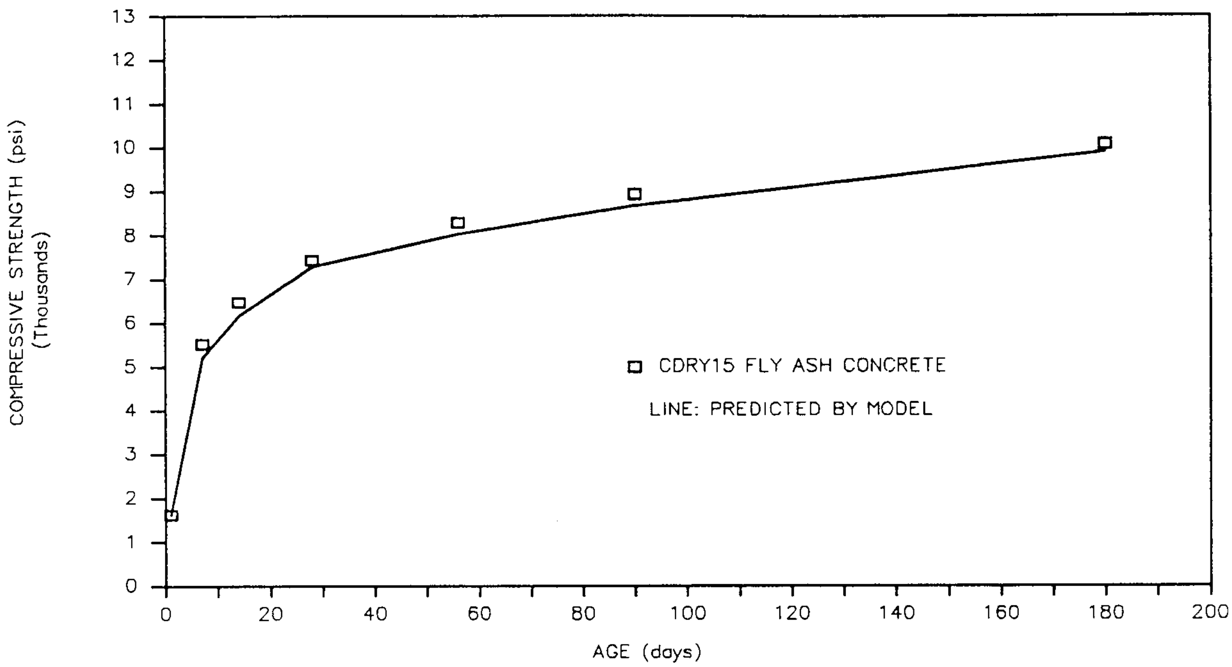

Figure 5.73 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

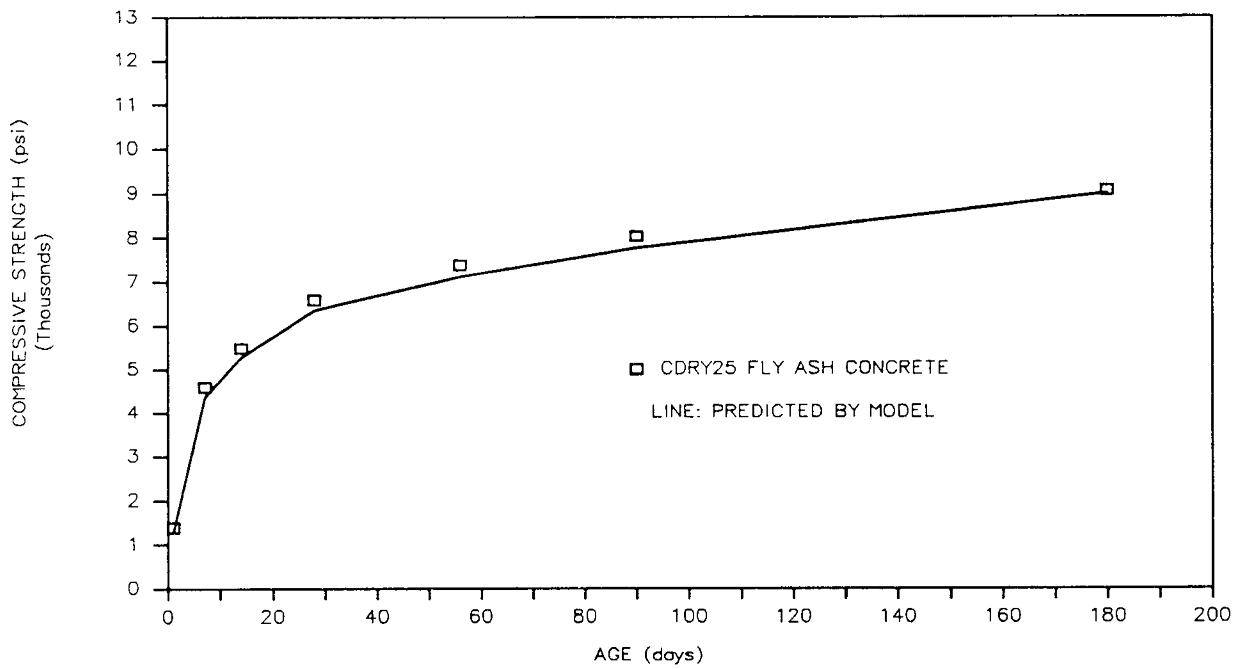

Figure 5.74 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

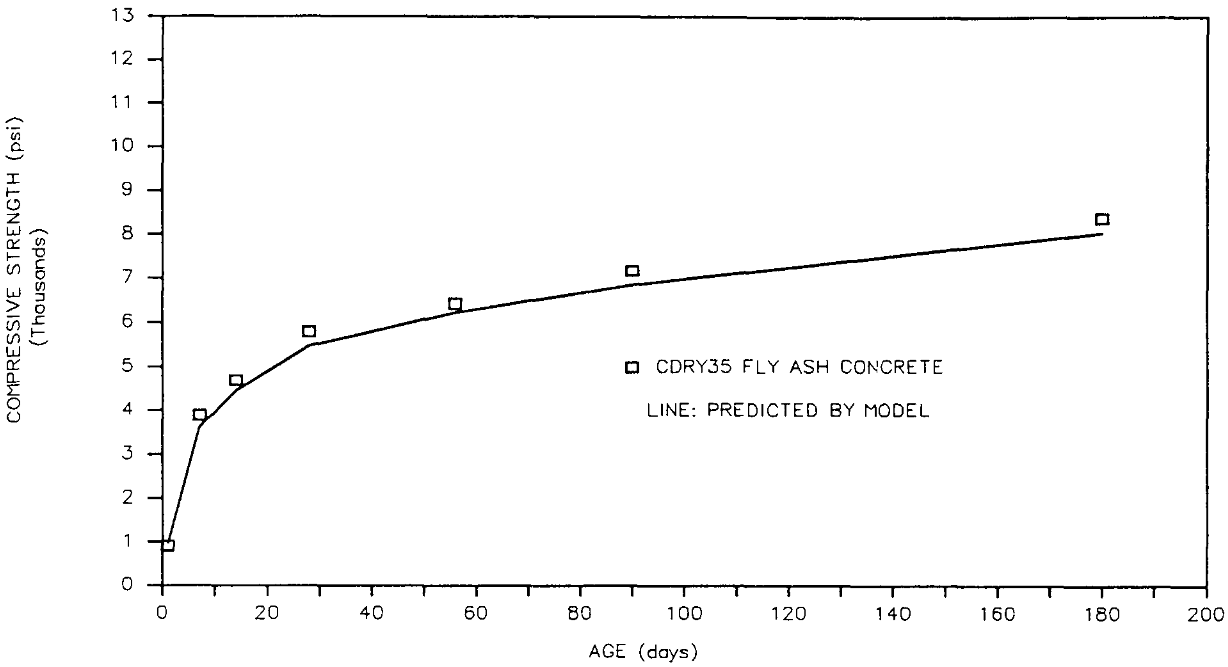

Figure 5.75 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

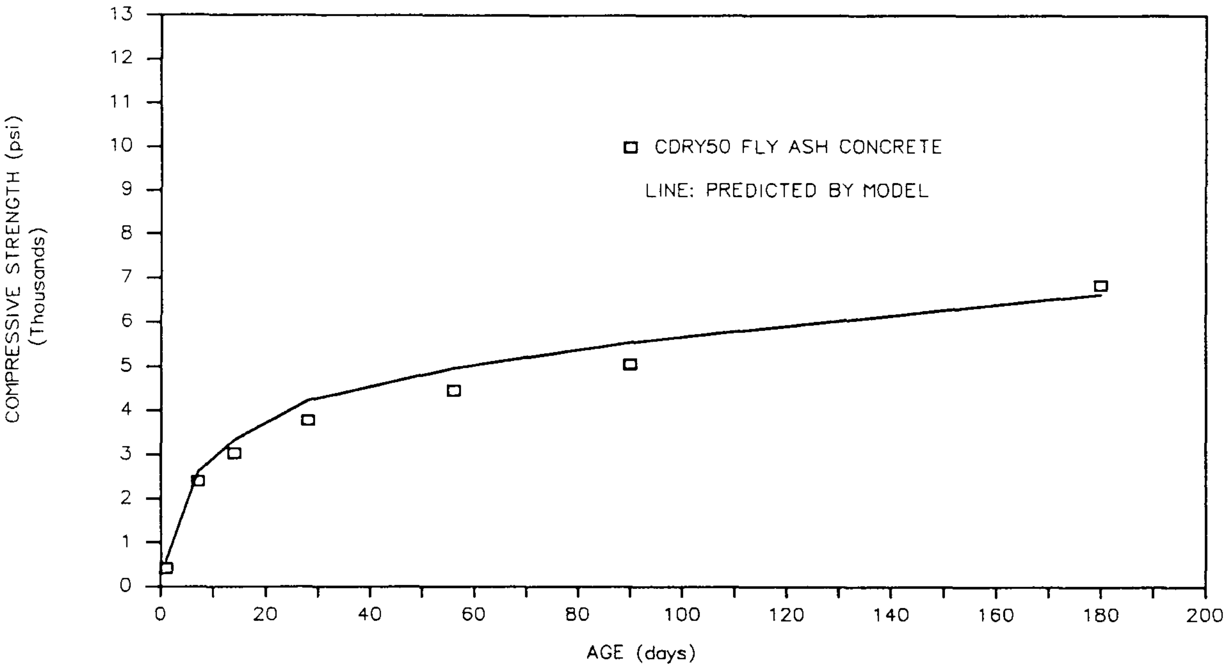

Figure 5.76 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

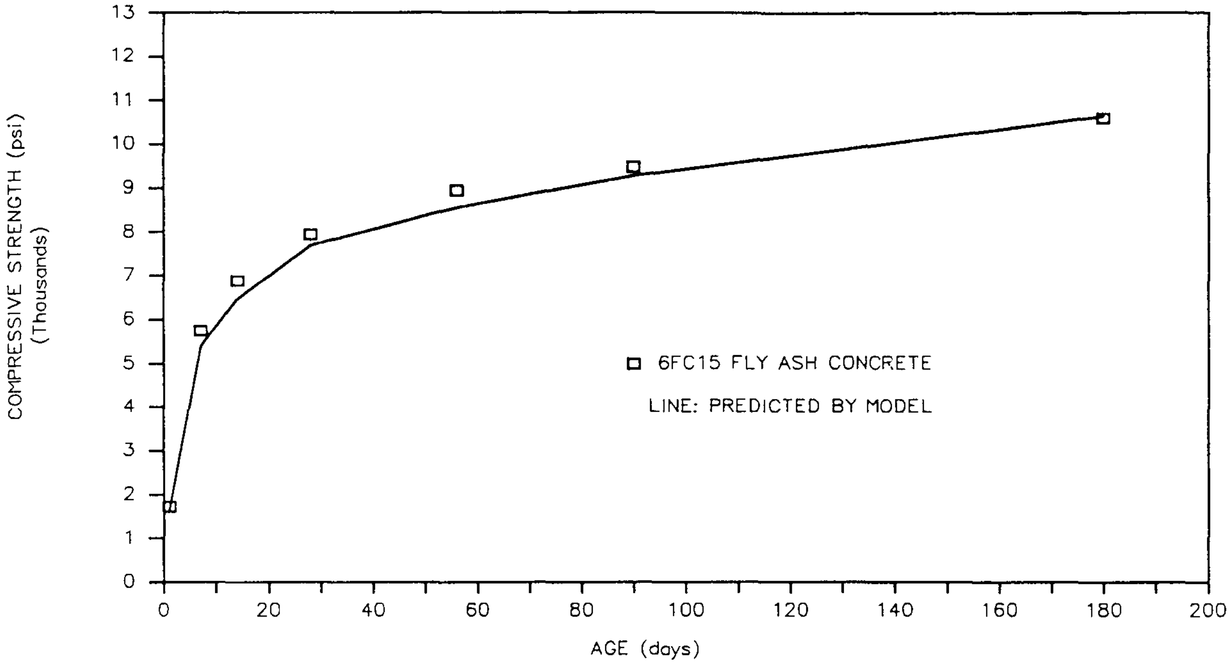

Figure 5.77 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

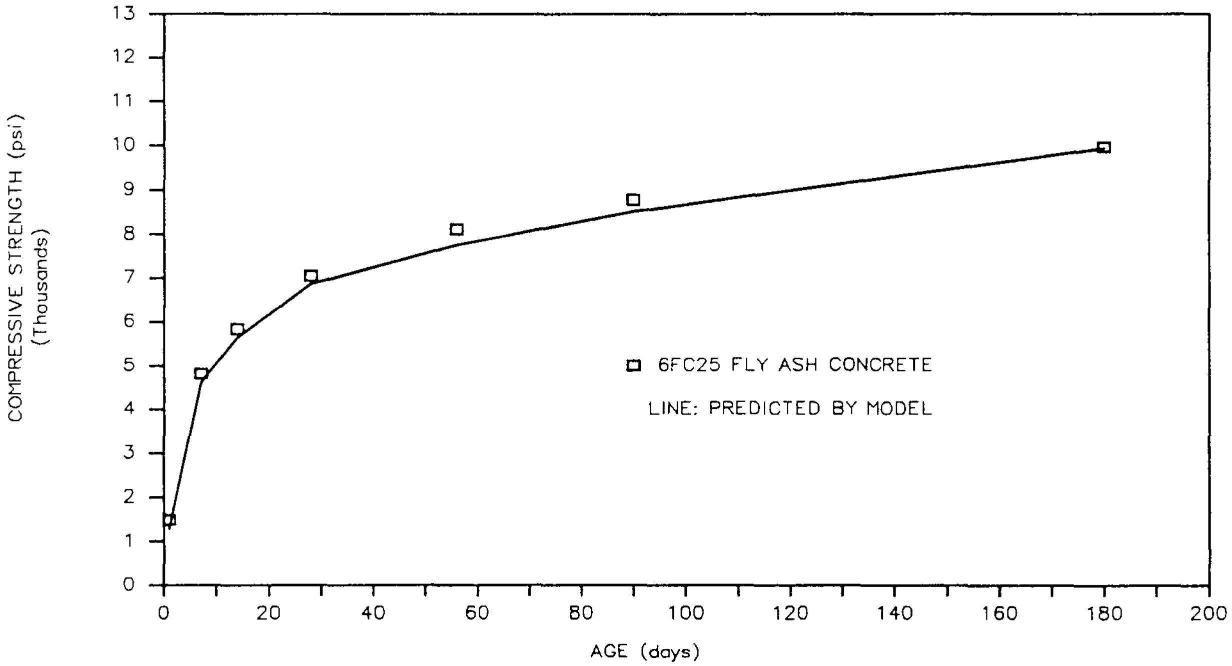

Figure 5.78 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

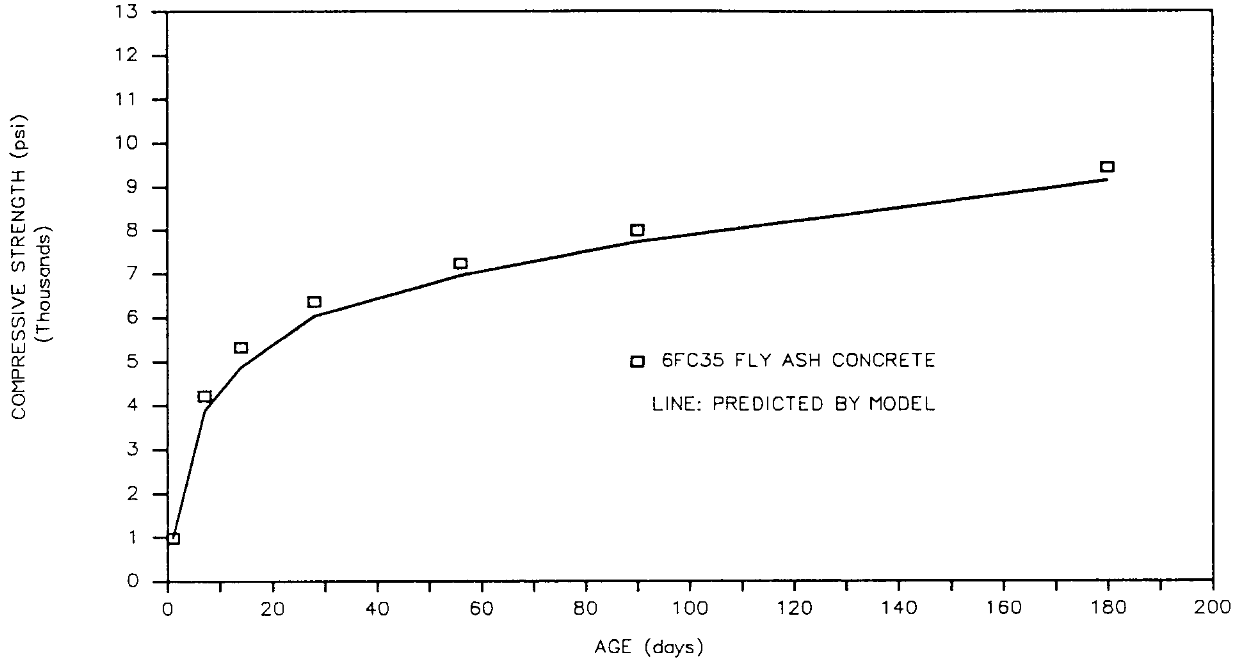

Figure 5.79 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

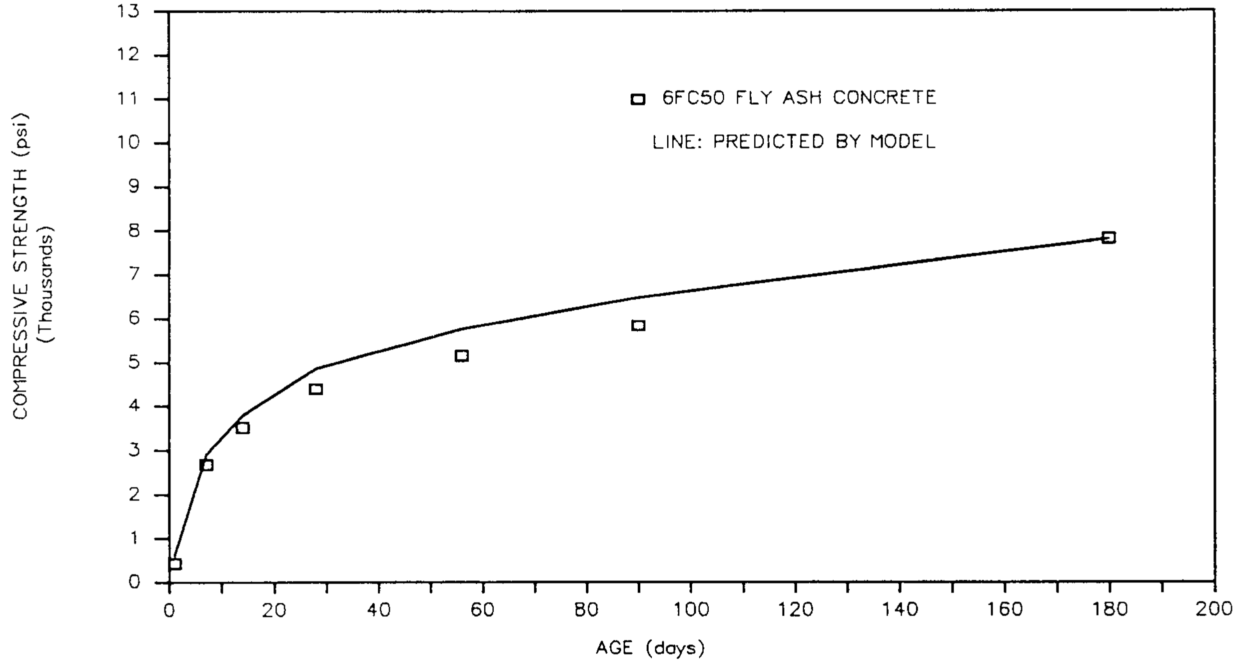

Figure 5.80 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

5.21.4 Prediction of Compressive Strength of the Fractionated of Wet Bottom Fly Ash Concrete

Regardless of the type of boiler use for burning coal to produce fly ash, the equation (5.7) also gives a very close prediction on the compressive strengths of the fractionated of wet bottom fly ash concrete. Figures 5.81 to 5.84 show the results of compressive strength of the original feed of wet bottom fly ash concrete and the proposed model when use fly ash 15%, 25%, 35%, and 50% as a replacement of cement. The predictions of compressive strengths of the fractionated 16F fly ash concrete by the proposed equation are shown in Figures 5.85 to 5.88. The other predictions of the fractionated of wet bottom fly ash concrete are shown in Figures A 25 to A 48 in Appendix A.

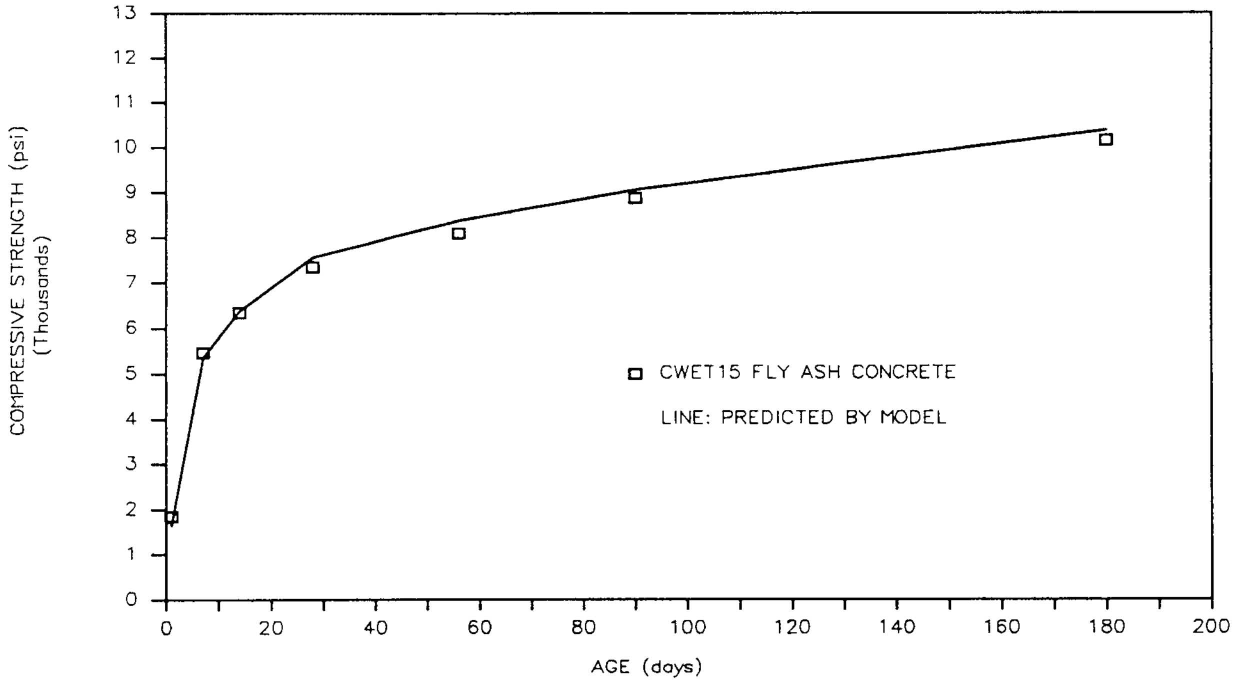

Figure 5.81 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

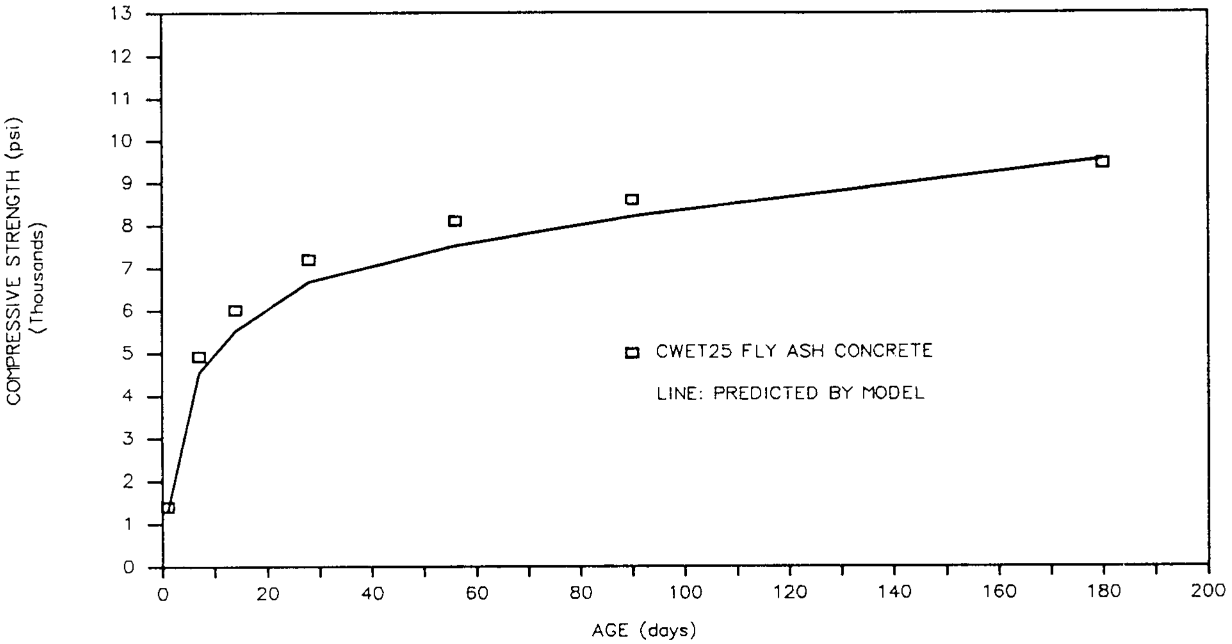

Figure 5.82 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

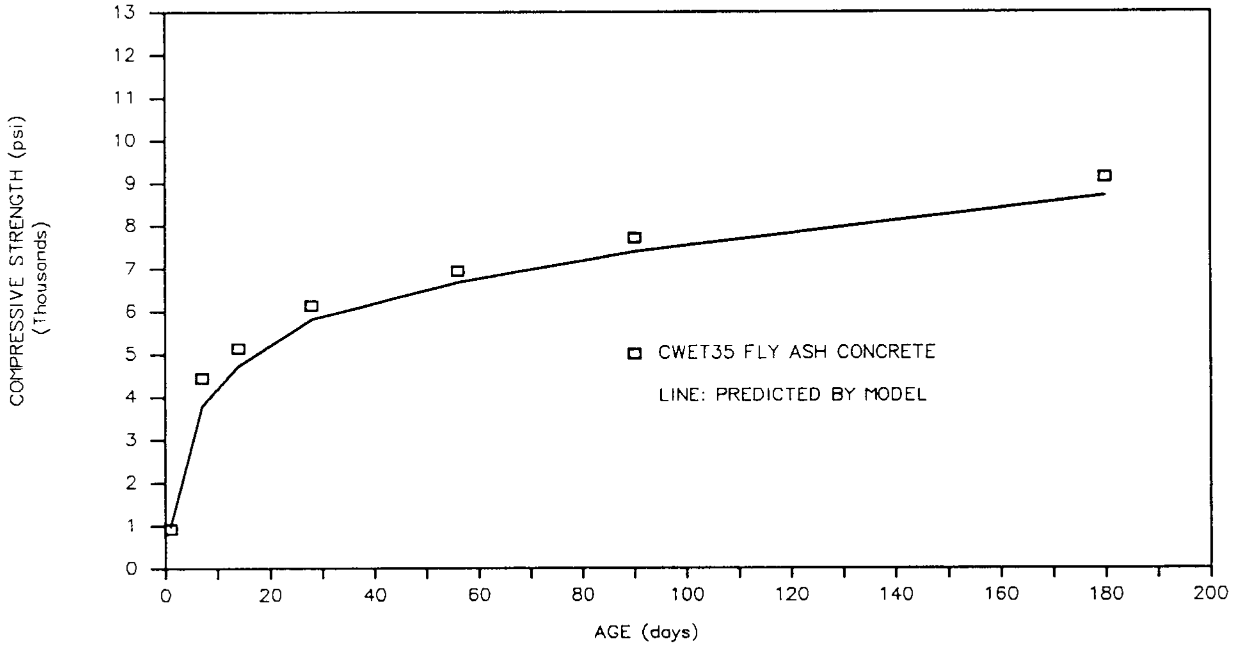

Figure 5.83 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

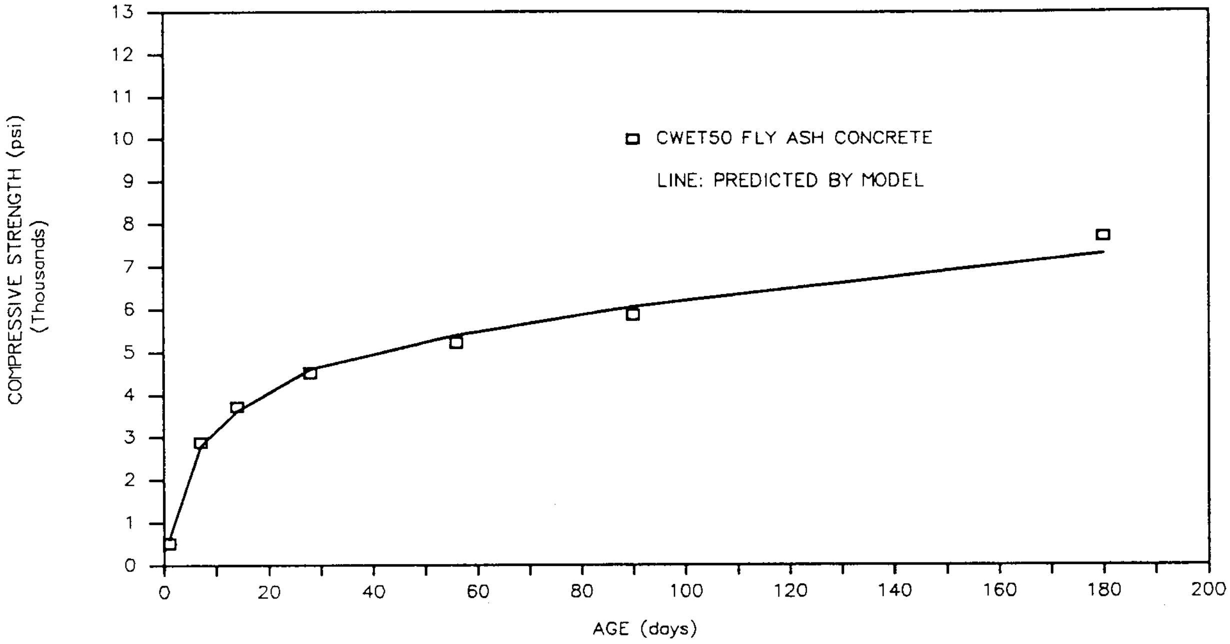

Figure 5.84 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

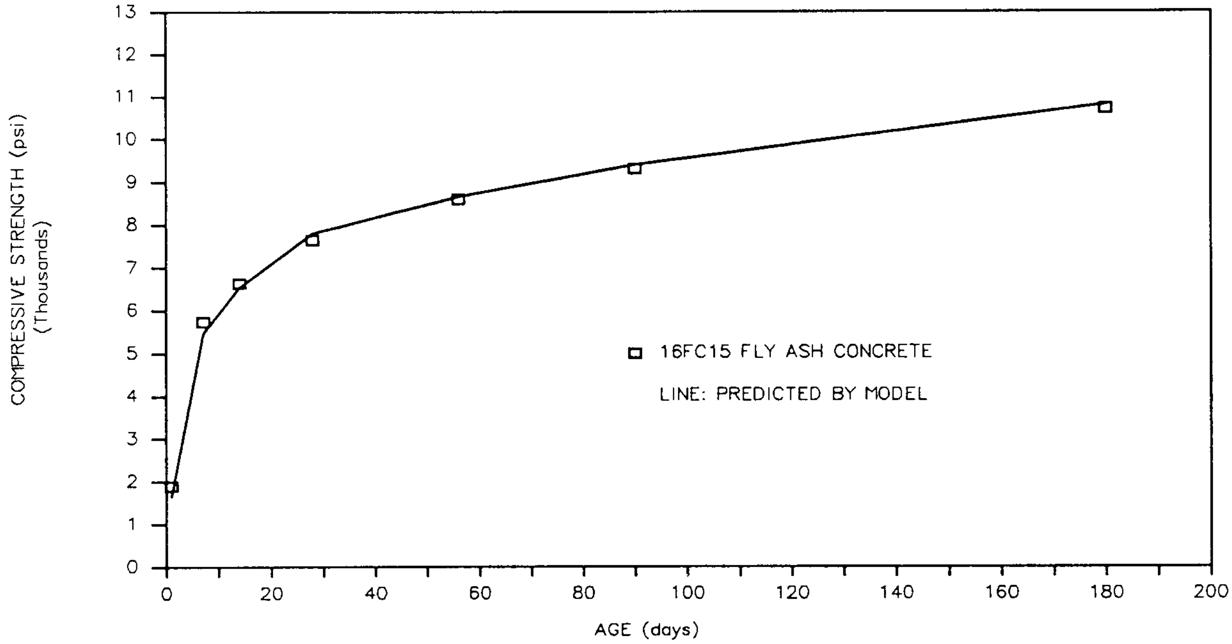

Figure 5.85 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

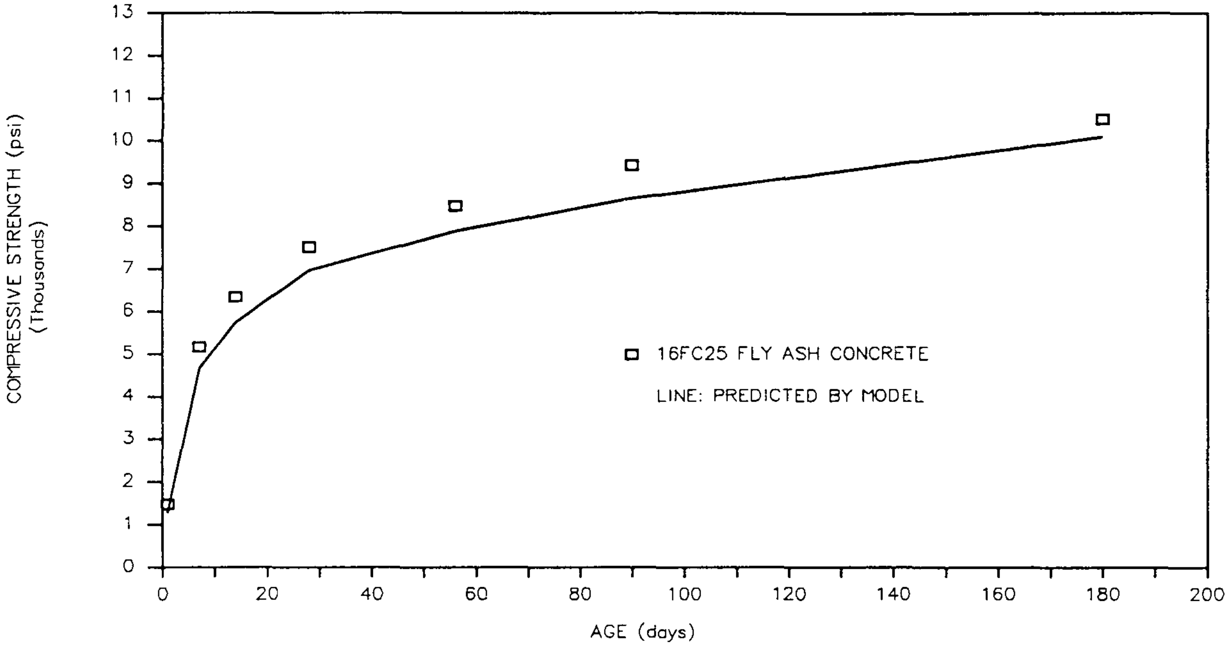

Figure 5.86 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

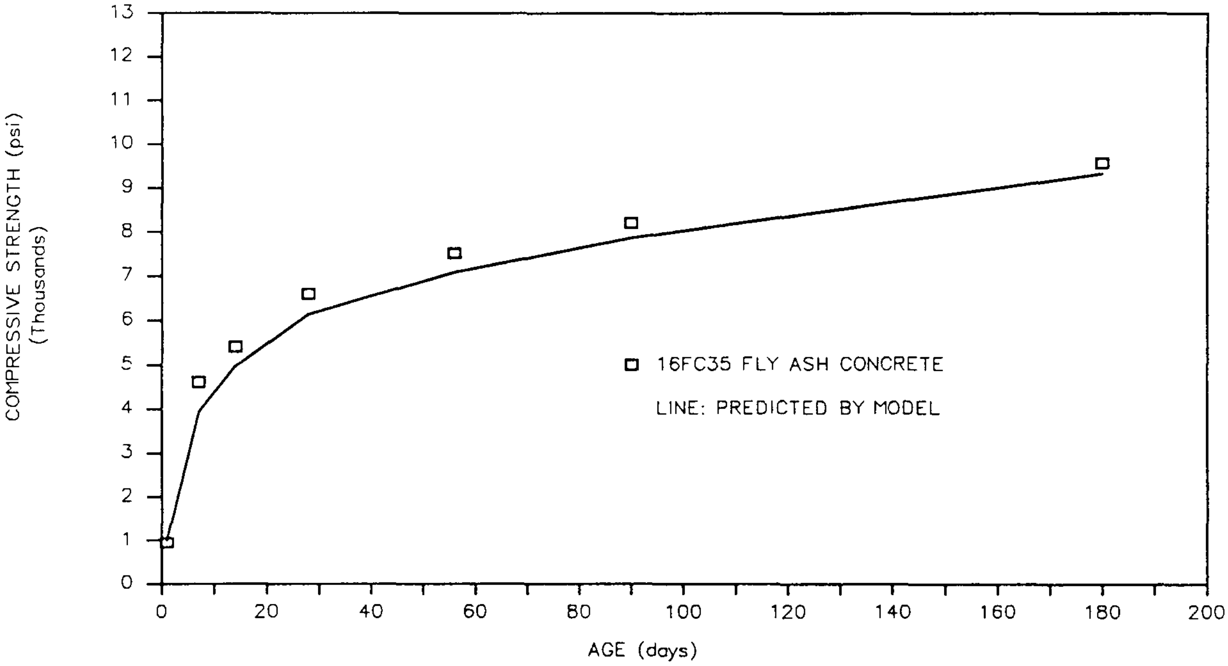

Figure 5.87 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

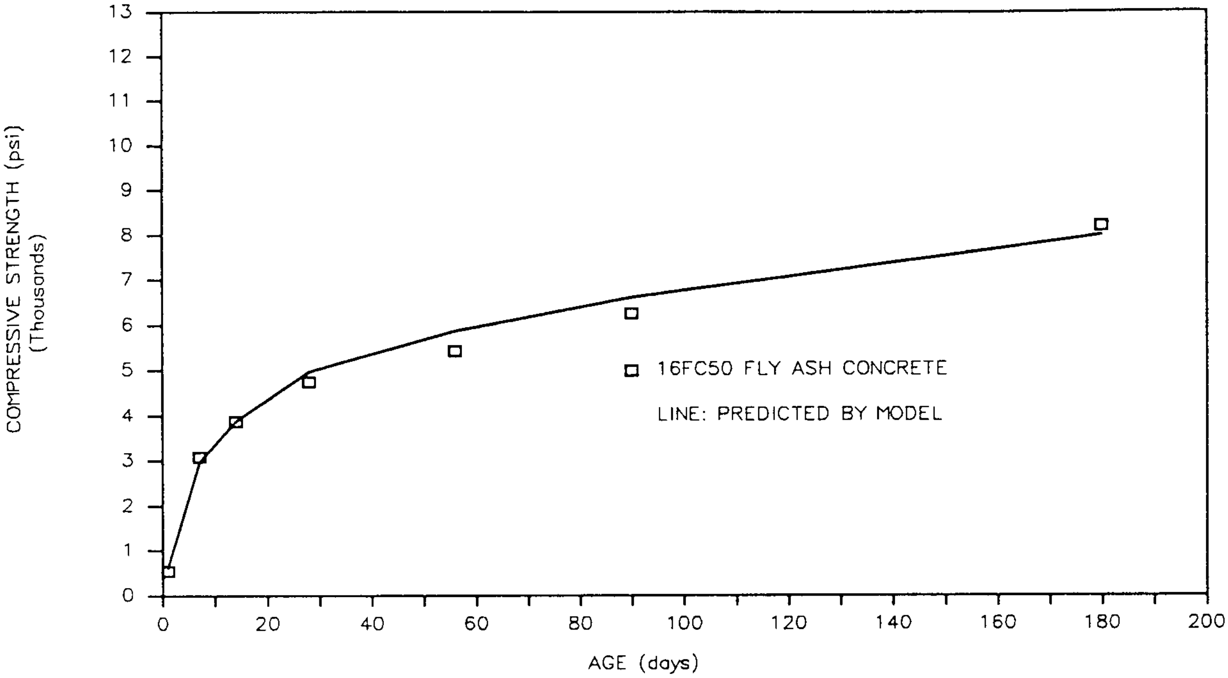

Figure 5.88 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

5.21.5 Prediction of Fly Ash Concrete Strength from Other Researchers

To verify the model, several data from different researchers are used to predict the compressive strength of fly ash concrete. Figures 5.89 to 5.94 show some comparison between the results from other researchers and the proposed model. Completed results are shown in Figures A 49 to A 67 in Appendix A. It is seen that the proposed model gives a very close result to predict the compressive strength of fly ash concrete with an error less than about 10%. The error is due to the difficulty to obtain the fineness modulus of fly ash used in those data. The fineness modulus of other researcher fly ash is obtained based on the Blaine fineness. The Blaine fineness is related to the fineness modulus of fly ash as shown in Figure 5.95.

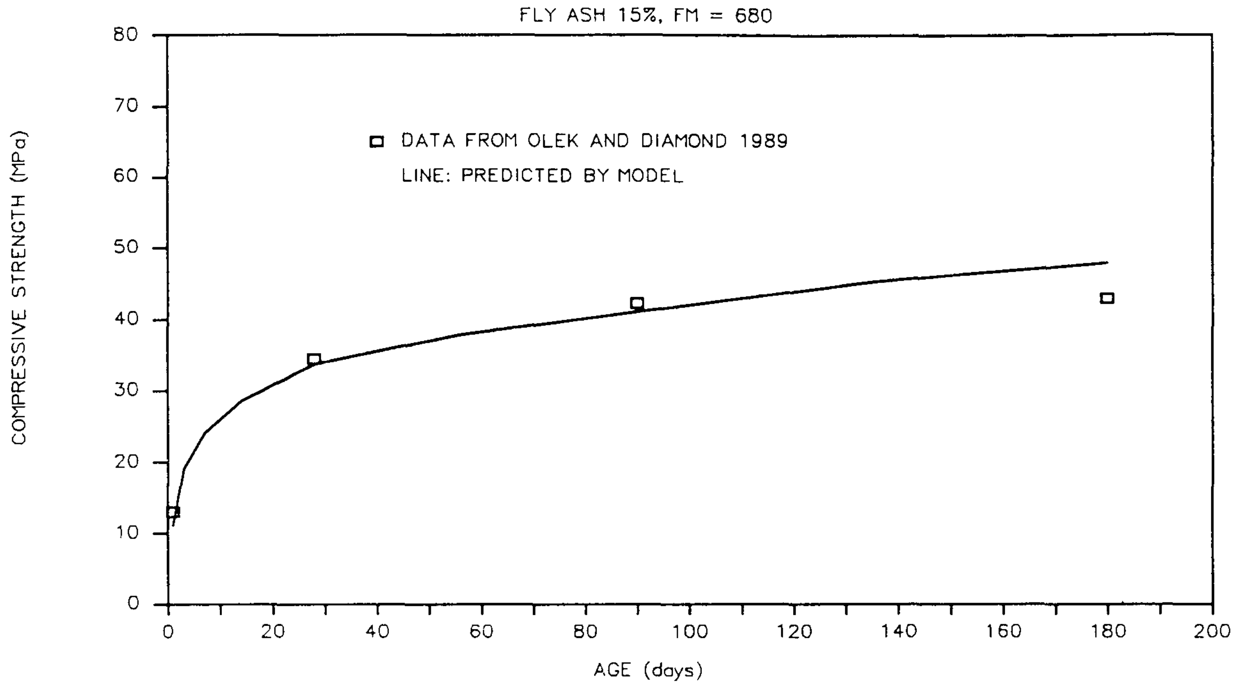

Figure 5.89 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Olek and Diamond (1989) and from the Proposed Model

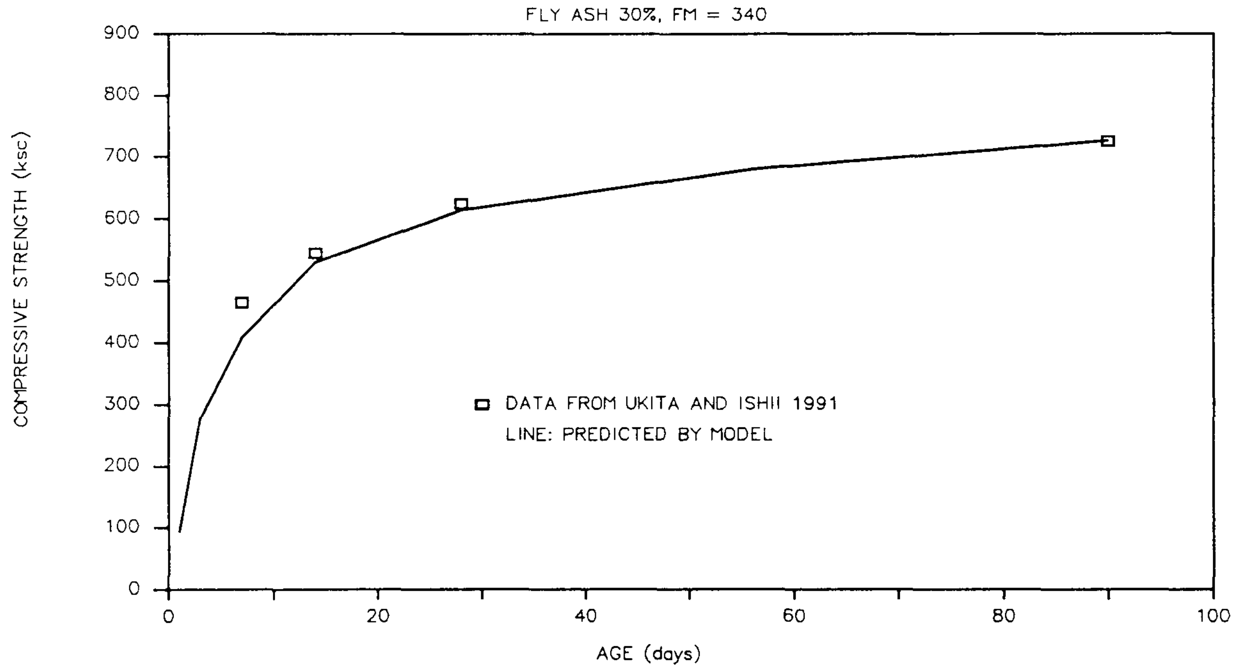

Figure 5.90 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita and Ishii (1991) and from the Proposed Model

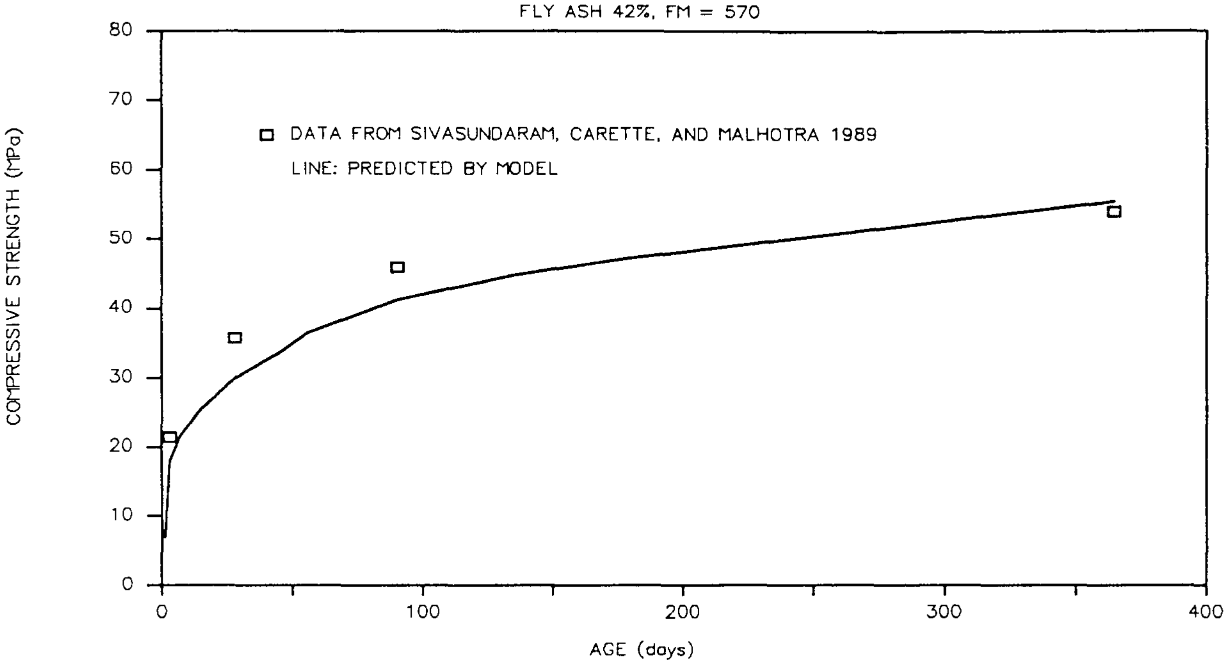

Figure 5.91 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Sivasundaram, Carette, and Malhotra (1989) and from the Proposed Model

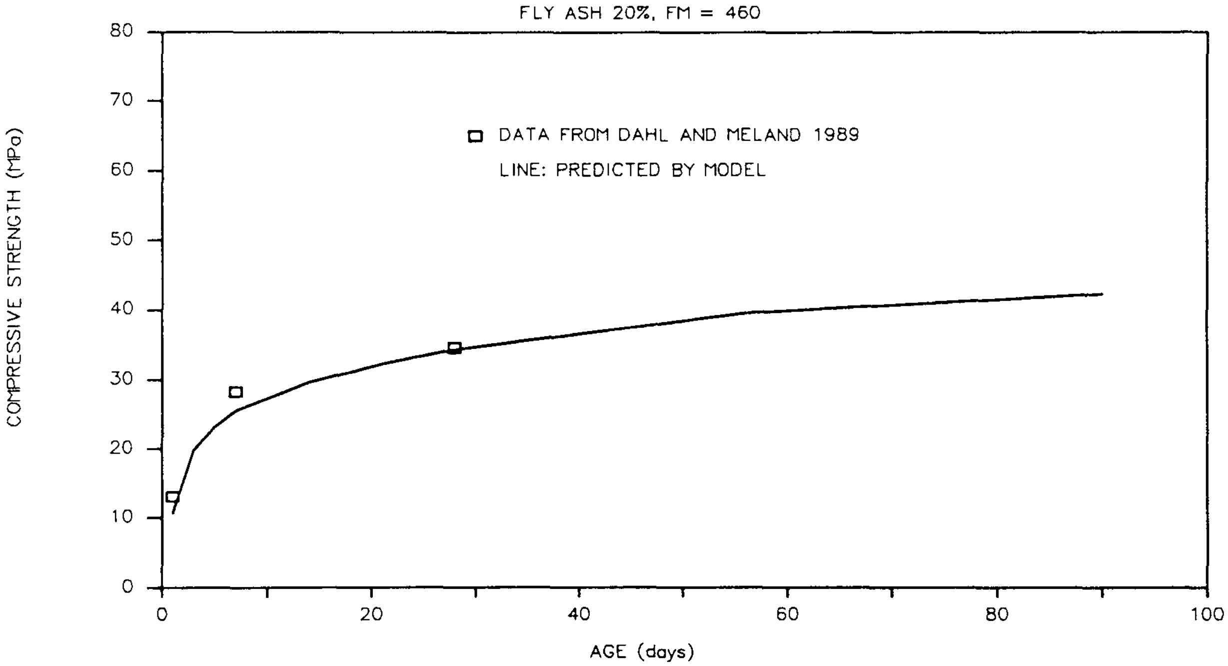

Figure 5.92 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Dahl and Meland (1989) and from the Proposed Model

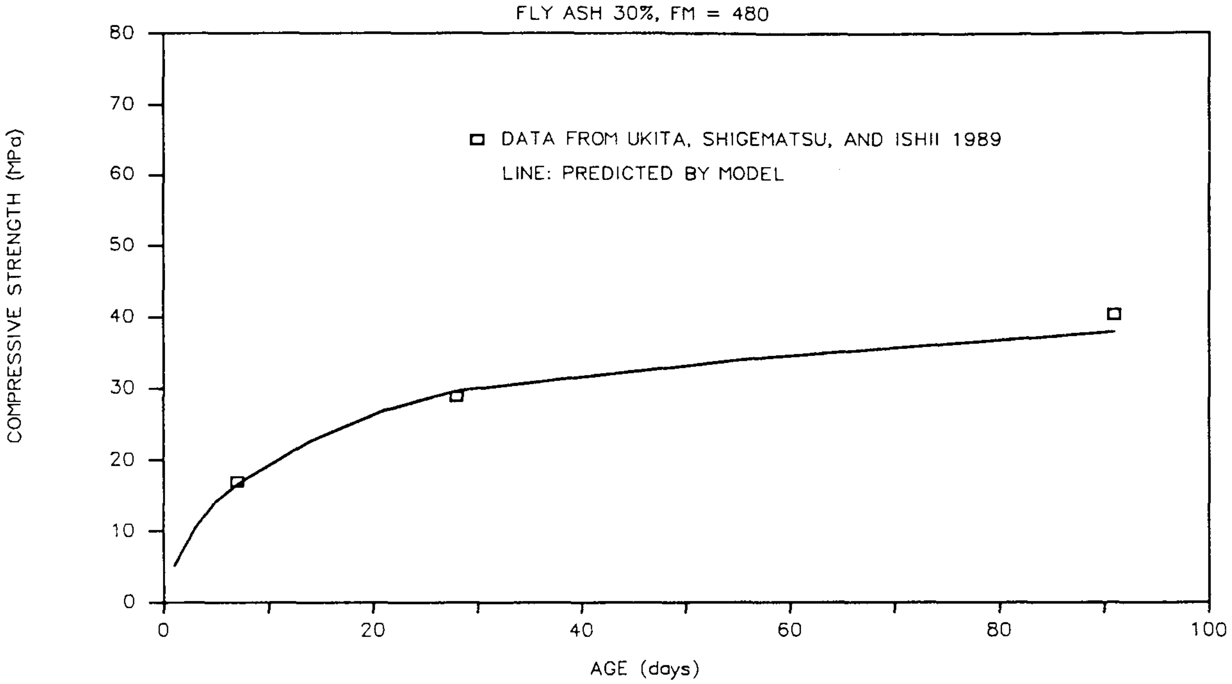

Figure 5.93 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model

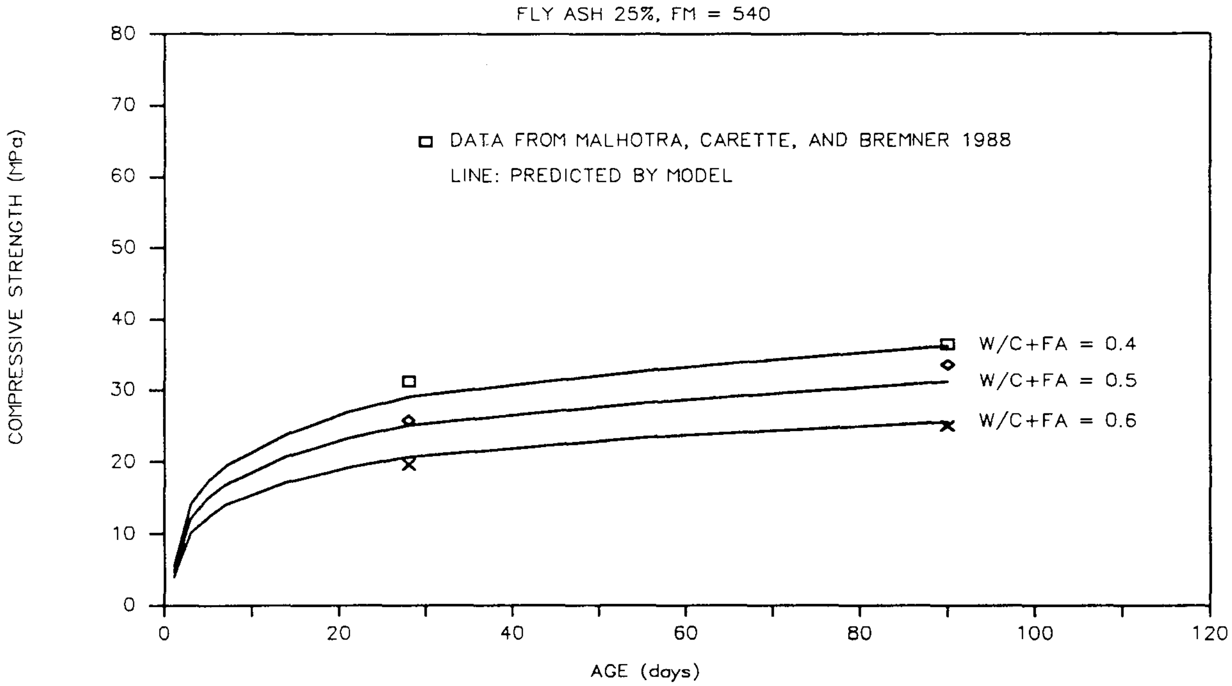

Figure 5.94 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Malhotra, Carette, and Bremner (1988) and from the Proposed Model

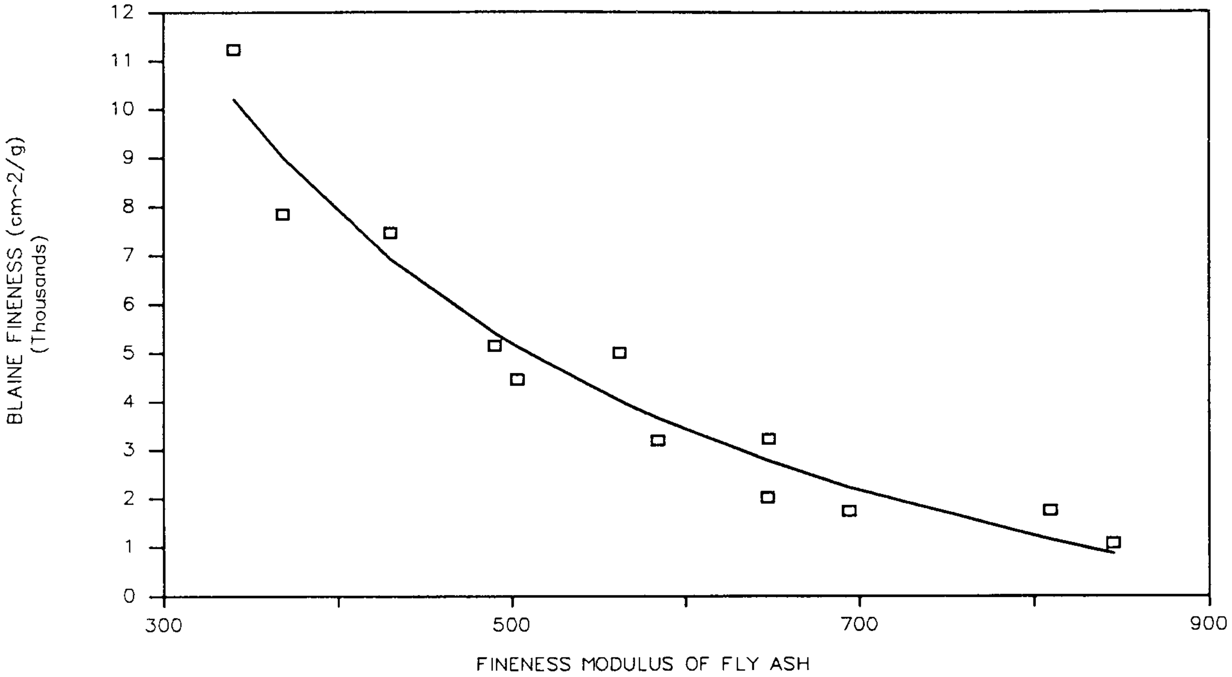

Figure 5.95 Relationship between Blaine Fineness and Fineness Modulus of Fly Ash
[Blaine = 26820 - 62.2FM - $0.038FM^2$]

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS

6.1 Conclusions on Physical and Chemical Properties of Fly Ash

1. There is almost no variation in the chemical composition of fly ashes as a result of the weathering process.
2. The chemical composition of fractionated fly ashes varies slightly when fly ashes are separated into different particle sizes with LOI and sulfate contents being the two parameters slightly affected by the fractionated process.
3. The specific gravity of the original feed of wet bottom fly ash is higher than that of the dry bottom fly ash. For the same type of fly ash, the finer the average particle size, the higher is the specific gravity of fly ash.
4. The average particle size of the original feed of wet bottom fly ash is much finer than that of the original feed of dry bottom fly ash.
5. Fineness of fly ash is better measured by the fineness modulus of fly ash since it gives more consistent results for the compressive strength than the Blaine fineness and the residue retained on sieve No. 325.

6.2 Conclusions on Setting Times of Fly Ash-Cement Paste

1. The presence of fly ash prolongs the setting times. For the same quantity of fly ash in a cement-fly ash paste, the weathered fly ash has longer setting times than the dry fly ash.
2. The setting times of fractionated fly ash cement paste vary with the particle size. The smaller size of fly ash seems to set faster than the coarser one.

6.3 Conclusions on Fly Ash Mortar with the Dry and Weathered Fly Ashes

1. As a cement replacement, weathered fly ash mortar exhibits lower

compressive strength than the dry fly ash. After 180 days, the replacement with the dry fly ash or weathered fly ash up to 30% gives the same compressive strength as the control mortar.

2. The addition of fly ash to mortar gives higher compressive strength than the control mortar. The optimum addition of the dry fly ash is about 20% of cement and about 30% for the weathered fly ash.
3. The 2 months of simulated weathering of the H fly ash for use in cement mortar does not seem to have any affect on the strength of mortar when used as a 15% replacement of cement.
4. The presence of dispersing agent made the fresh mortar more workable than for the specimen without dispersing agent. Fly ash mortars with dispersing agent are very weak at the age of 1 day. The effect may be because the dispersing agent retards the hardening of mortar.

6.4 Conclusions on the Effect of Fly Ash and Kiln Dust

1. With the same mix proportion, the compressive strength of fly ash-kiln dust mortar from the dry fly ash is higher than that from the weathered fly ash.
2. At early ages (1 to 3 days), the compressive strength of fly ash-kiln dust paste is higher with the higher percentage of kiln dust in the mix. At 28 days, the optimum mix is the WK30 series (fly ash 30% and kiln dust 70%) with the compressive strength of 3023 psi.
3. Samples with high fly ash content, WK70, WK80, and WK90, had very weak strengths that were very weak and disintegrated in water.

6.5 Conclusions on the Effect of Cement-Fly Ash-Kiln Dust Mortar

1. The use of the dry fly ash gives higher strength than the use of the weathered fly ash in cement-fly ash-kiln dust paste.

2. The higher the cement content in the mix, the higher the compressive strength of the cement-fly ash-kiln dust mortar.
3. For mixes with a constant amount of cement, the proportion of fly ash and kiln dust must be adjusted to obtain the optimum compressive strength. For 20% constant cement content in cementitious materials, the optimum mix has 40% fly ash and 40% kiln dust. For 40% constant cement content, the optimum mix has 40% fly ash and 20% kiln dust. And for the 60% constant cement content, the optimum mix contains 40% fly ash and no kiln dust. For the 80% constant cement content, the optimum mix is with 20% of fly ash and no kiln dust.
4. The lower the cement content, the longer the setting time of the cement-fly ash-kiln dust paste. Kiln dust, which has some cementing material properties, accelerates setting time. When the cement content is constant, the paste with higher percentage of kiln dust has a shorter setting time than the paste with less kiln dust.

6.6 Conclusions on Soaked and Washed Fly Ashes

1. The 15% replacement of soaked or washed fly ash gives the compressive strength of mortar higher than the control strength after 90 days. With the same amount of replacement of soaked or washed fly ash, the compressive strength of fly ash mortar is almost the same.
2. The addition of 15% of soaked or washed fly ash gives the same compressive strength. Generally, the addition of 25% by weight of cementitious materials of soaked or washed fly ashes, produces a higher strength than the addition of only 15% of the same fly ash at 180 days.

6.7 Conclusions on the Effect of Fractionated Fly Ash Concrete

1. The workability of fresh fly ash concrete tends to reduce with the decrease of the average particle size of fly ash.
2. The early strength of fractionated fly ash concrete is always lower than the control strength when fly ash is used as a replacement of cement.
3. Fineness of fly ash is a very important factor affecting the rate of pozzolanic activity. Finer average particle size of fly ash gives a higher rate of pozzolanic reaction.
4. The compressive strength of fractionated fly ash concrete is equal to or higher than the control strength after 14 days with the fine particles (samples 3FC15 and 13FC15) used as a 15% replacement. With 25% replacement, it takes about 28 days for the sample of 13FC25 to gain the same strength as the control concrete, and takes at least 56 days for the sample 3FC25 to reach the control strength. With 35% replacement of 13FC35 and 3FC35 fly ash, the concrete needs 90 days and 180 days, respectively, to reach the same strength of the control concrete. The use of the coarsest fly ash, 1C, with 50% replacement of cement provides the compressive strength at 180 days of only 54.9% of the control strength.

6.8 Conclusions on the Effect of Fractionated Fly Ash Mortar

1. The effect of fractionated fly ashes on the compressive strength of mortar is the same as concrete. The finer the particle size of fly ash in the mix, the higher the compressive strength.
2. With 15% replacement of the fractionated 3F or 13F fly ash, the compressive strengths of fly ash mortar are equal to or higher than the control mortar at the age of 14 days. With 25% replacement, it takes 28 days and 56 days for 13F and 3F fly ashes, respectively, to gain the same strength as the control

mortar.

3. In general, the compressive strength of the original feed of wet bottom fly ash mortar is higher than that of the dry bottom fly ash mortar when used at the same mix proportions.

6.9 Conclusions on the Corrosion Resistance of Fly Ash Mortar

1. The type of fly ash does not seem to have any significant affect on corrosion resistance against acid attack. The wet bottom fly ash showed a slight better resistance than the dry bottom fly ash.
2. The amount of fly ash needed to provide corrosion resistance is about 35% and or higher. The data presented here are for 50% samples only. With this high volume content of fly ash in the mix, the fly ash mortar samples exhibit excellent corrosion resistance against H_2SO_4 in particular.
3. The compressive strength of mortar is not a correct measure for corrosion resistance to H_2SO_4. It is rather the amount of fly ash in the mix which governs the corrosion resistance properties of the fly ash mortar.
4. Finer particle fly ash tends to exhibit better corrosion resistance than the coarser particle ash when used in cement-based materials.

6.10 Conclusions on High Strength Fly Ash and Silica Fume Concrete

1. Concrete with silica fume gains strength faster at early ages than the fly ash and control concrete. This behavior can be attributed to the packing and a pozzolanic effect. Since the particle sizes of silica fume are very fine, they fill the voids in the fresh concrete and make the concrete denser and more compacted.
2. The early strengths of high strength fly ash concrete are lower than the high strength of control and silica fume concrete but, after 28 days of curing,

strengths of fly ash concrete are higher than those of control high strength concrete.

3. It is obvious that the silica fume in concrete reacts faster than fly ash and control concrete but the rate of strength gain becomes slower after 7 days.

6.11 Conclusions on the Bending Strength of Fly Ash Concrete

1. The bending strengths of both fly ash and plain concrete beams are in the range of 8.7% to 10.1% of the compressive strengths.
2. The splitting tensile strength is slightly higher than that of the bending strength. It varies from 11.4% to 12.5% of the compressive strength.
3. It can be concluded that the bending and splitting tensile strengths of fly ash concrete can be estimated in the same manner as plain concrete.

6.12 Conclusions on the Fly Ash Concrete Strength Model

1. The proposed fly ash concrete strength model is in the form of

$$\sigma(\%) = 0.010C^2+[6.74-0.00528FM]+\{(B/FM)\ln(T)\}$$

where $\sigma(\%)$ is the percentage compressive strength of fly ash concrete compared to the control concrete, C is the percentage of cement in the cementitious materials, FM is the fineness modulus of fly ash, B is the constant of the pozzolanic activity rate between fly ash and cement, and T is the age of concrete.

2. The results predicted by the model are in good agreement with the results of fractionated fly ash concrete obtained in this study and, other researchers.

6.13 Suggestions for Future Work

1. Study the effect of fractionated fly ash concrete to resist acid attack when the concrete is mixed with superplasticizer or water reducing agent. Also, study

the effect of fractionated fly ash concrete under attack by different kinds of acids.

2. Study the effect of the single size of fly ash on the strength of concrete. This means that the fractionated fly ashes will have a very narrow particle size distribution.

APPENDIX A

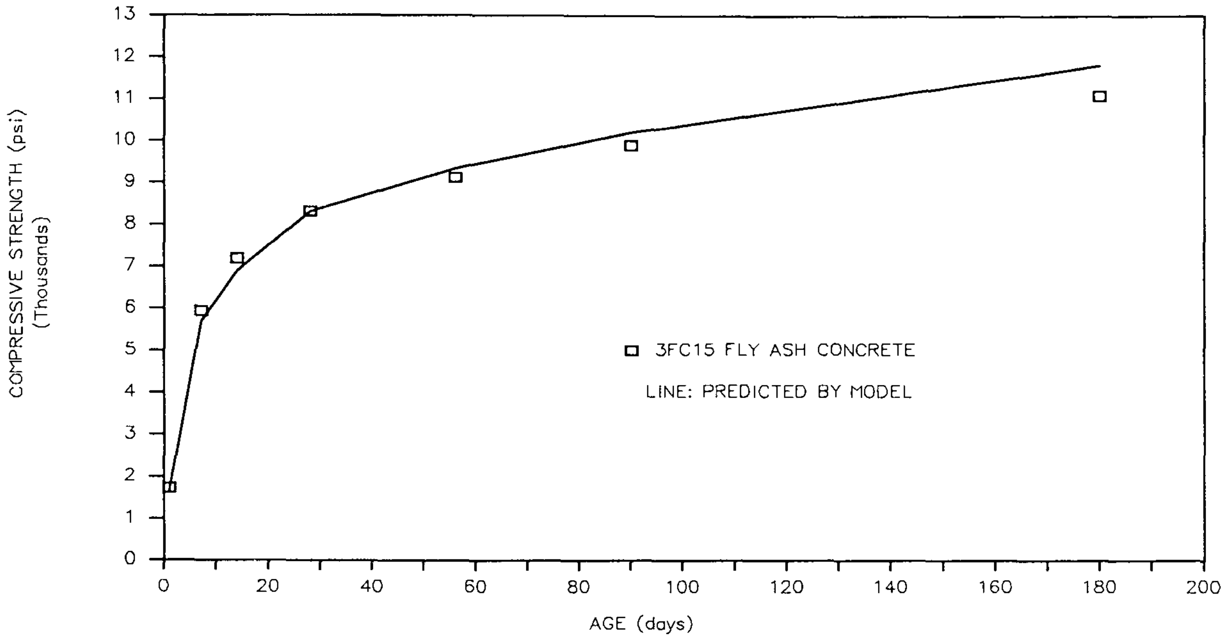

Figure A 1 Compressive Strength of the Fractionated 3F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

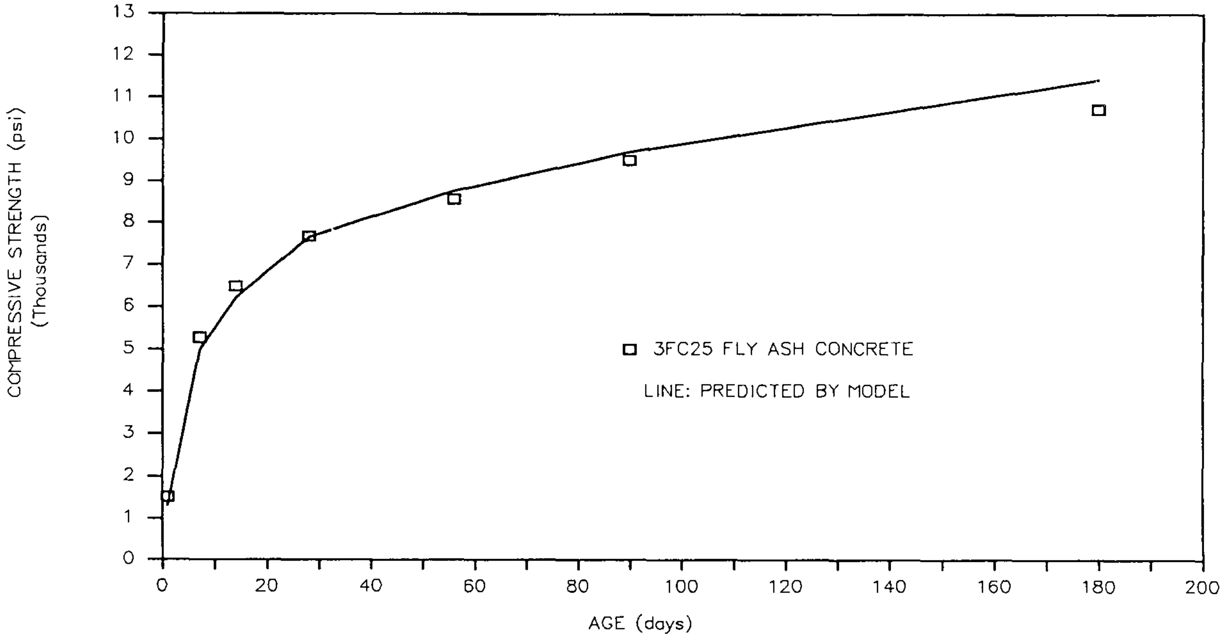

Figure A 2 Compressive Strength of the Fractionated 3F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

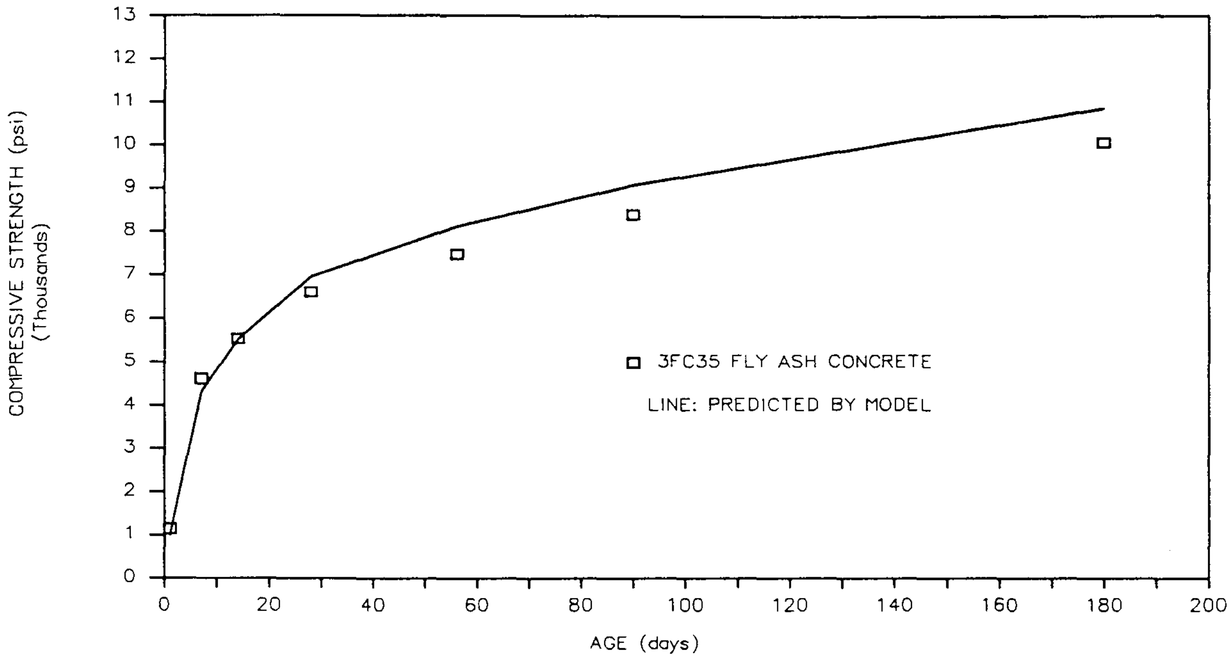

Figure A 3 Compressive Strength of the Fractionated 3F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

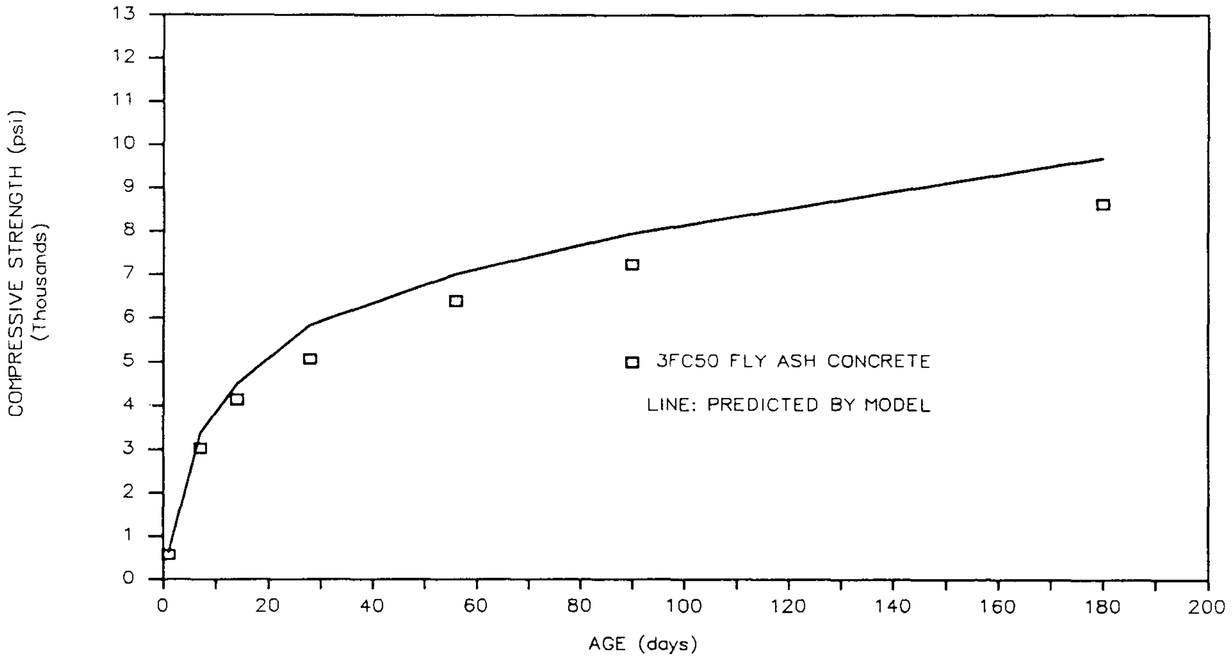

Figure A 4 Compressive Strength of the Fractionated 3F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

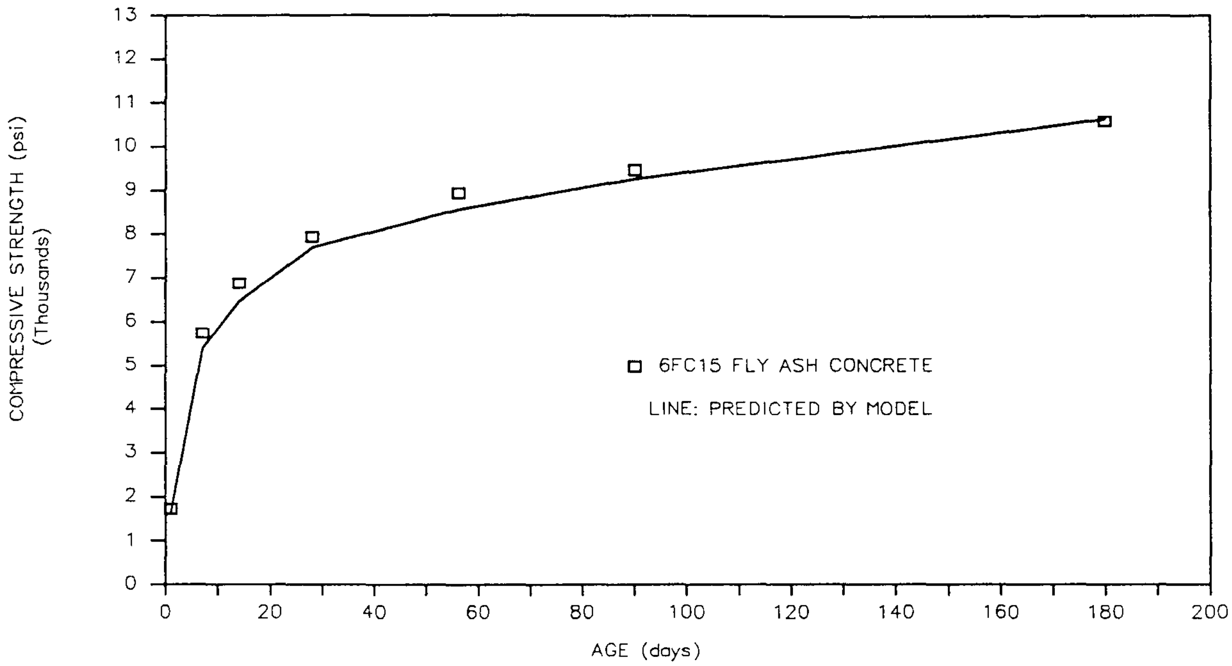

Figure A 5 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

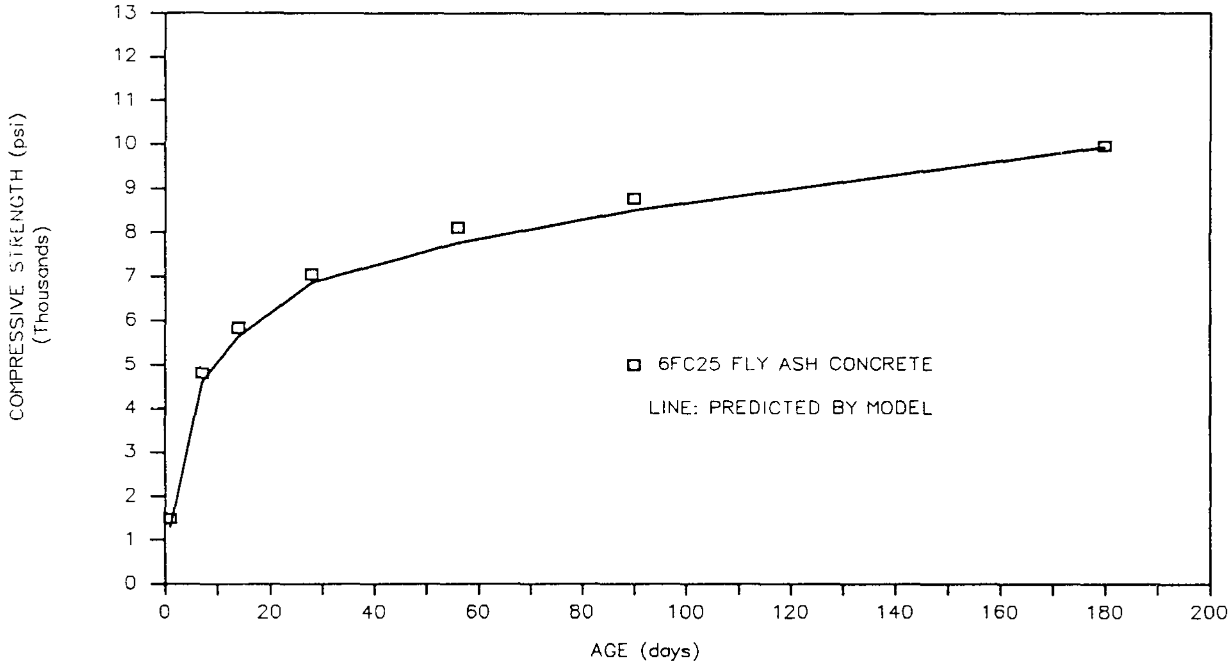

Figure A 6 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

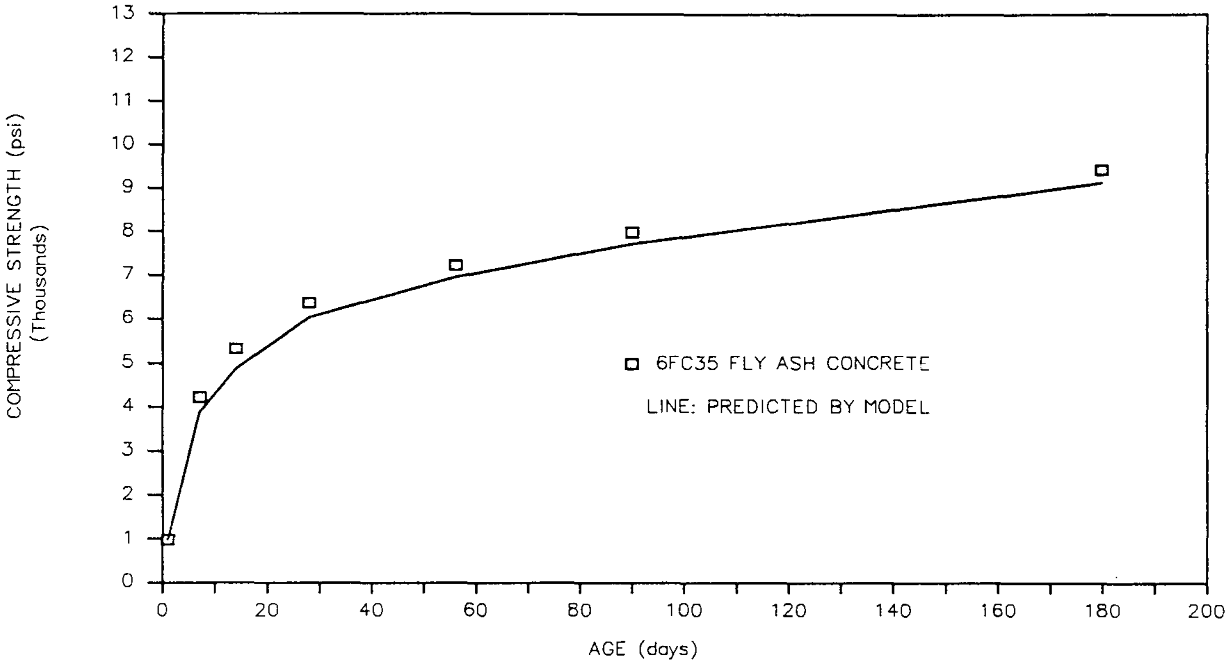

Figure A 7 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

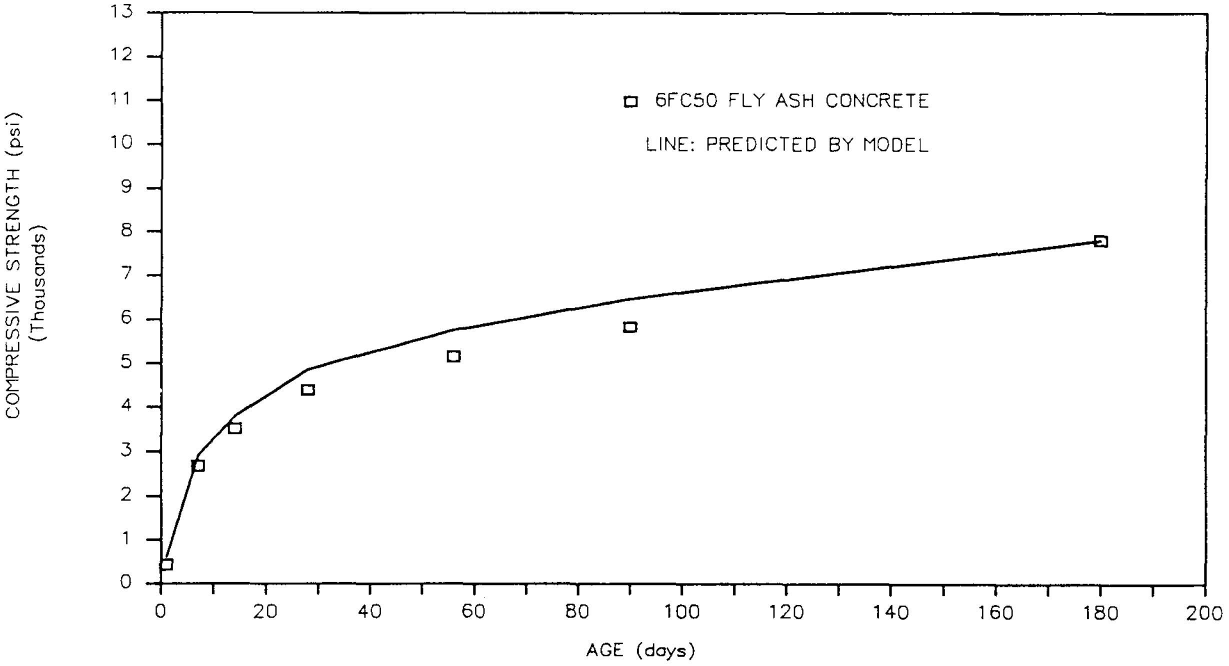

Figure A 8 Compressive Strength of the Fractionated 6F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

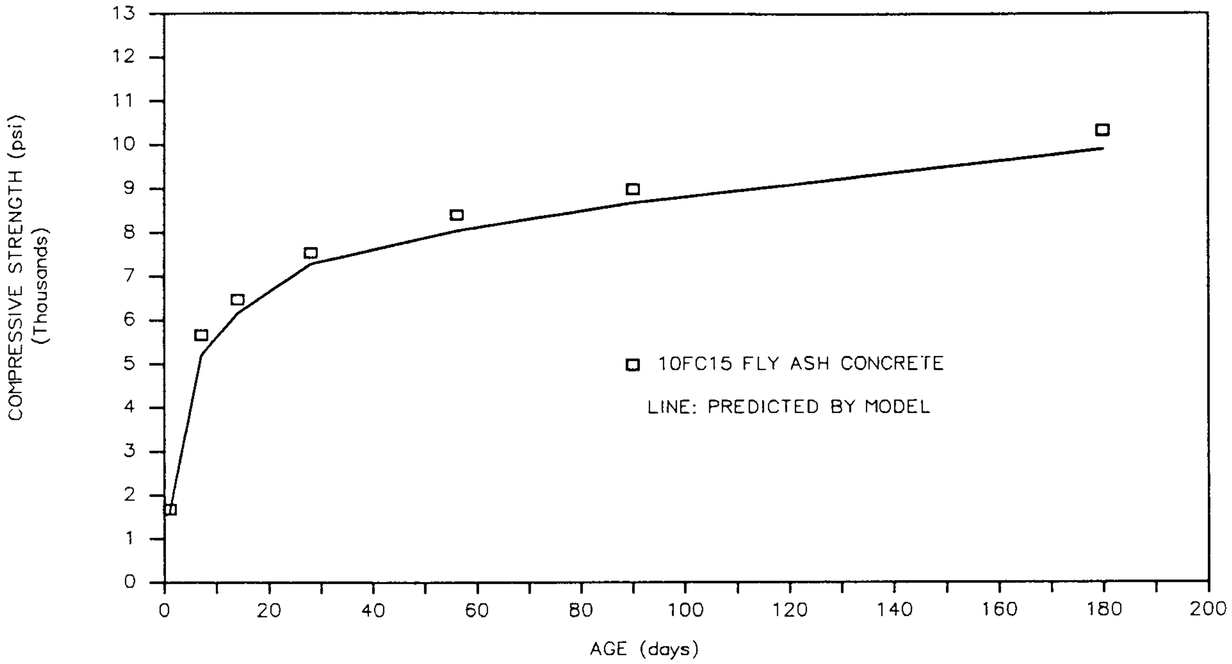

Figure A 9 Compressive Strength of the Fractionated 10F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

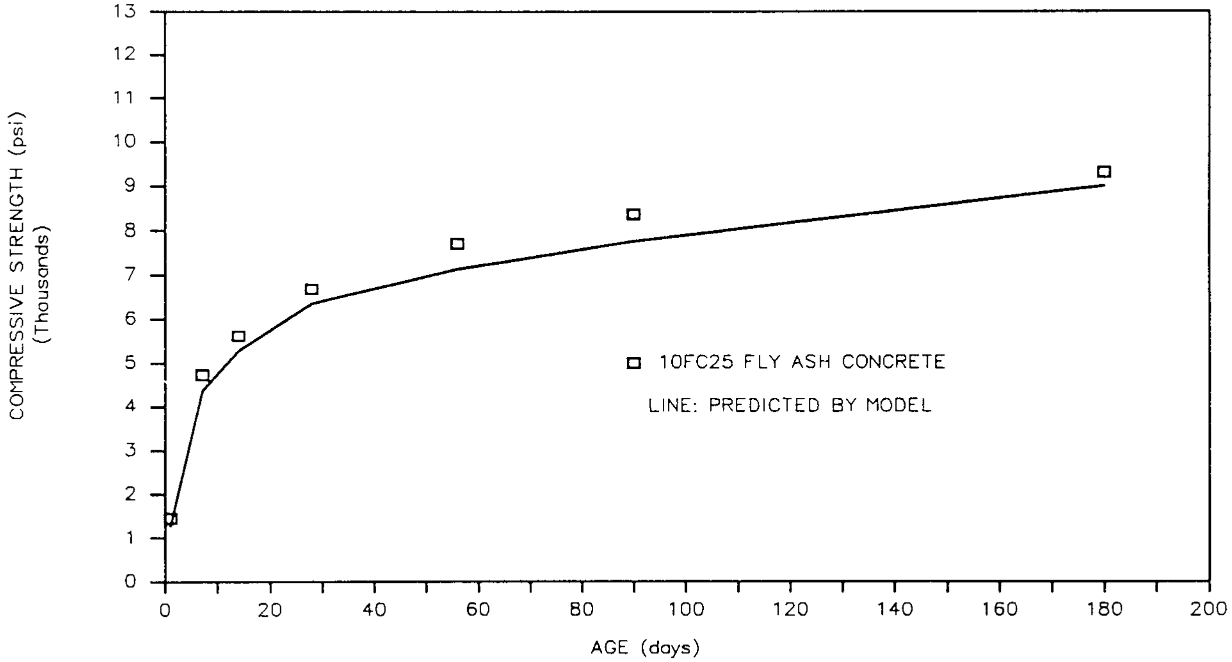

Figure A 10 Compressive Strength of the Fractionated 10F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

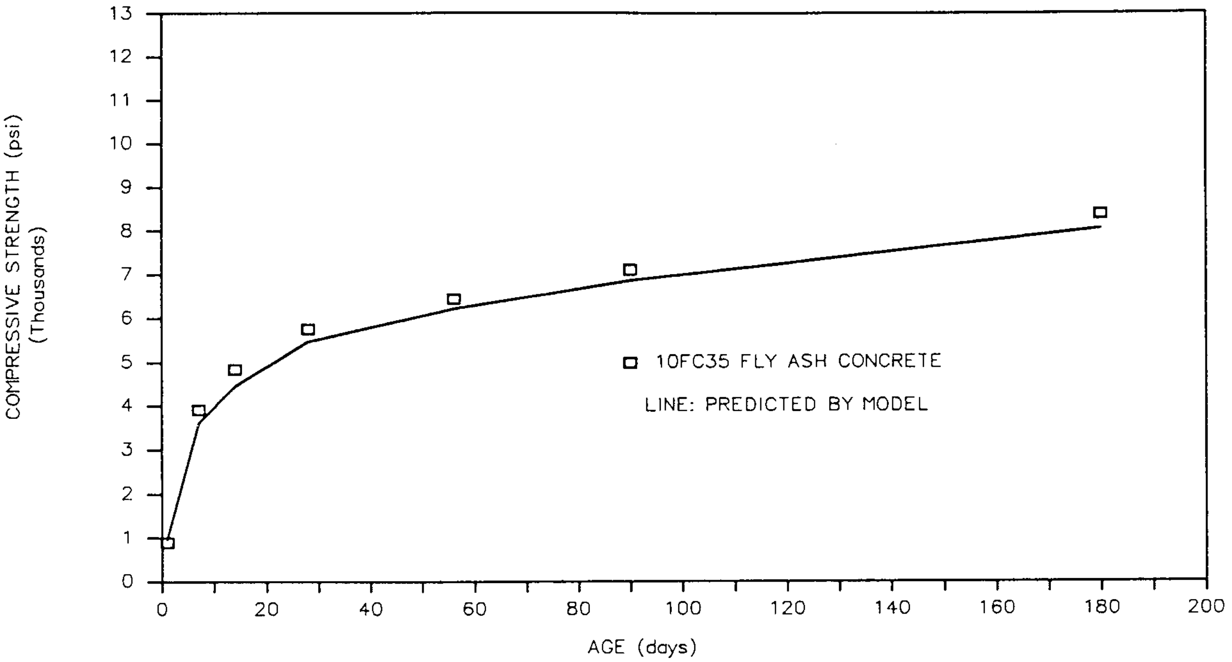

Figure A 11 Compressive Strength of the Fractionated 10F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

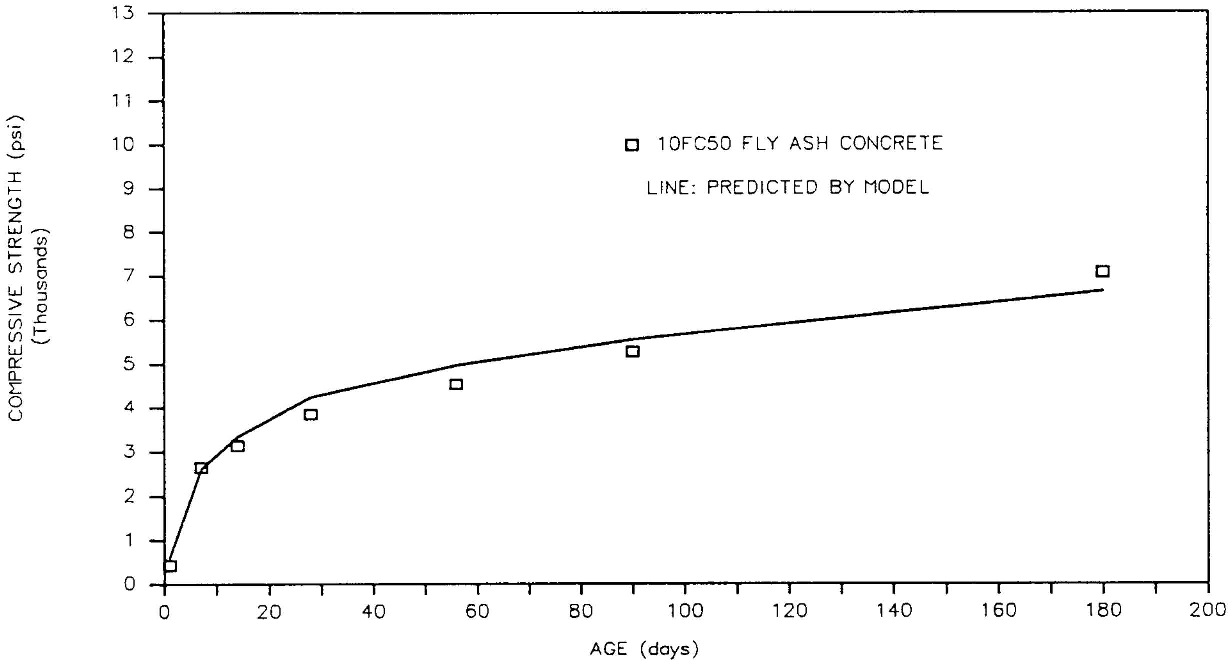

Figure A 12 Compressive Strength of the Fractionated 10F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

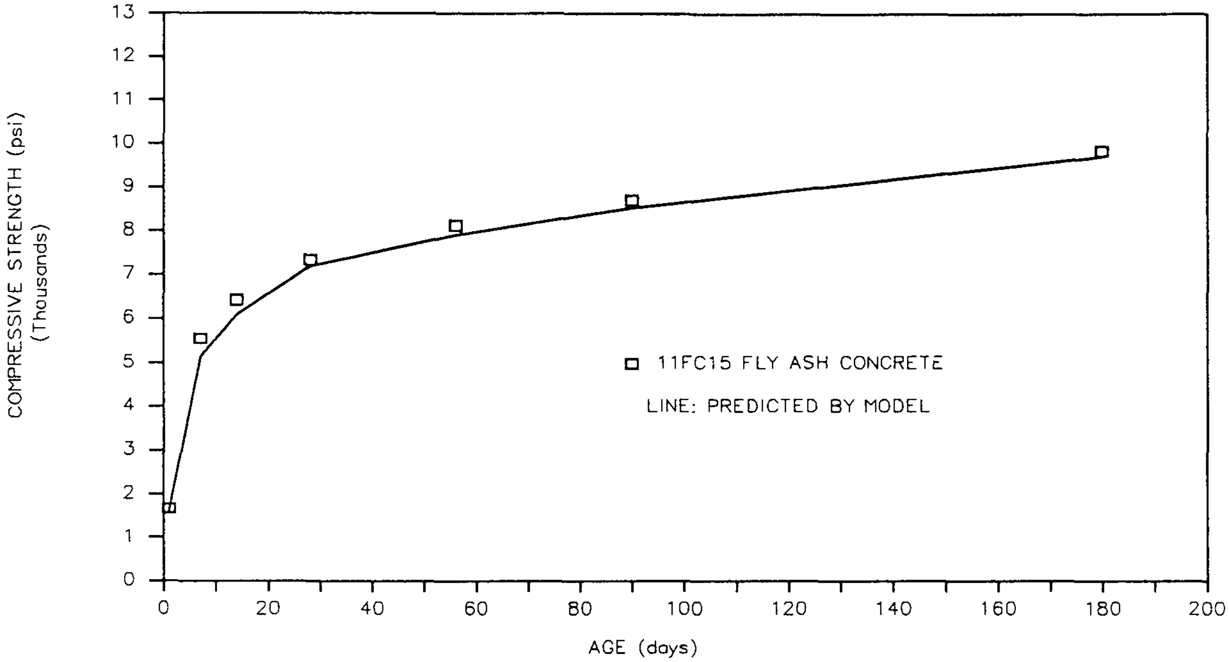

Figure A 13 Compressive Strength of the Fractionated 11F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

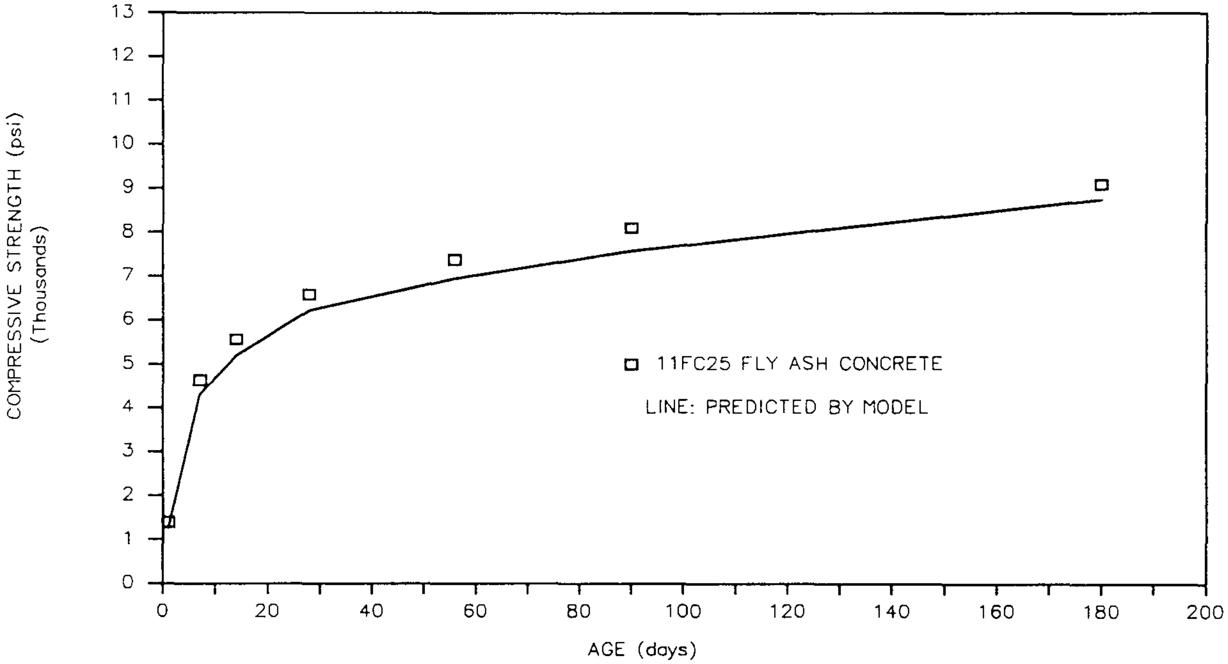

Figure A 14 Compressive Strength of the Fractionated 11F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

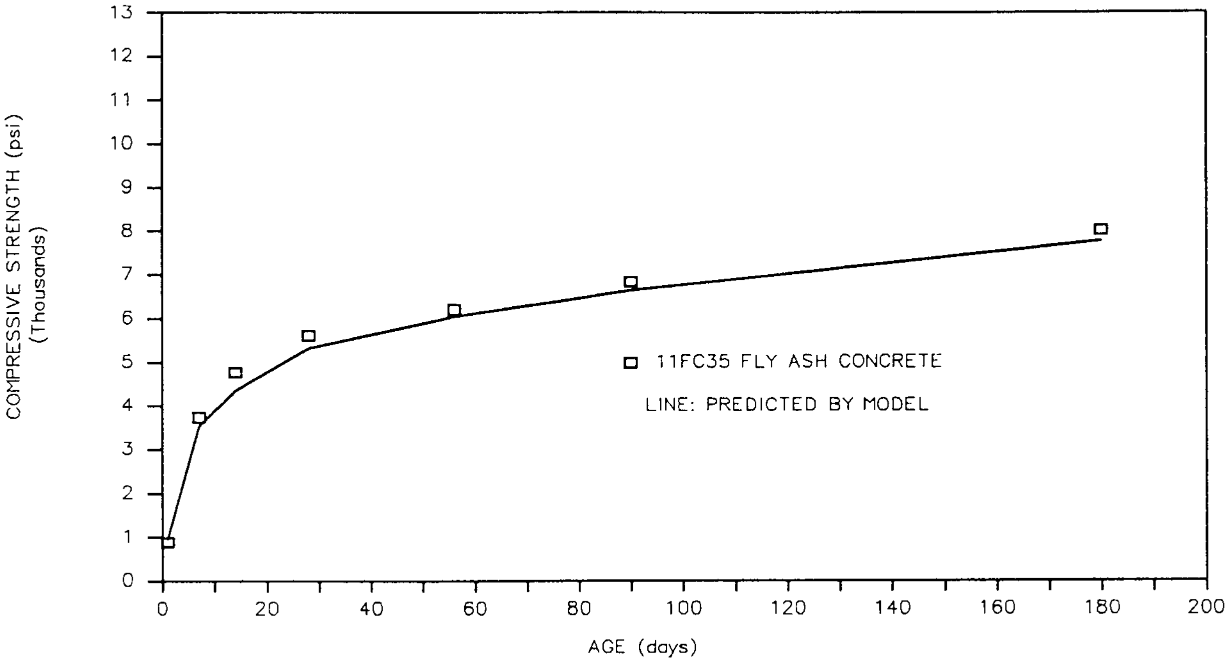

Figure A 15 Compressive Strength of the Fractionated 11F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

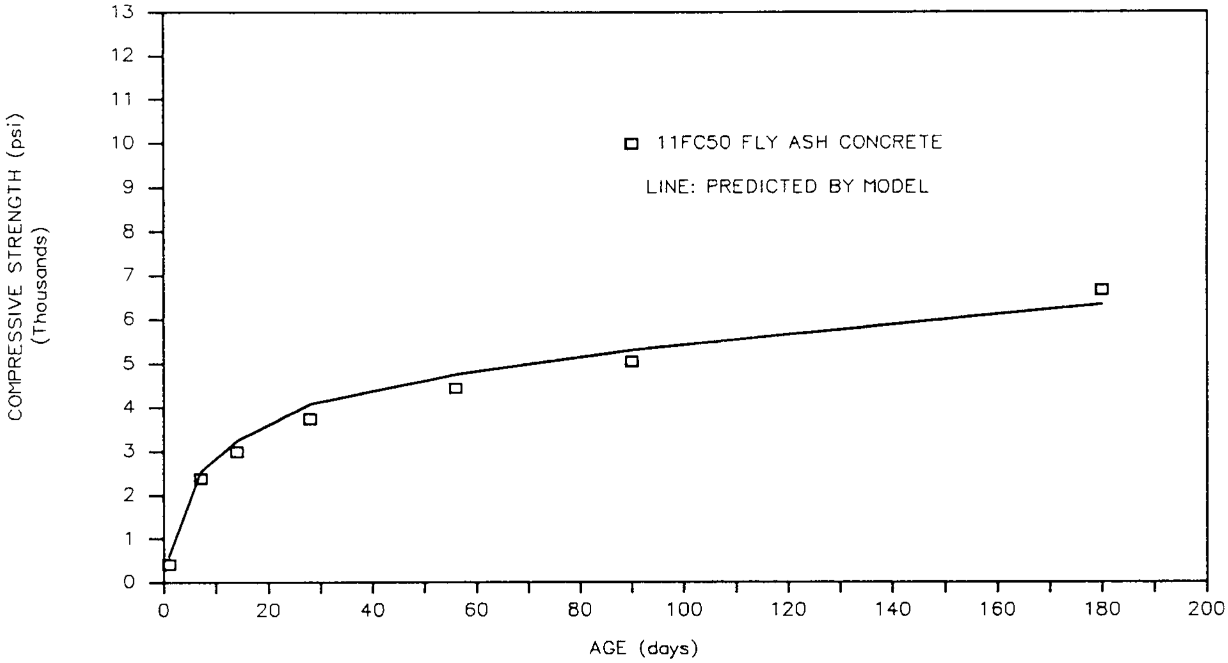

Figure A 16 Compressive Strength of the Fractionated 11F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

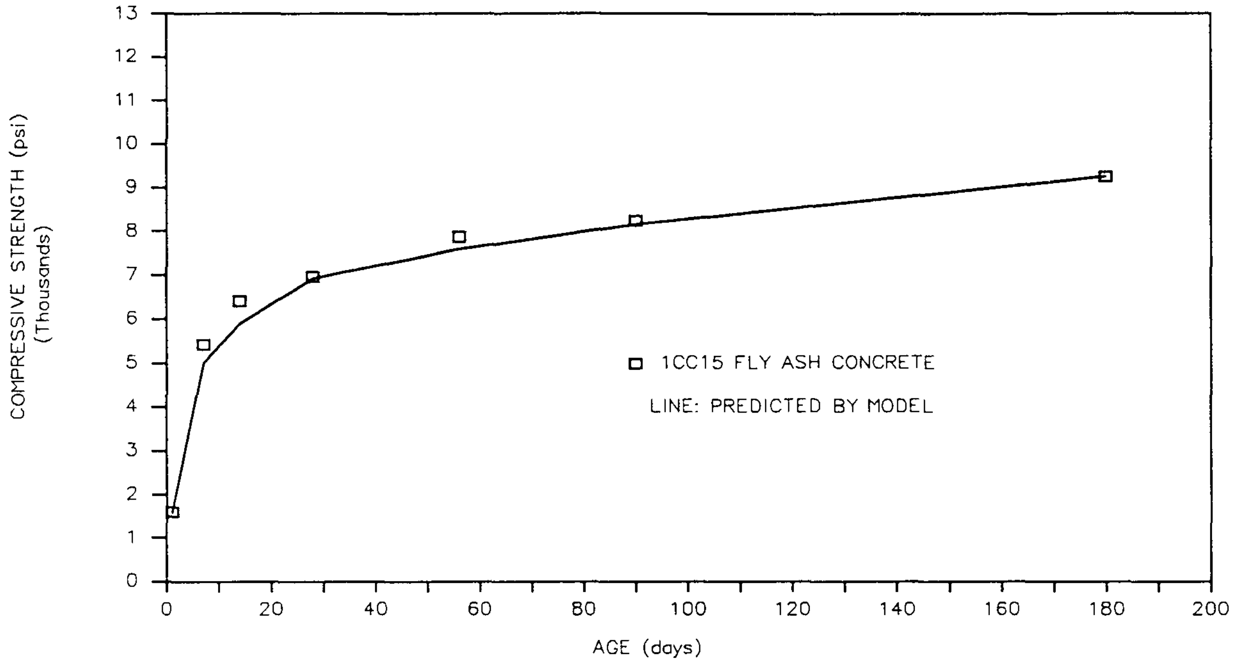

Figure A 17 Compressive Strength of the Fractionated 1CC Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

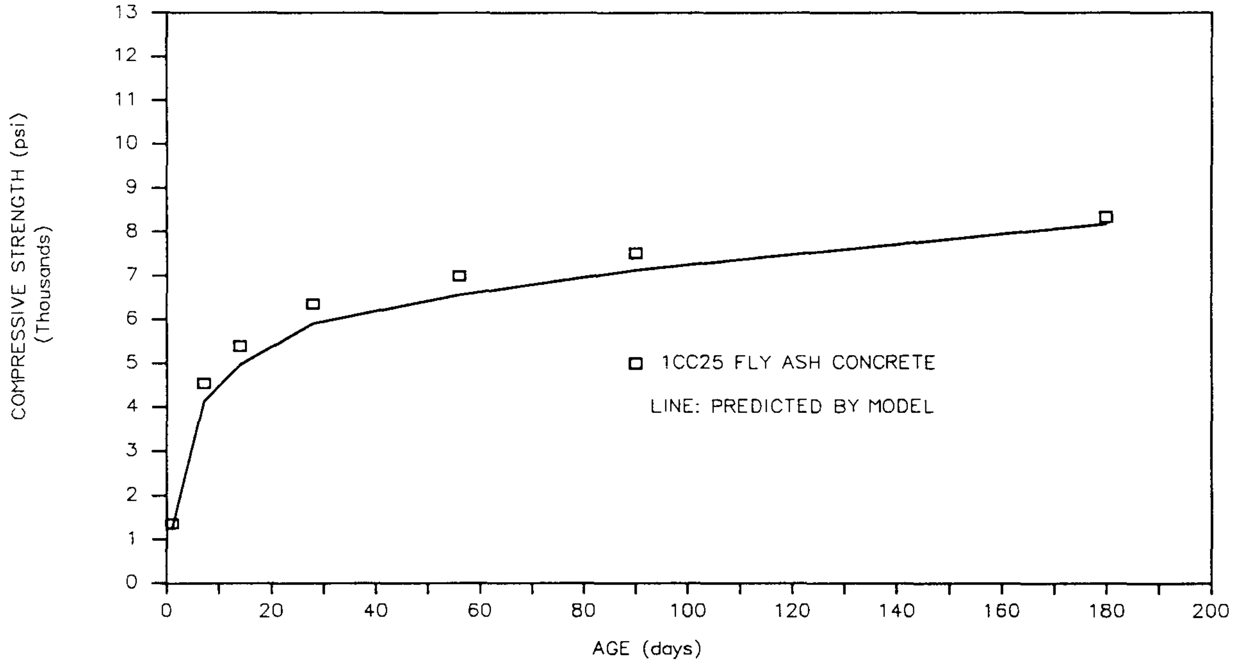

Figure A 18 Compressive Strength of the Fractionated 1CC Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

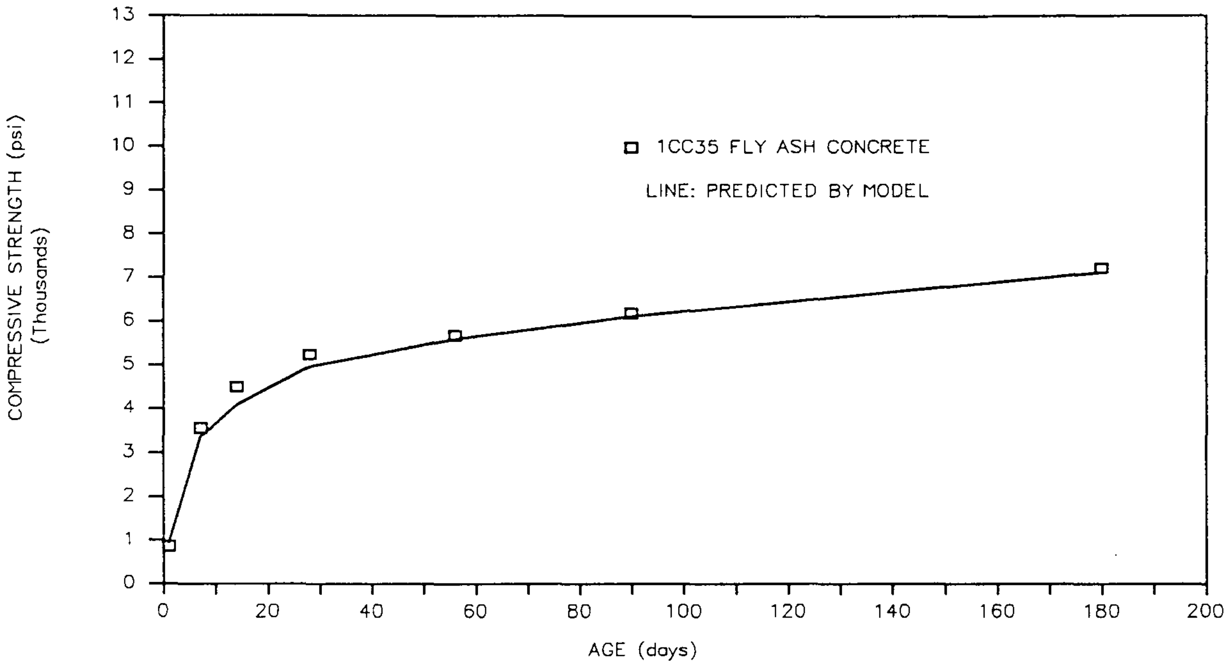

Figure A 19 Compressive Strength of the Fractionated 1CC Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

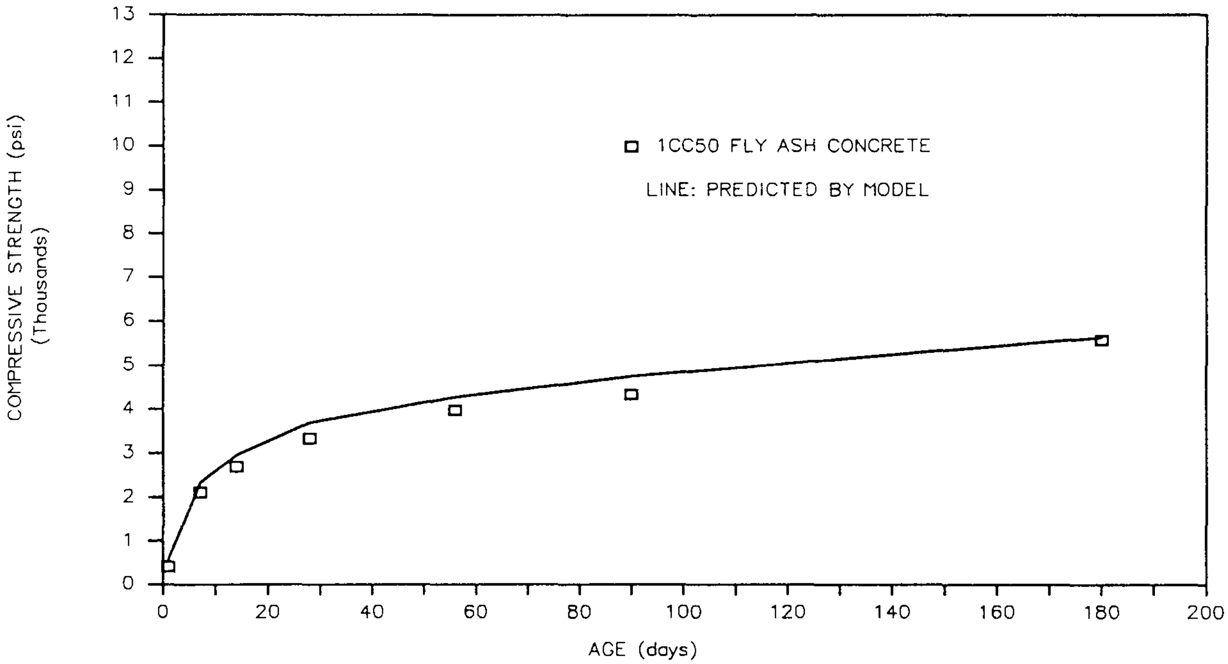

Figure A 20 Compressive Strength of the Fractionated 1CC Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

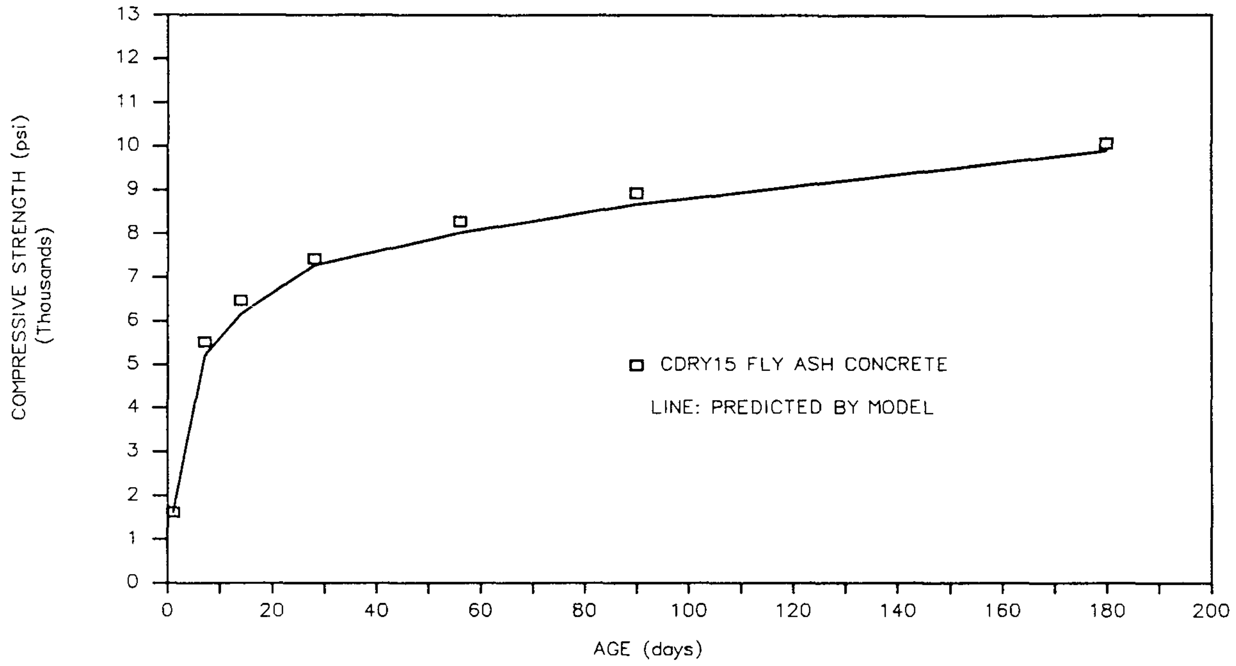

Figure A 21 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

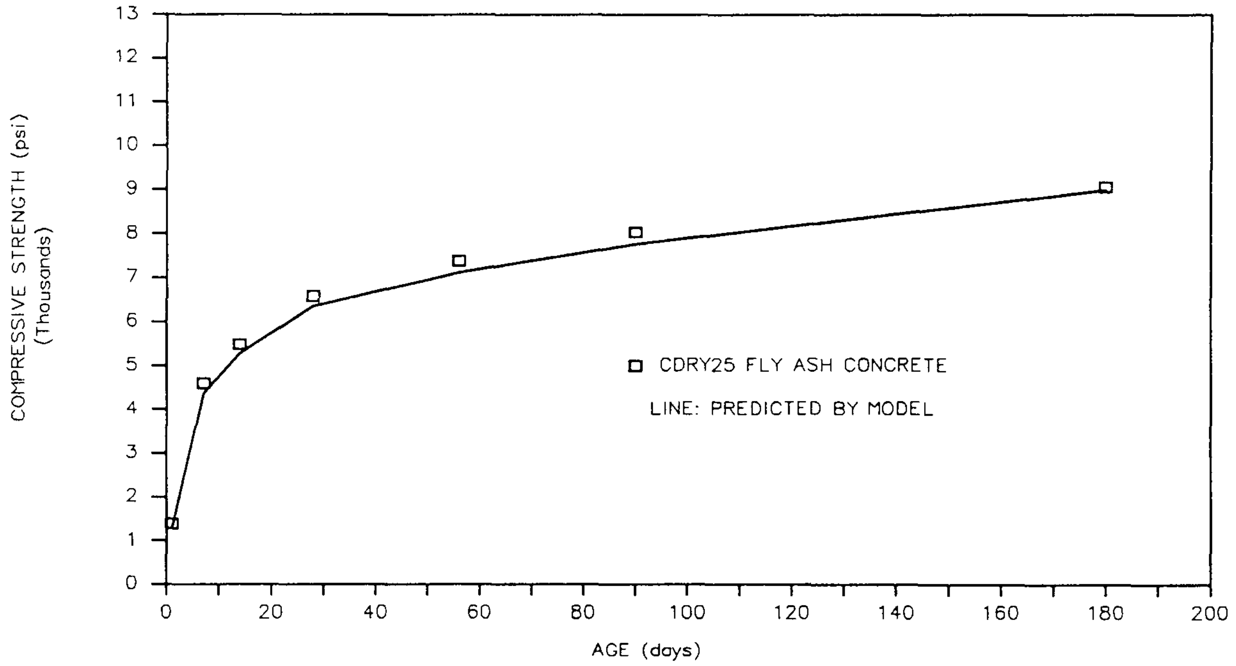

Figure A 22 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

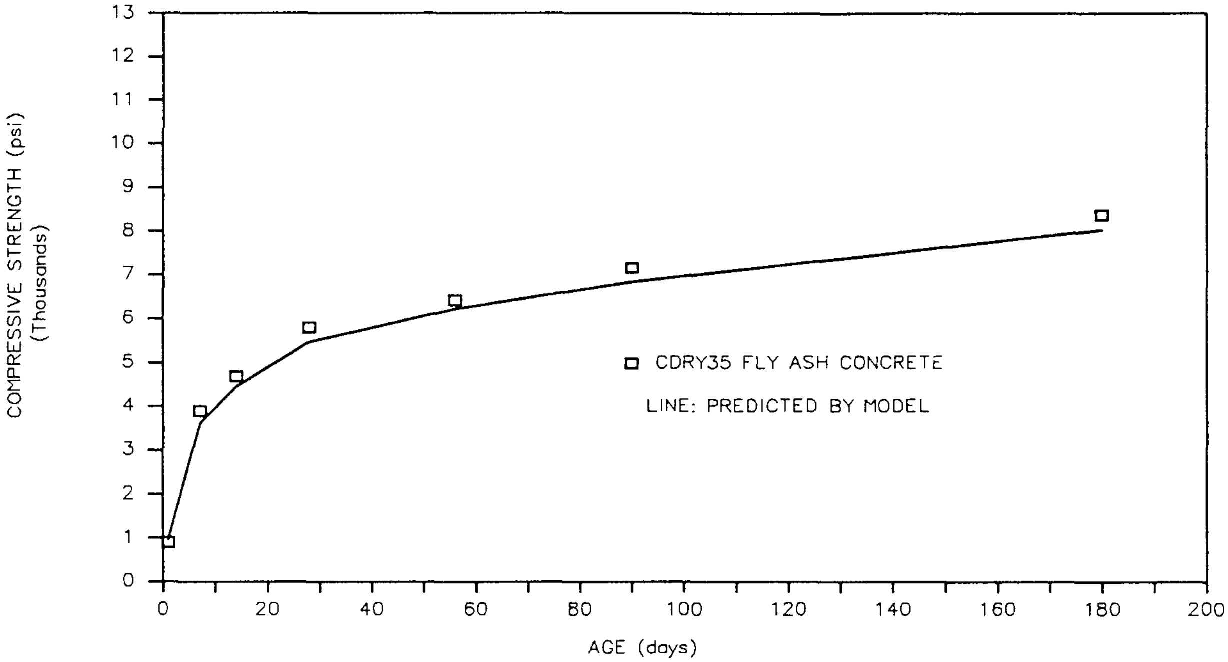

Figure A 23 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

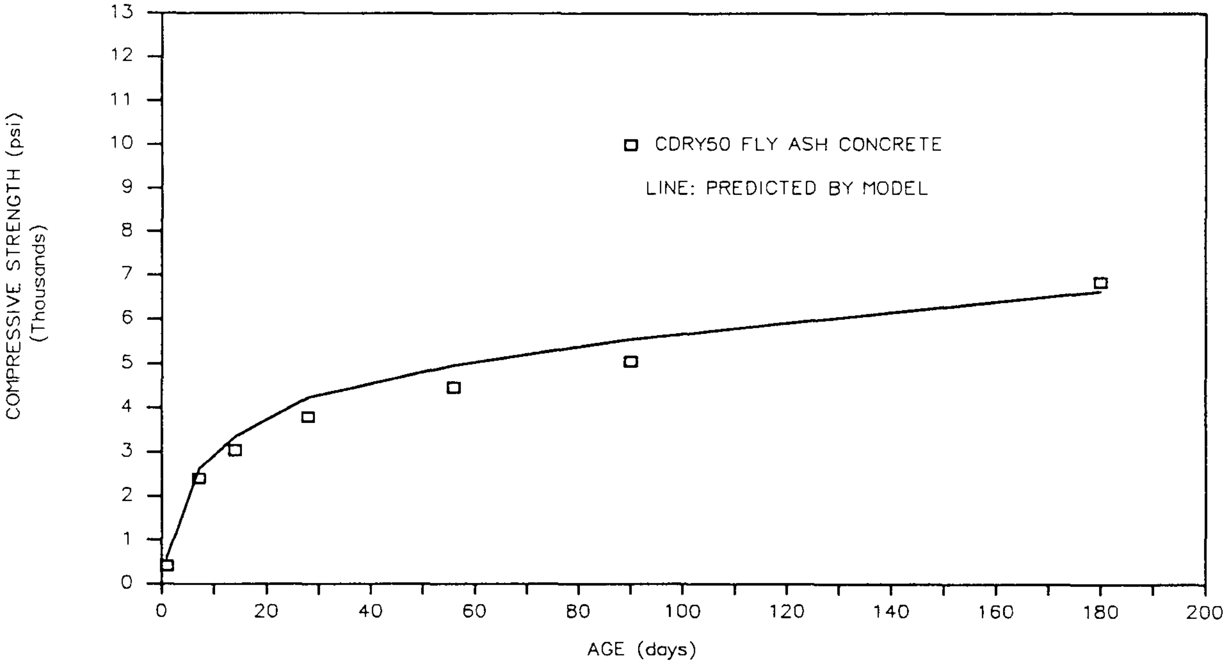

Figure A 24 Compressive Strength of the Original Feed of Dry Bottom Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

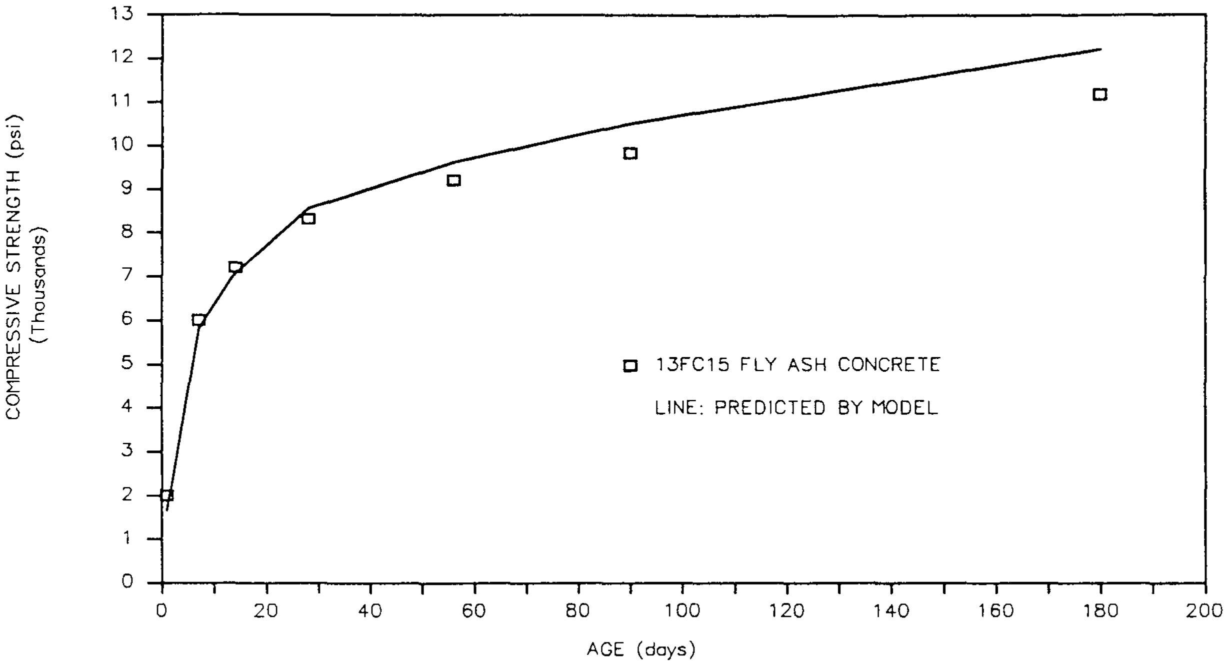

Figure A 25 Compressive Strength of the Fractionated 13F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

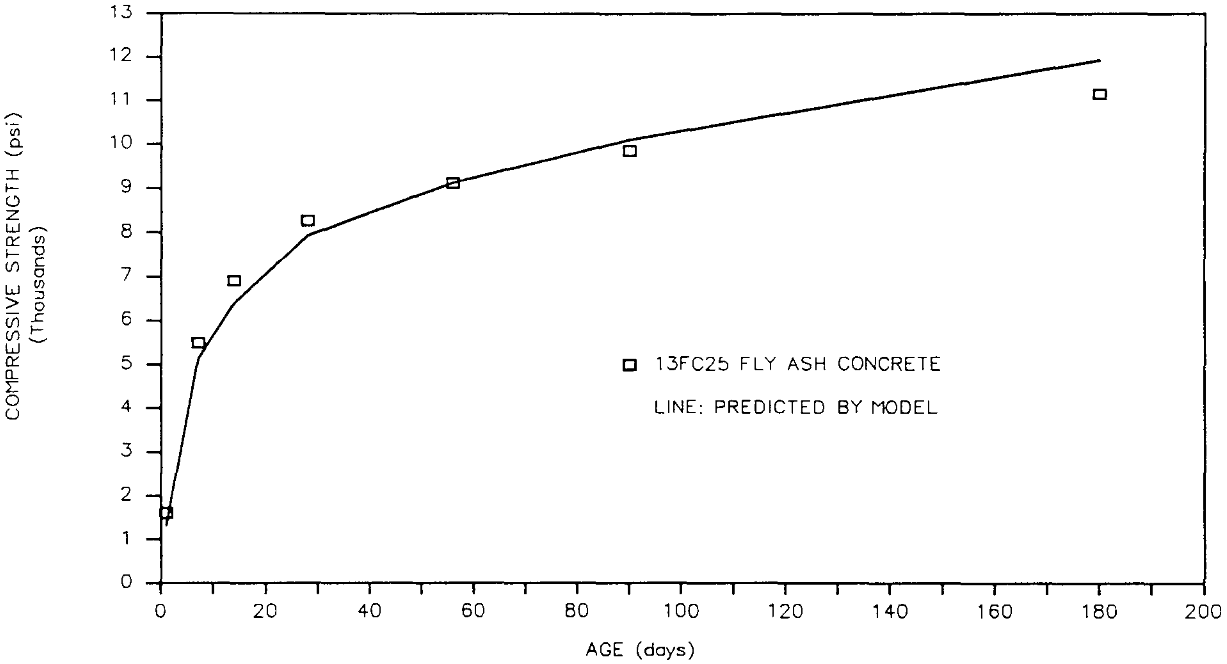

Figure A 26 Compressive Strength of the Fractionated 13F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

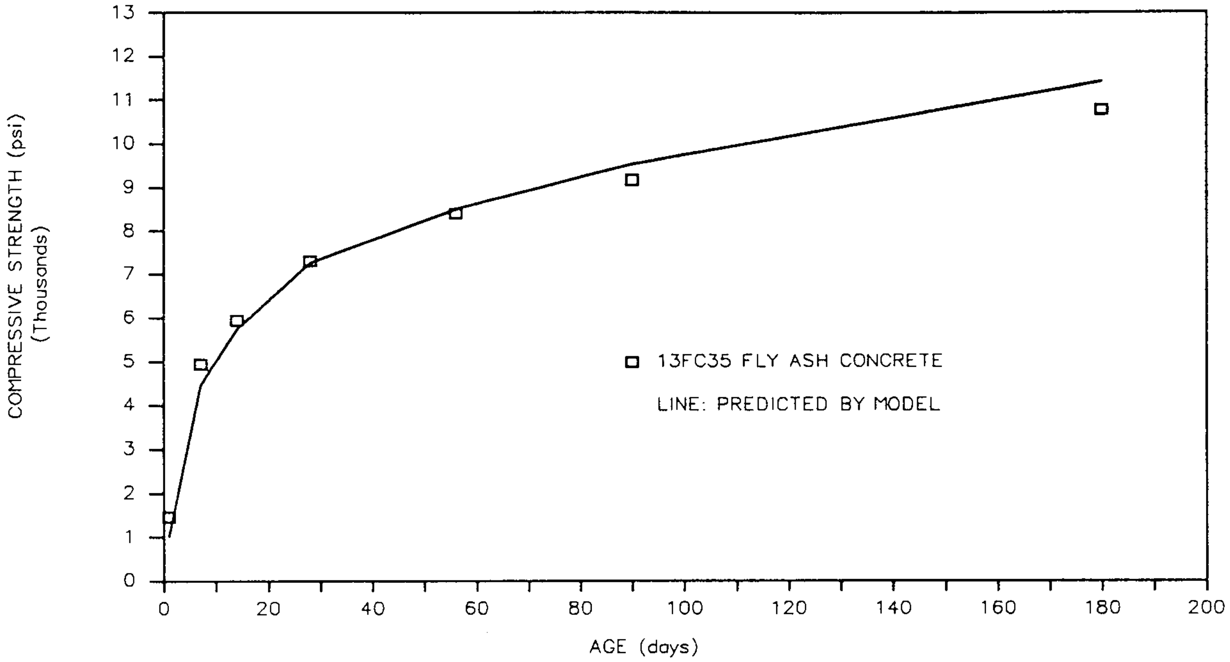

Figure A 27 Compressive Strength of the Fractionated 13F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

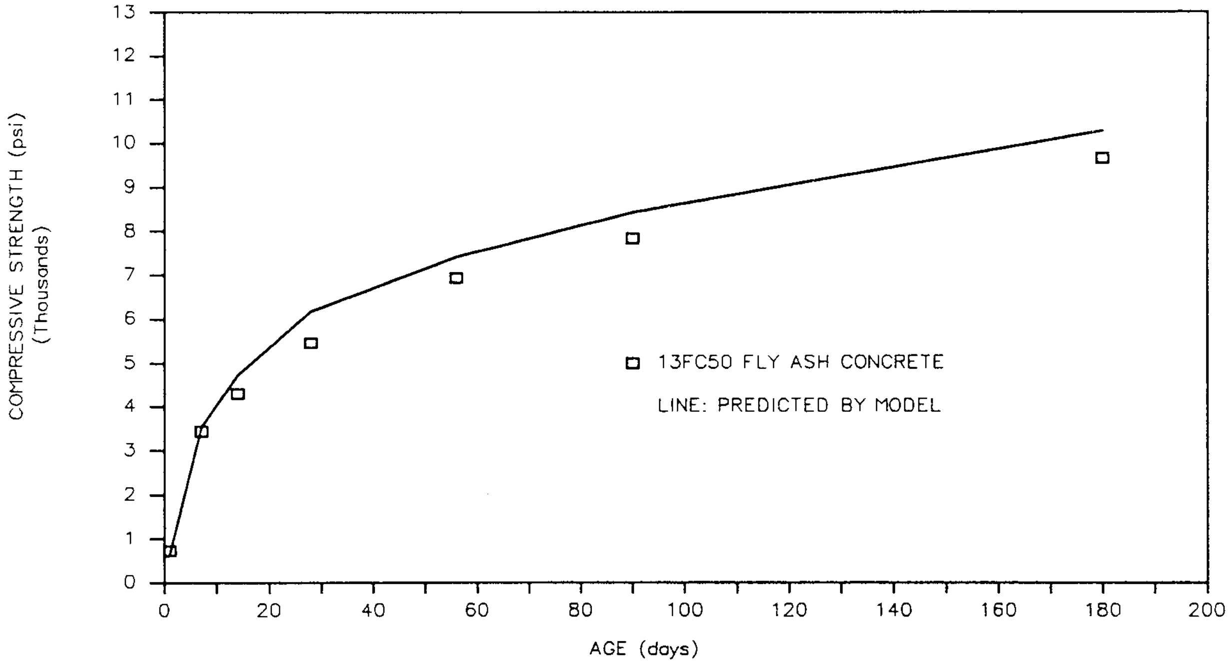

Figure A 28 Compressive Strength of the Fractionated 13F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

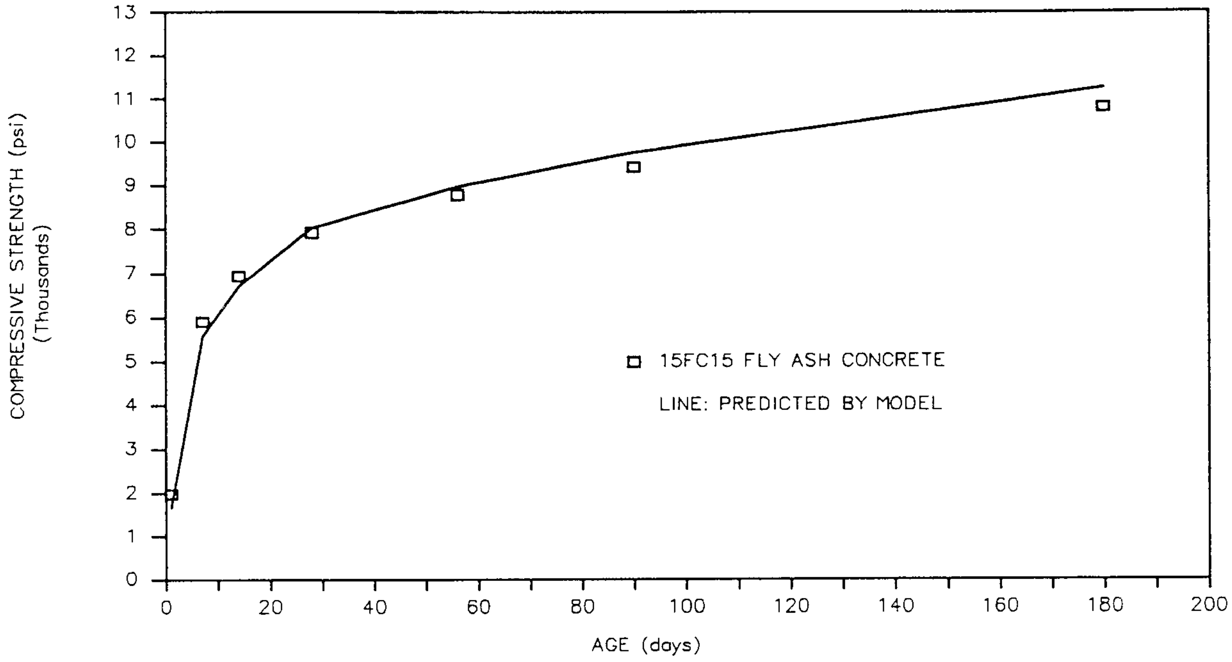

Figure A 29 Compressive Strength of the Fractionated 15F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

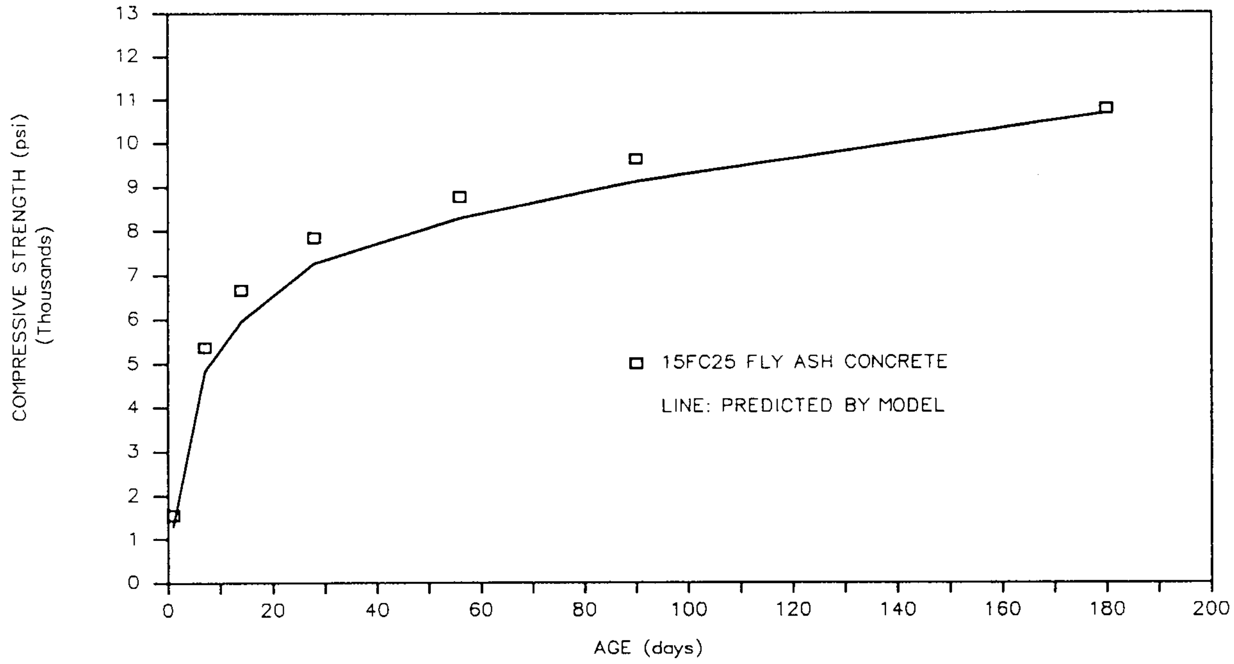

Figure A 30 Compressive Strength of the Fractionated 15F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

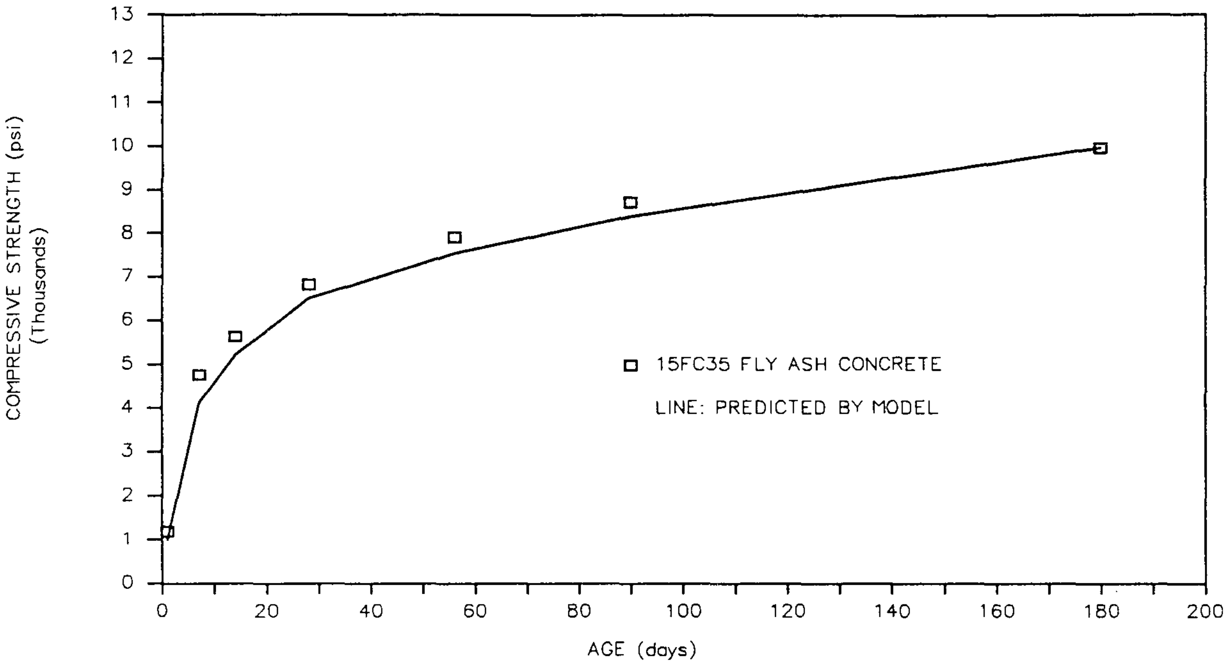

Figure A 31 Compressive Strength of the Fractionated 15F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

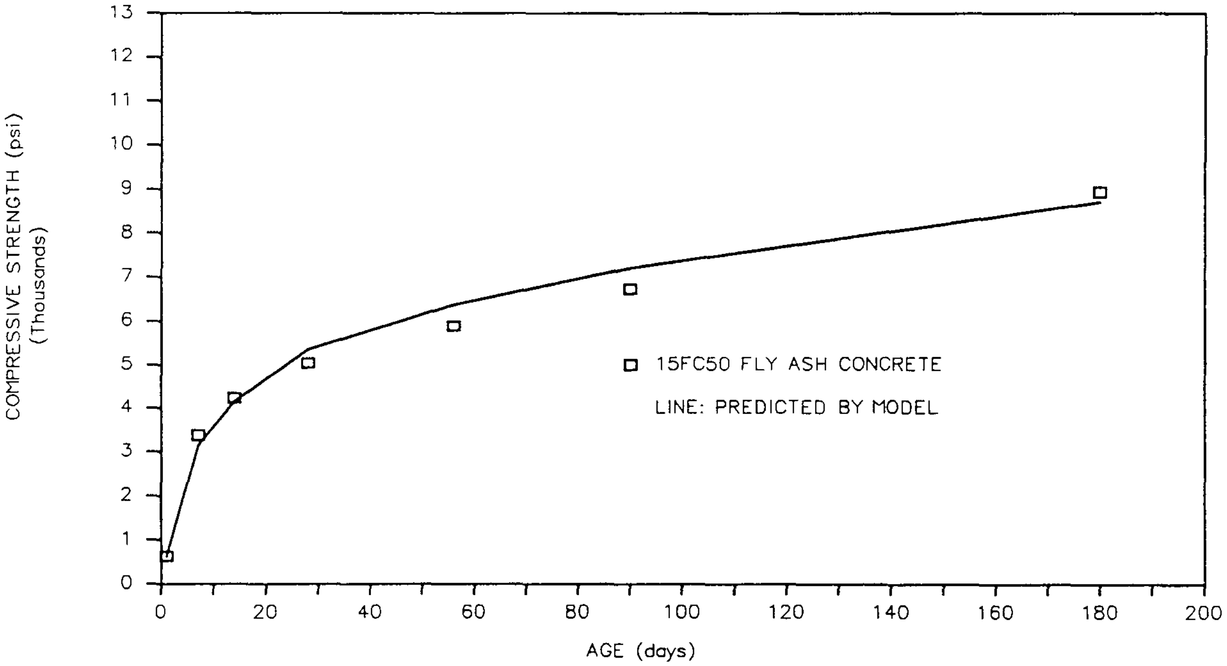

Figure A 32 Compressive Strength of the Fractionated 15F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

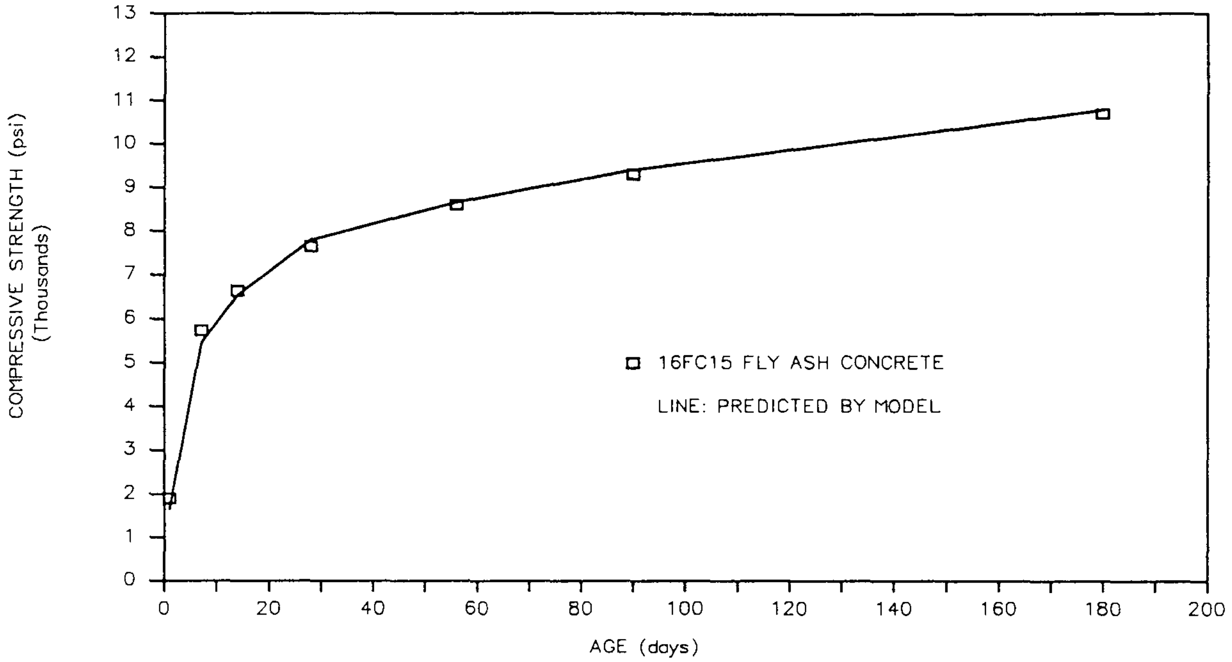

Figure A 33 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

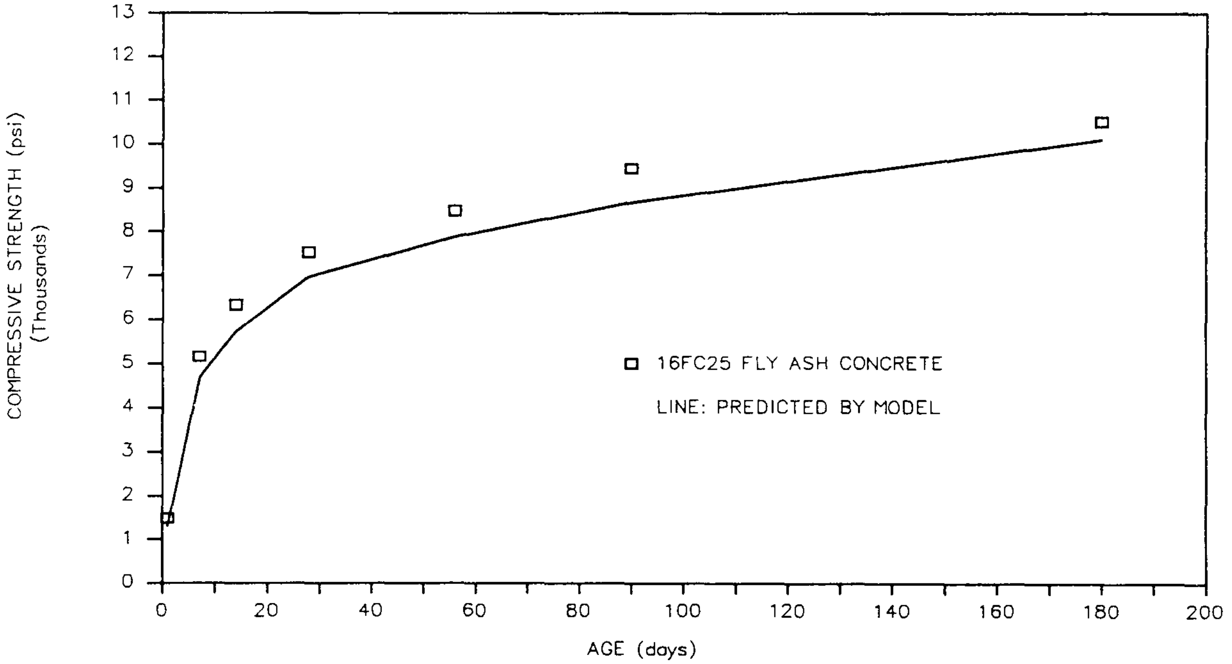

Figure A 34 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

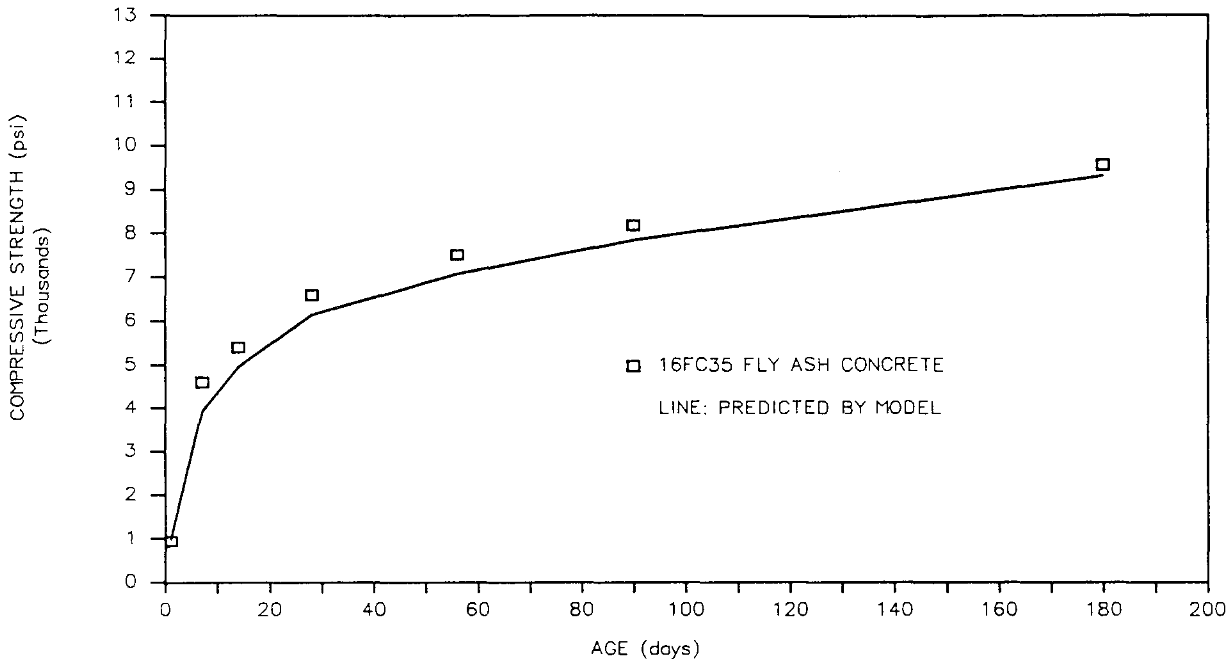

Figure A 35 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

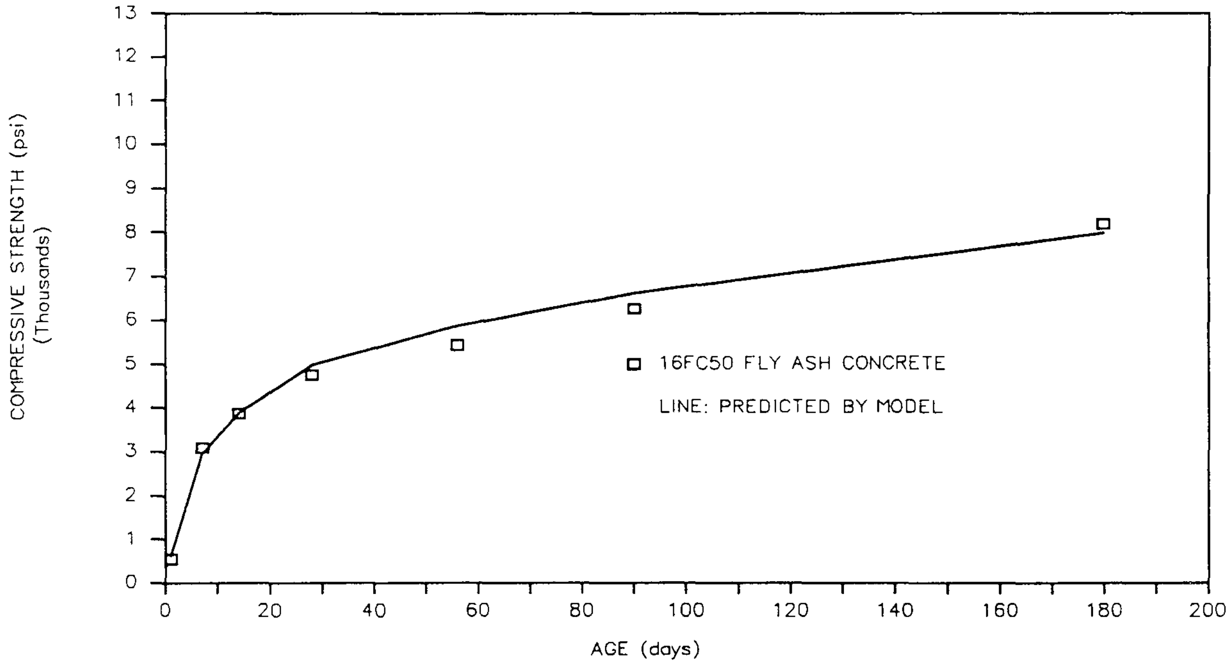

Figure A 36 Compressive Strength of the Fractionated 16F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

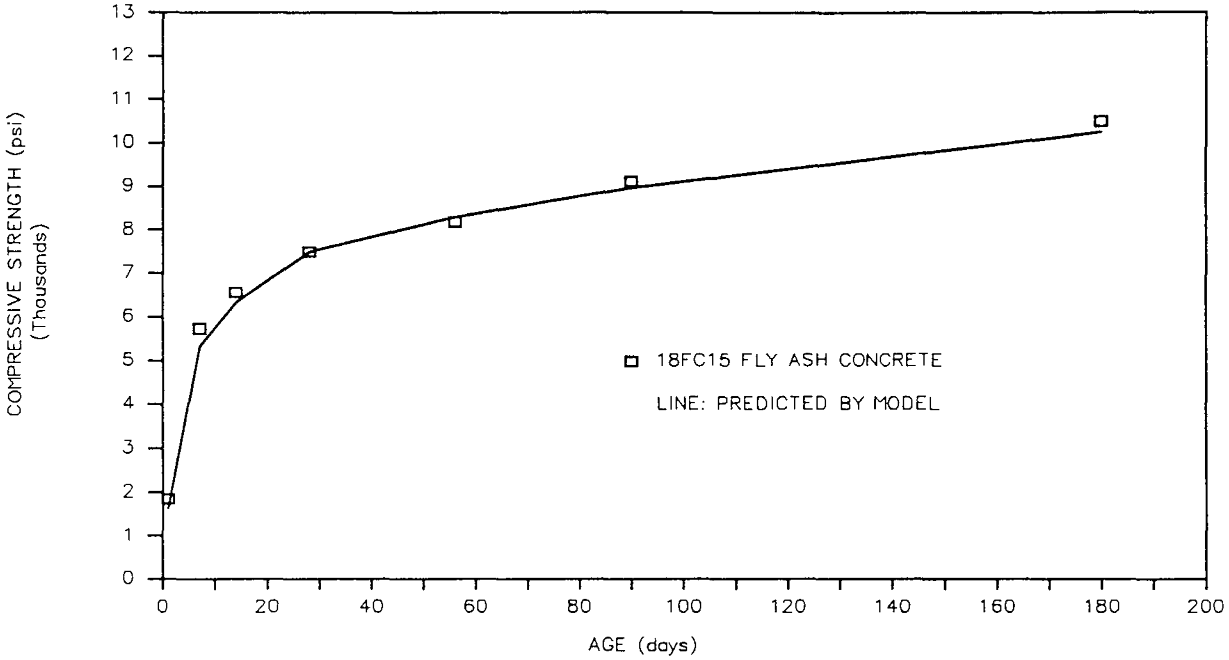

Figure A 37 Compressive Strength of the Fractionated 18F Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

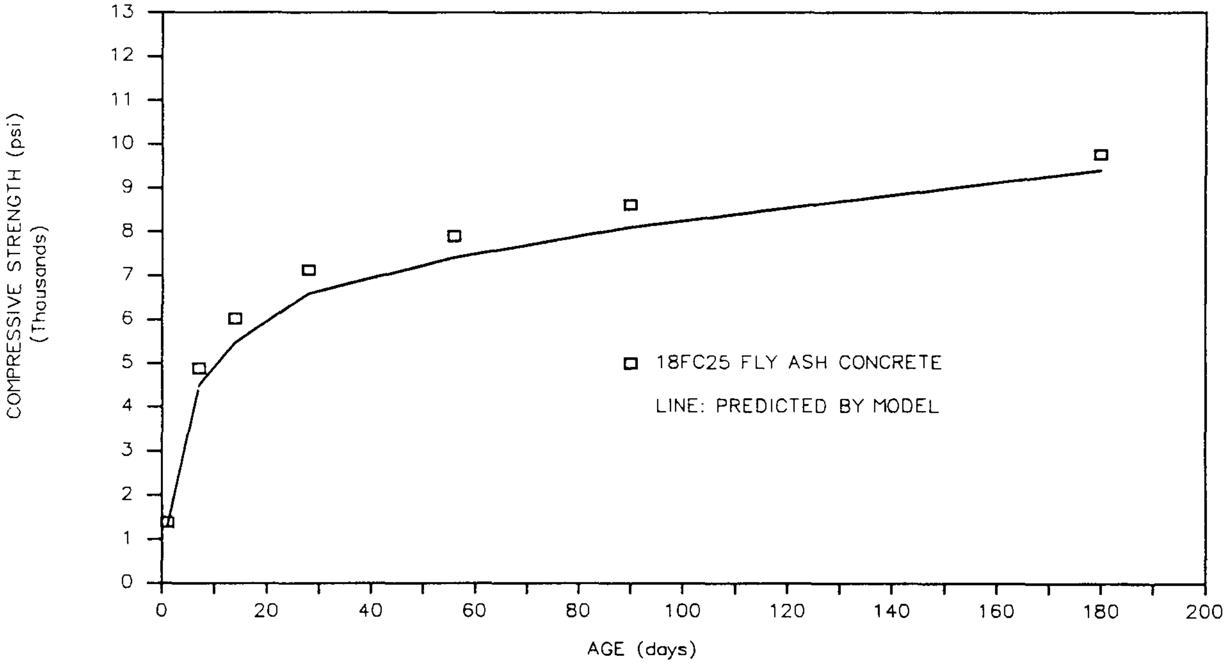

Figure A 38 Compressive Strength of the Fractionated 18F Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

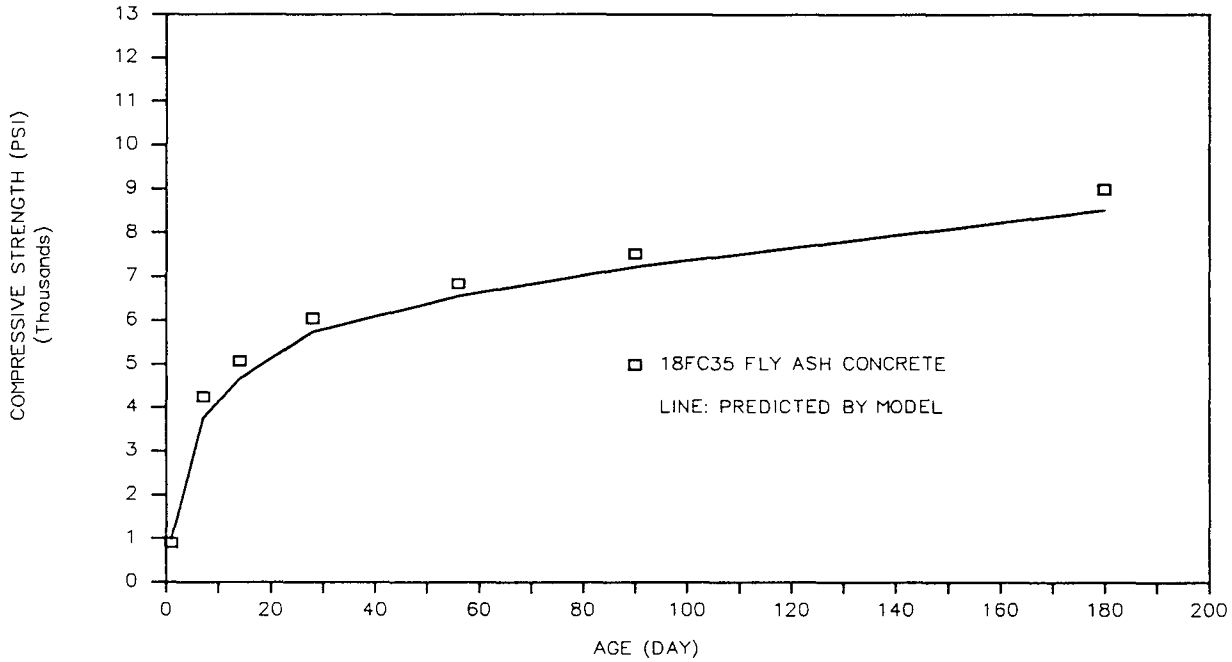

Figure A 39 Compressive Strength of the Fractionated 18F Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

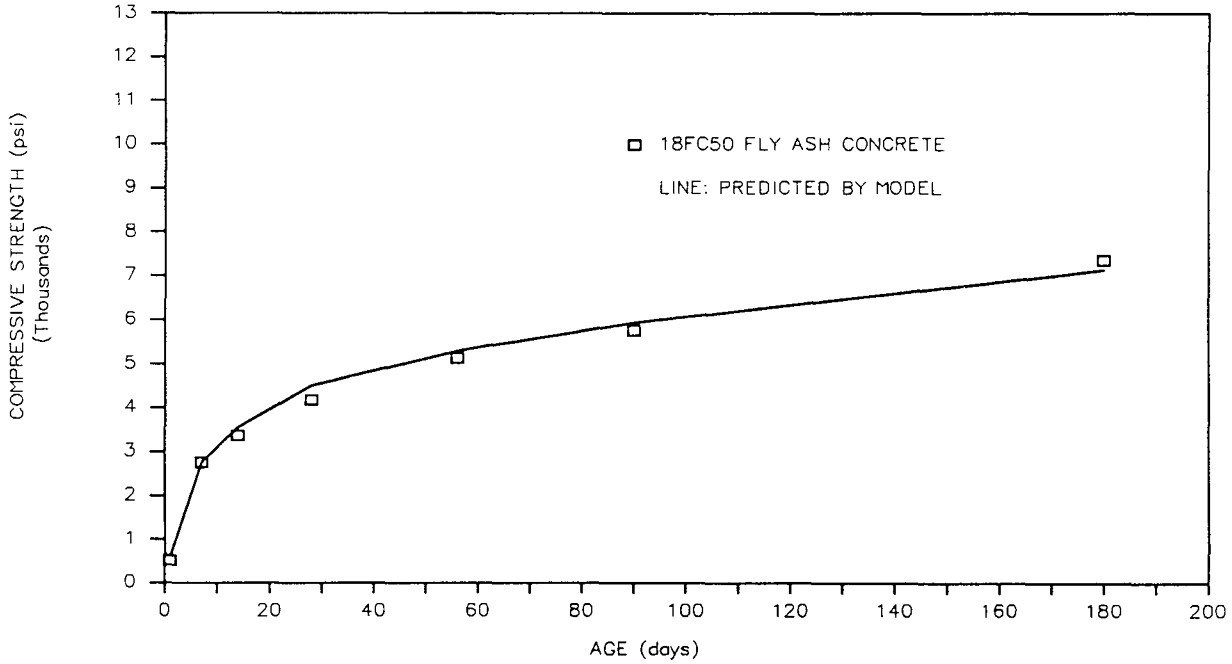

Figure A 40 Compressive Strength of the Fractionated 18F Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

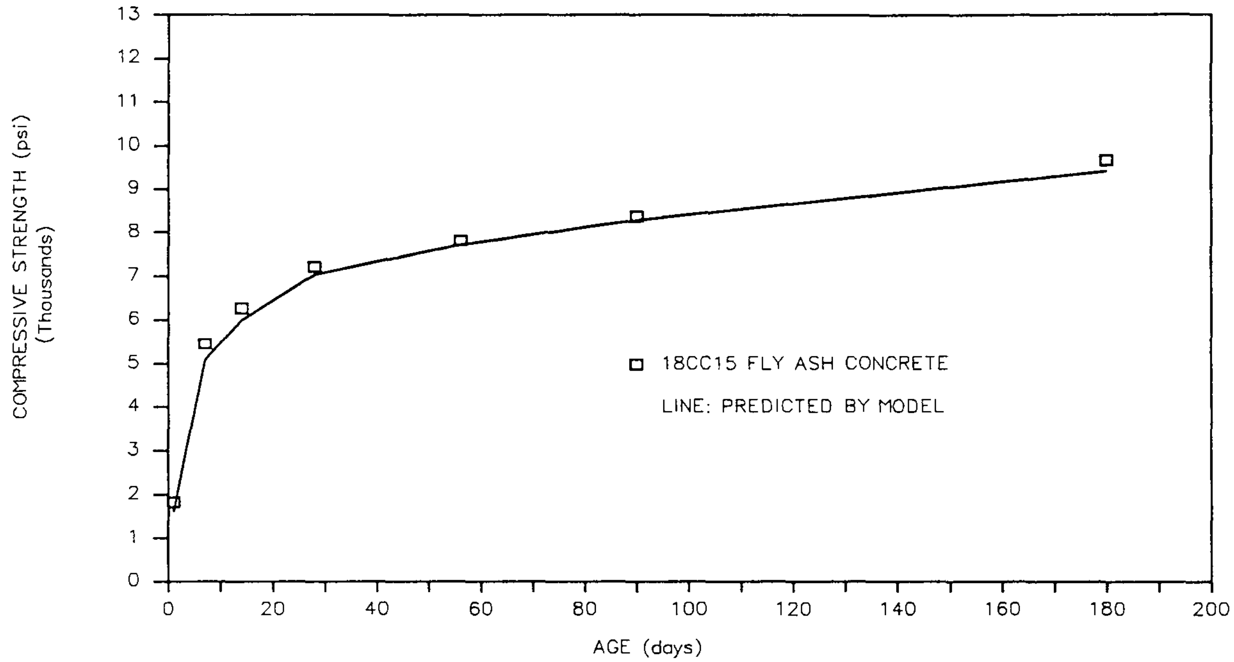

Figure A 41 Compressive Strength of the Fractionated 18C Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

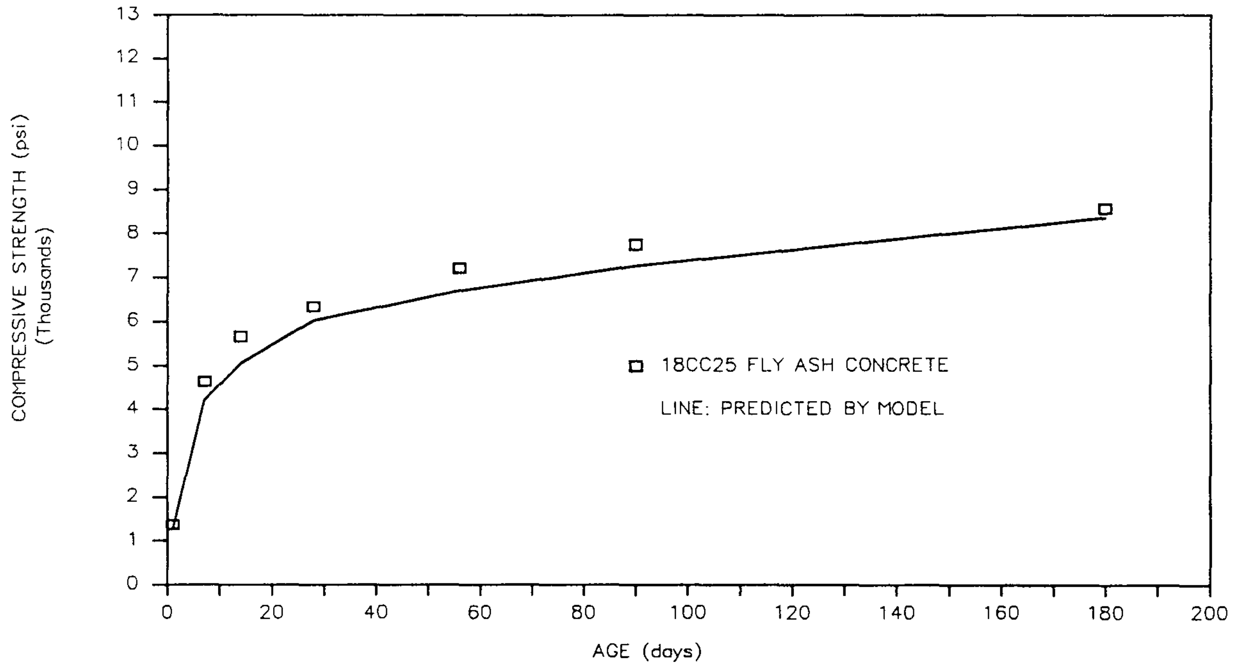

Figure A 42 Compressive Strength of the Fractionated 18C Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

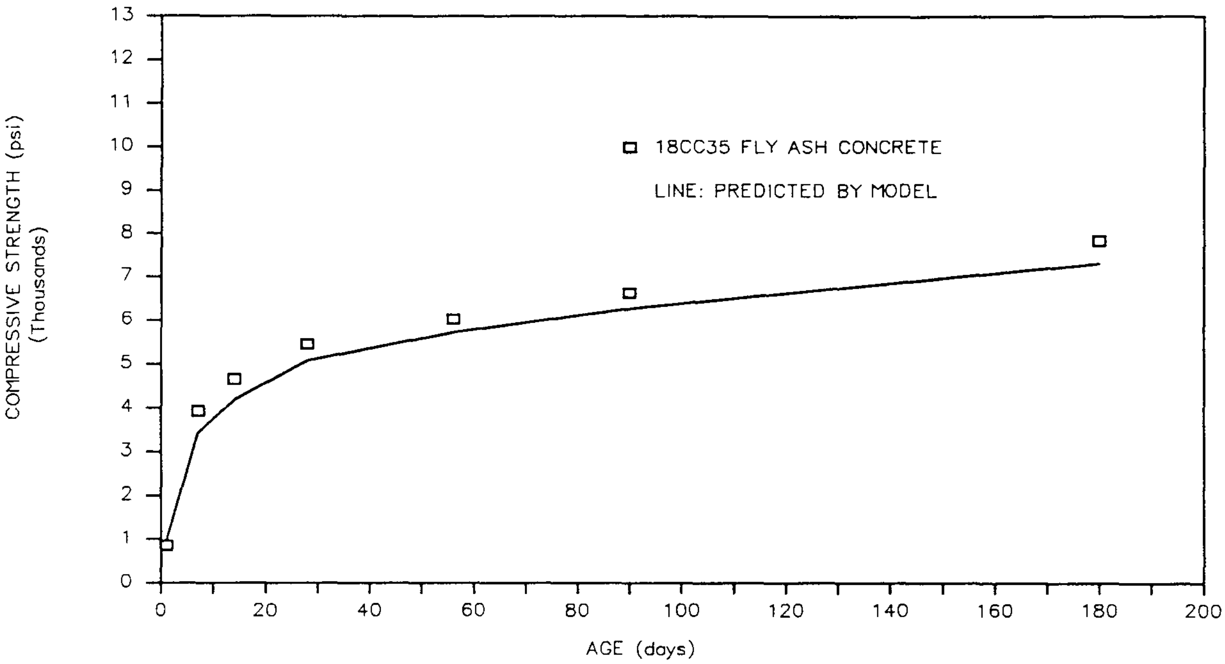

Figure A 43 Compressive Strength of the Fractionated 18C Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

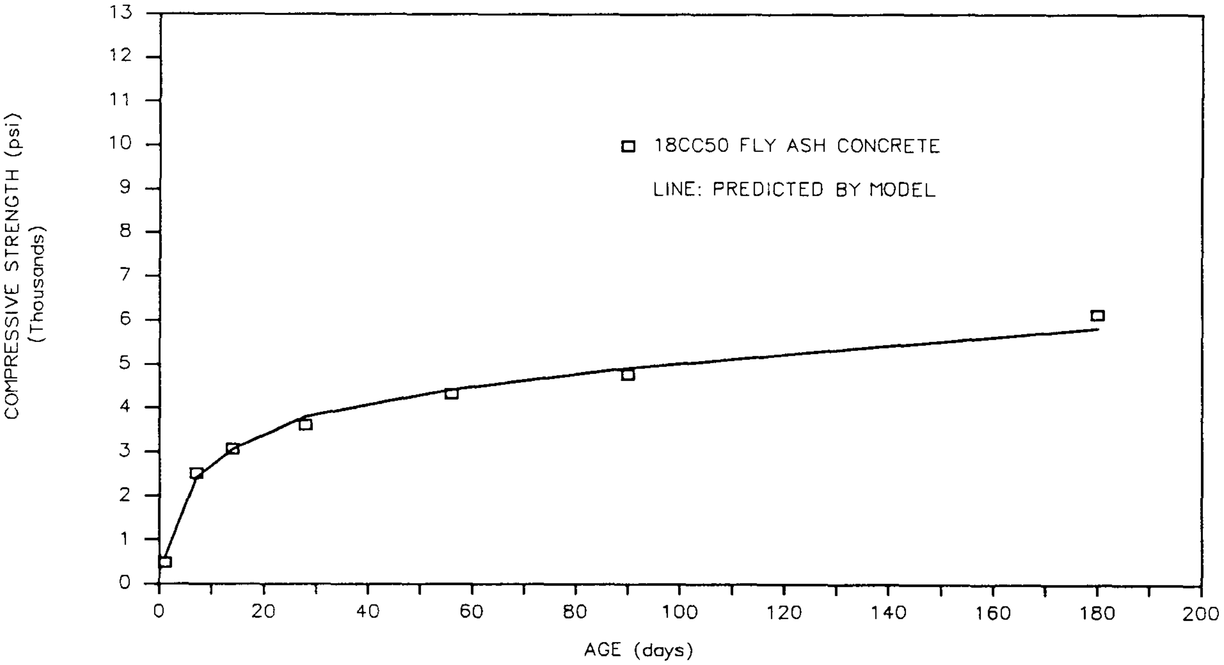

Figure A 44 Compressive Strength of the Fractionated 18C Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

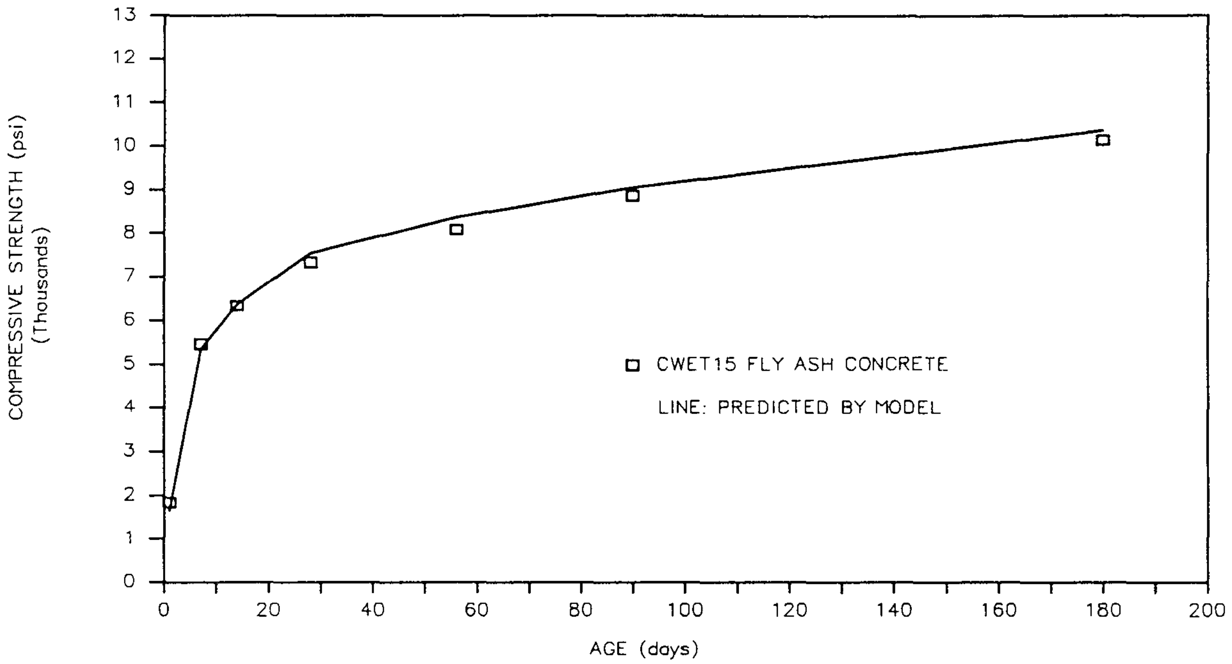

Figure A 45 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (15% Replacement)

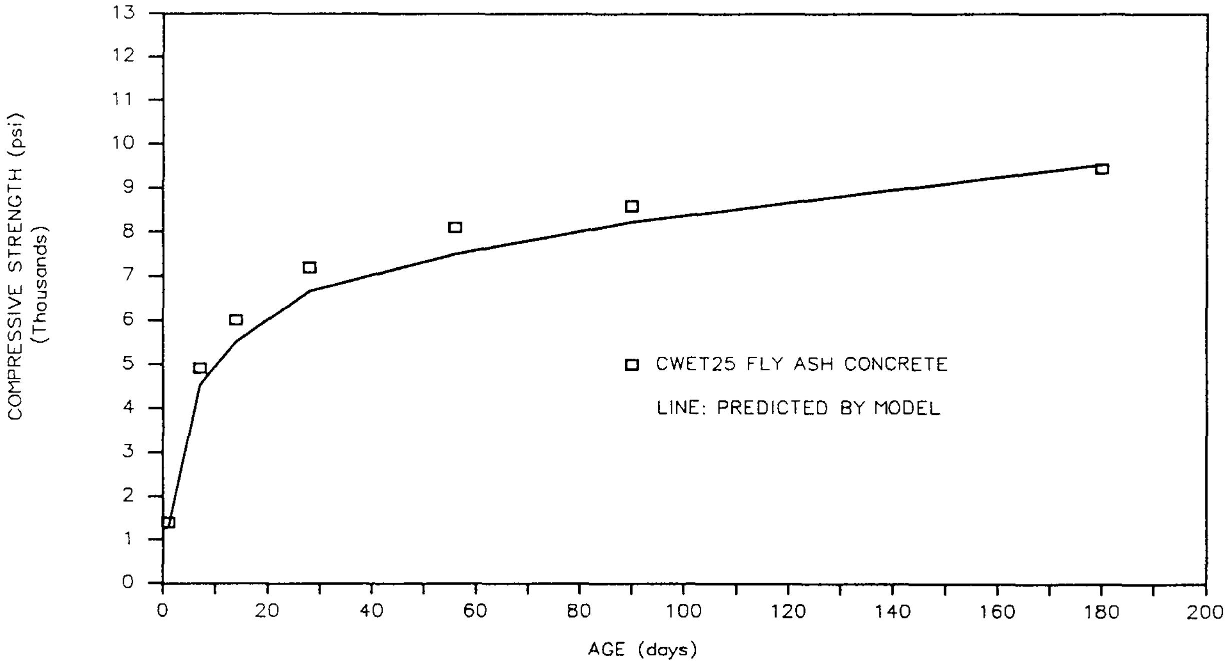

Figure A 46 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (25% Replacement)

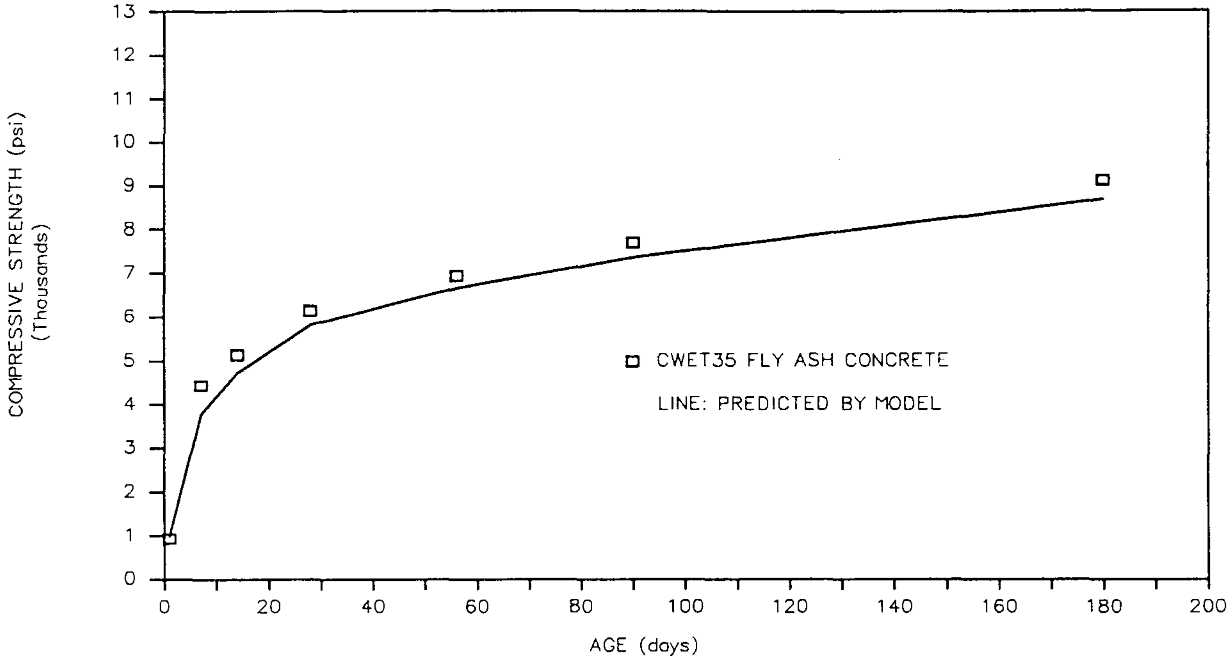

Figure A 47 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (35% Replacement)

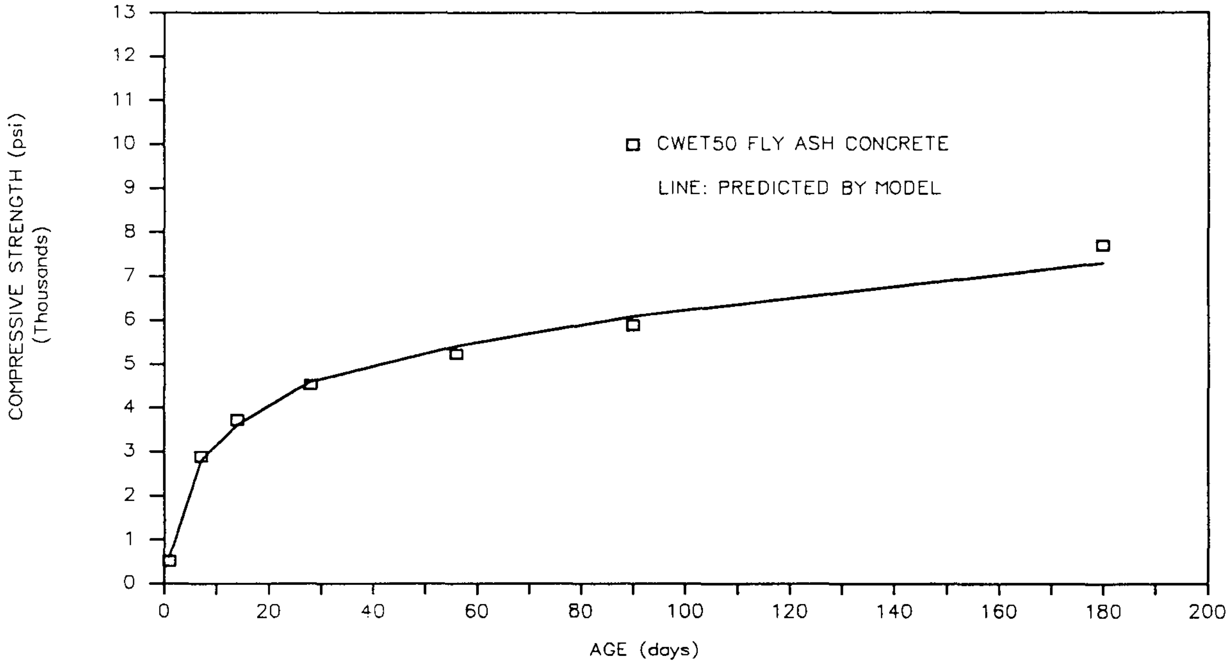

Figure A 48 Compressive Strength of the Original Feed of Wet Bottom Fly Ash Concrete Predicted by the Proposed Model (50% Replacement)

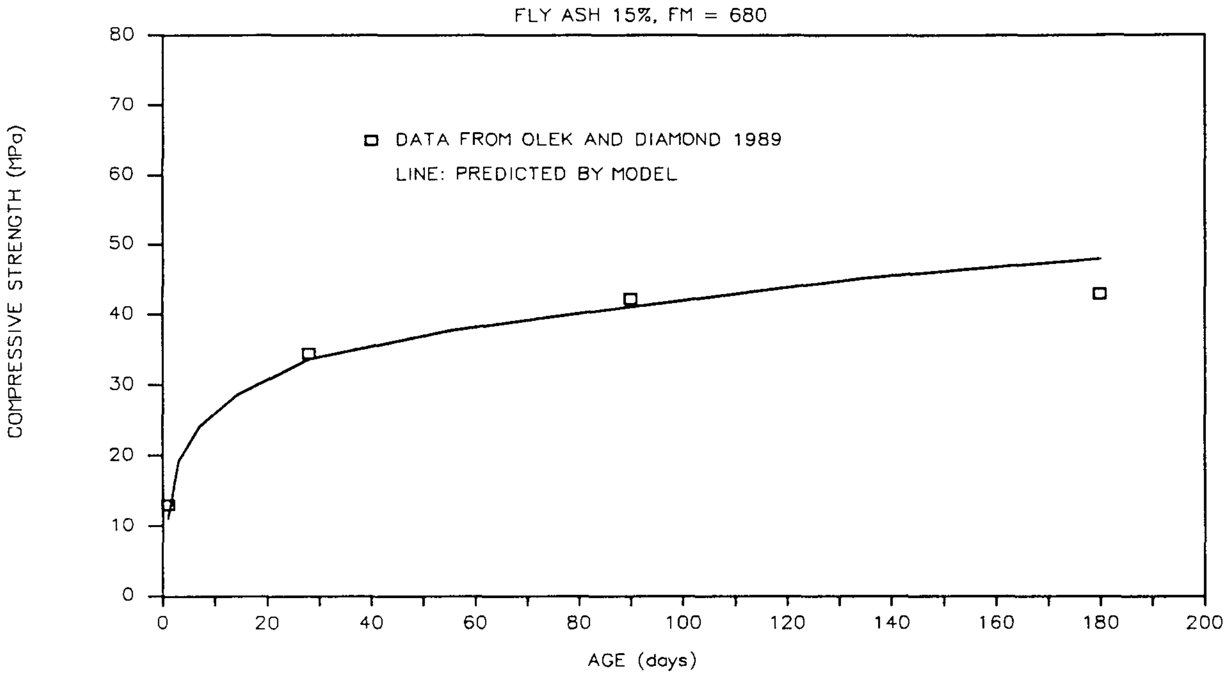

Figure A 49 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Olek and Diamond (1989) and from the Proposed Model (Fly Ash 15%, FM = 680)

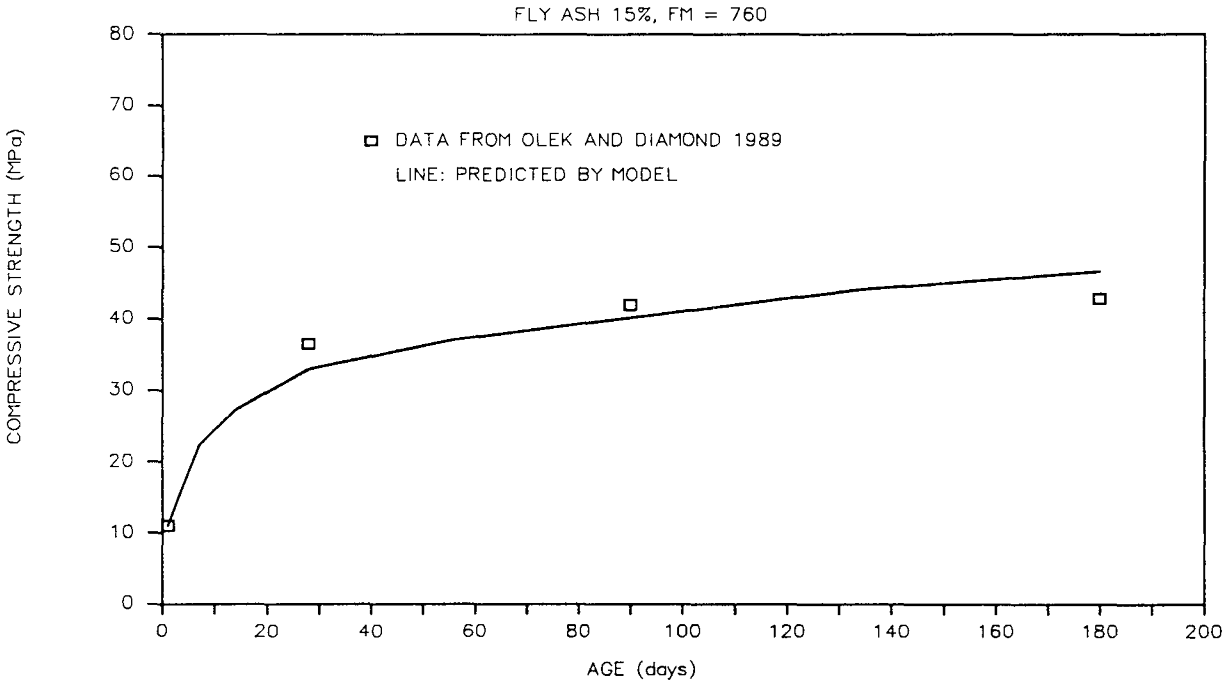

Figure A 50 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Olek and Diamond (1989) and from the Proposed Model (Fly Ash 15%, FM = 760)

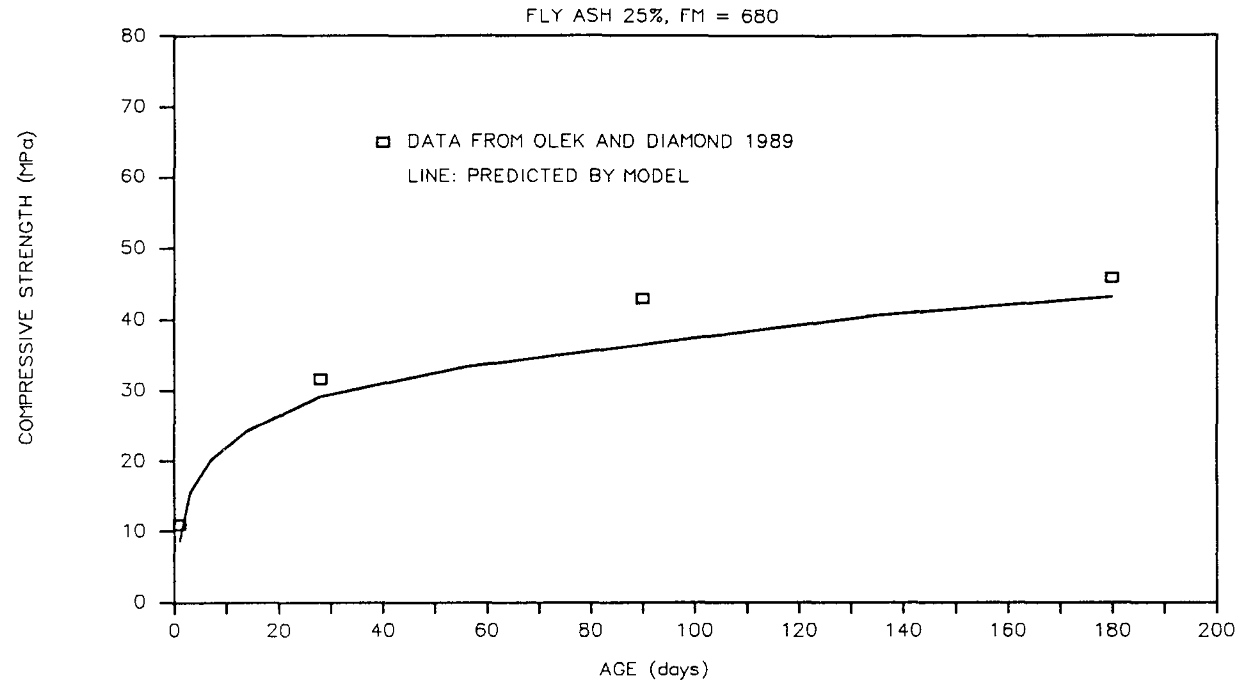

Figure A 51 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Olek and Diamond (1989) and from the Proposed Model (Fly Ash 25%, FM = 680)

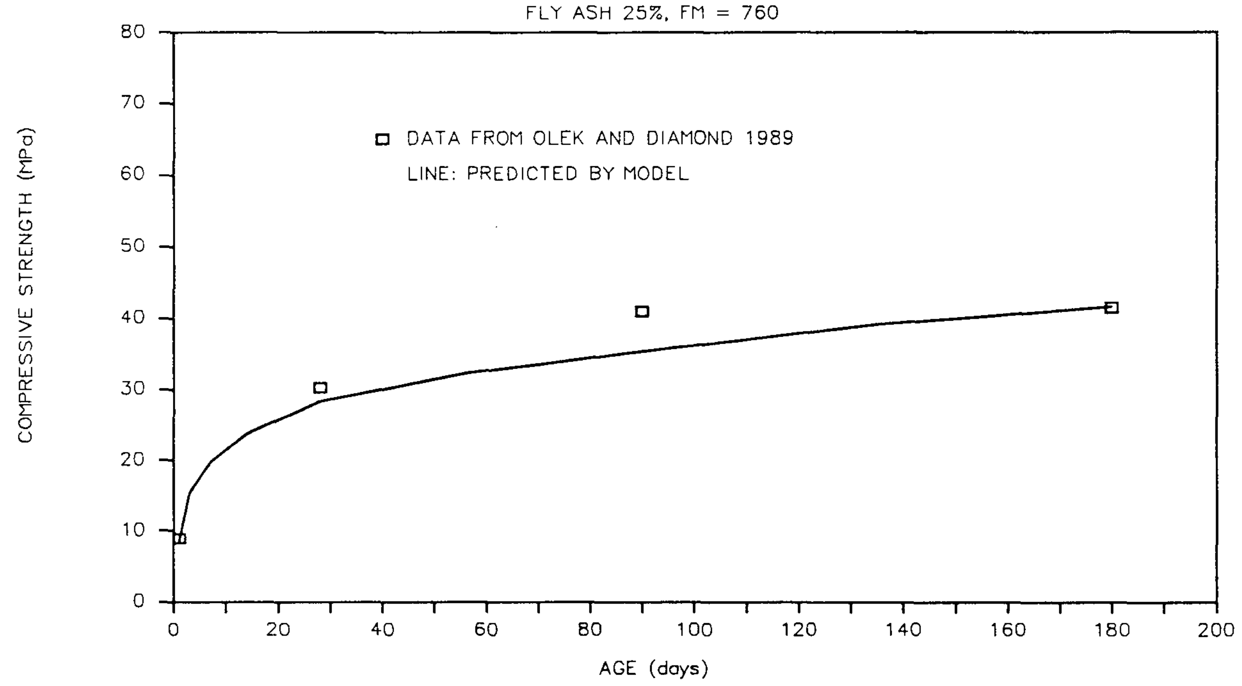

Figure A 52 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Olek and Diamond (1989) and from the Proposed Model (Fly Ash 25%, FM = 760)

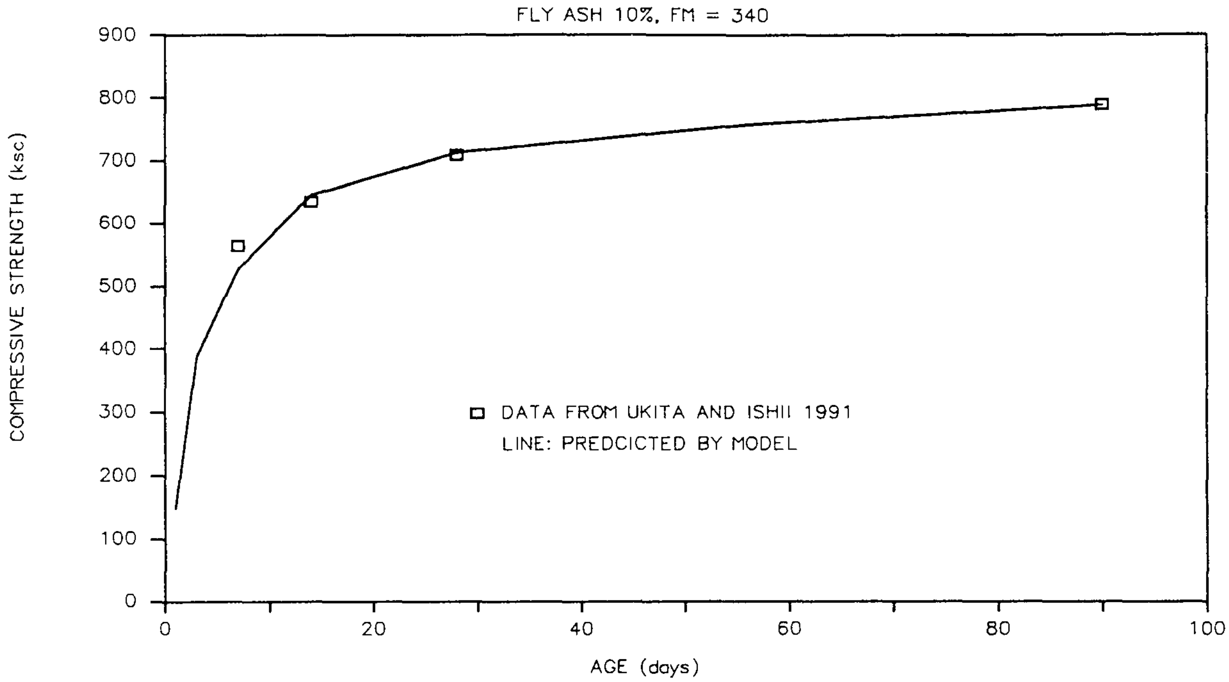

Figure A 53 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita and Ishii (1991) and from the Proposed Model (Fly Ash 10%, FM = 340)

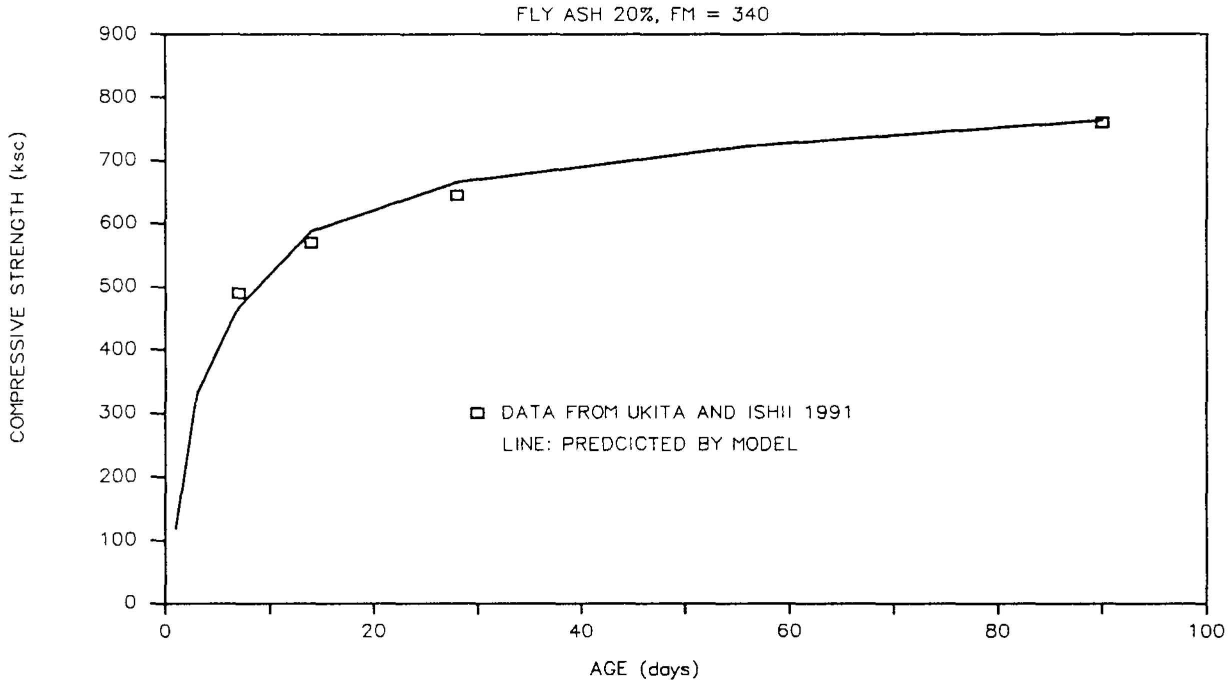

Figure A 54 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita and Ishii (1991) and from the Proposed Model (Fly Ash 20%, FM = 340)

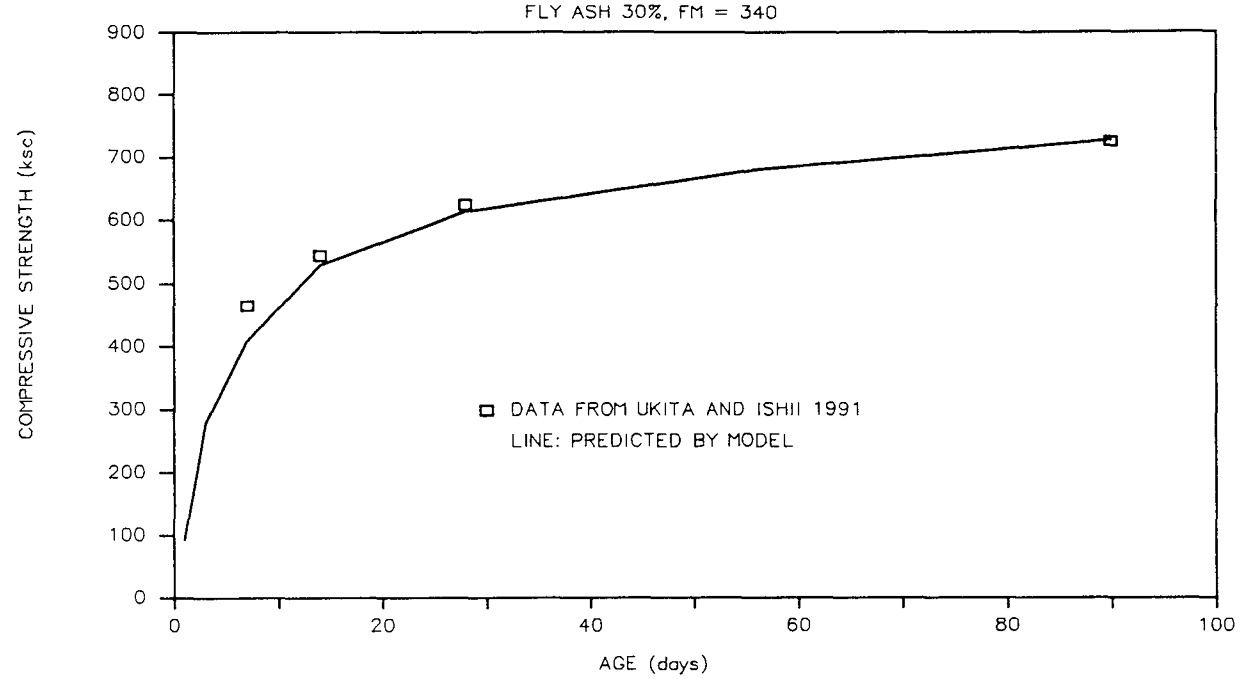

Figure A 55 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita and Ishii (1991) and from the Proposed Model (Fly Ash 30%, FM = 340)

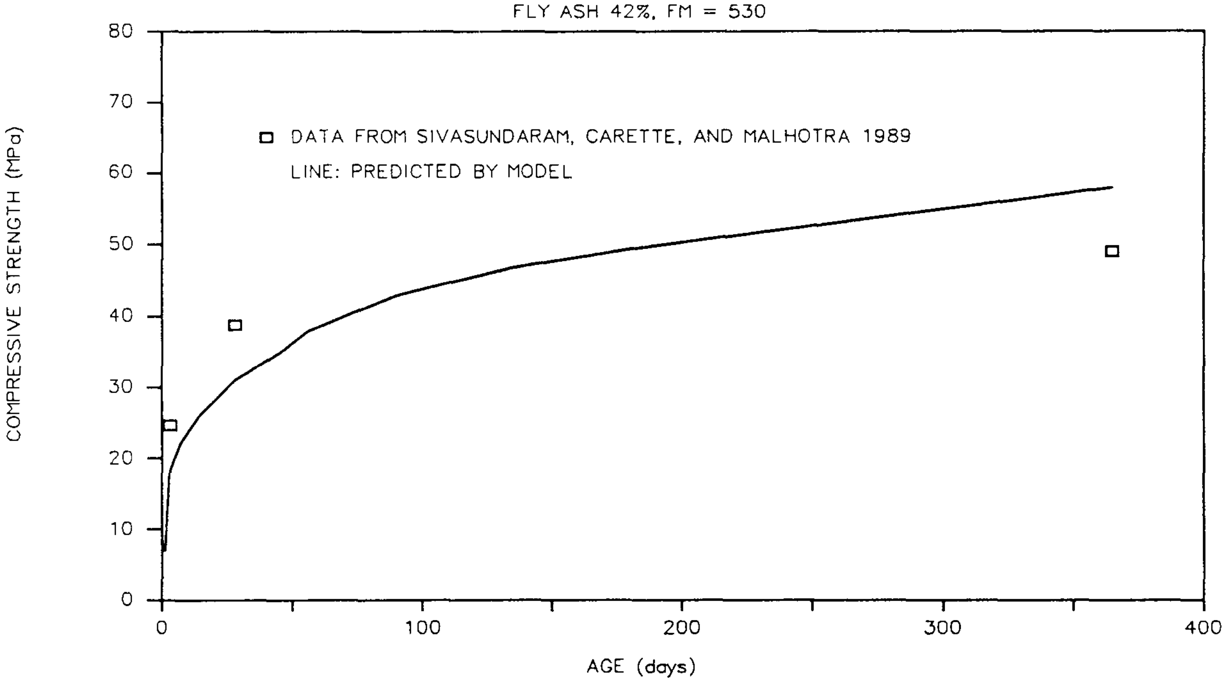

Figure A 56 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Sivasundaram, Carette, and Malhotra (1989) and from the Proposed Model (Fly Ash 42%, FM = 530)

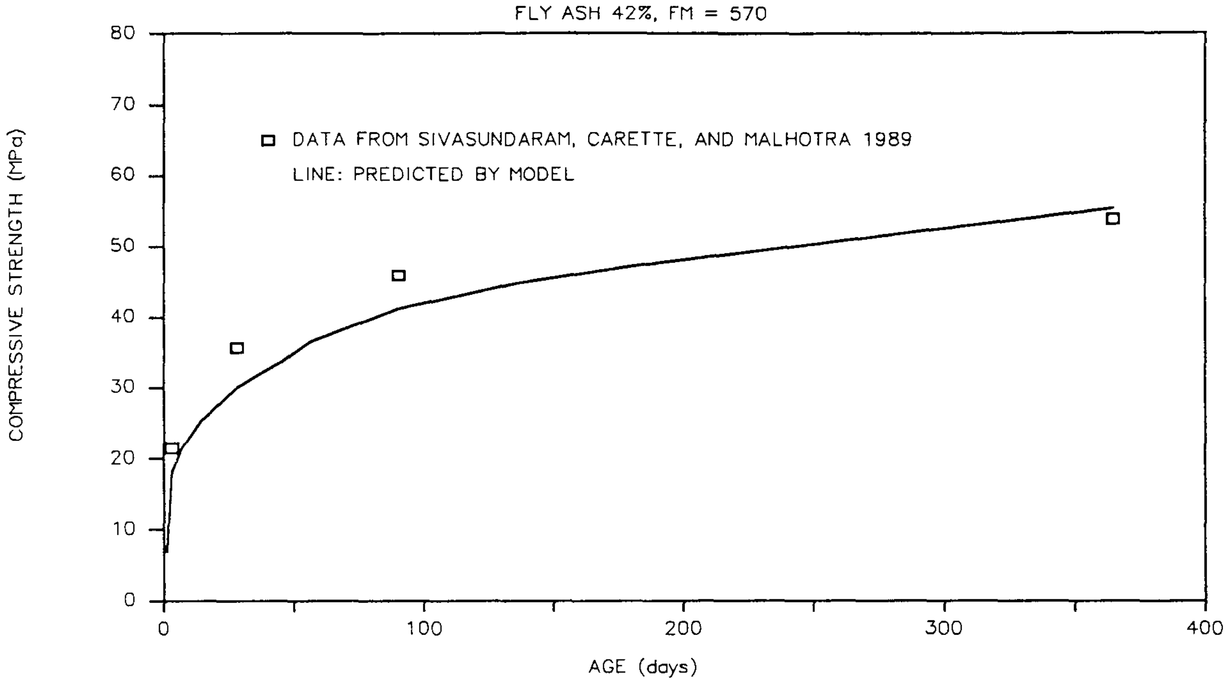

Figure A 57 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Sivasundaram, Carette, and Malhotra (1989) and from the Proposed Model (Fly Ash 42%, FM = 570)

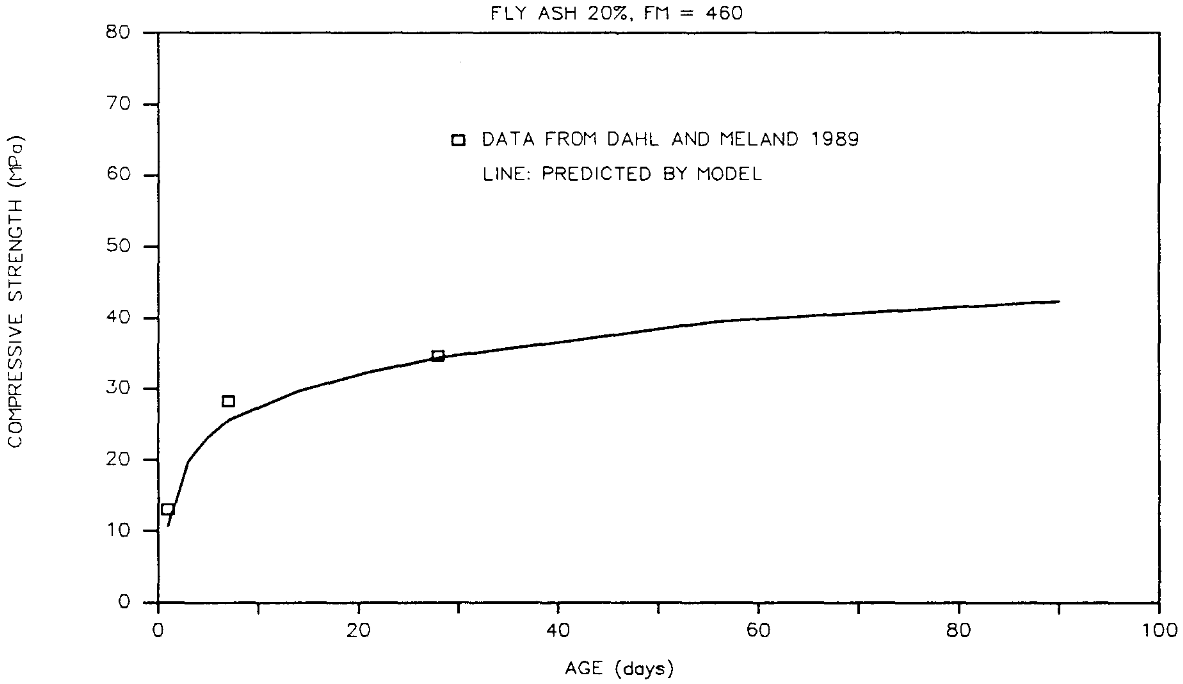

Figure A 58 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Dahl and Meland (1989) and from the Proposed Model (Fly Ash 20%, FM = 460)

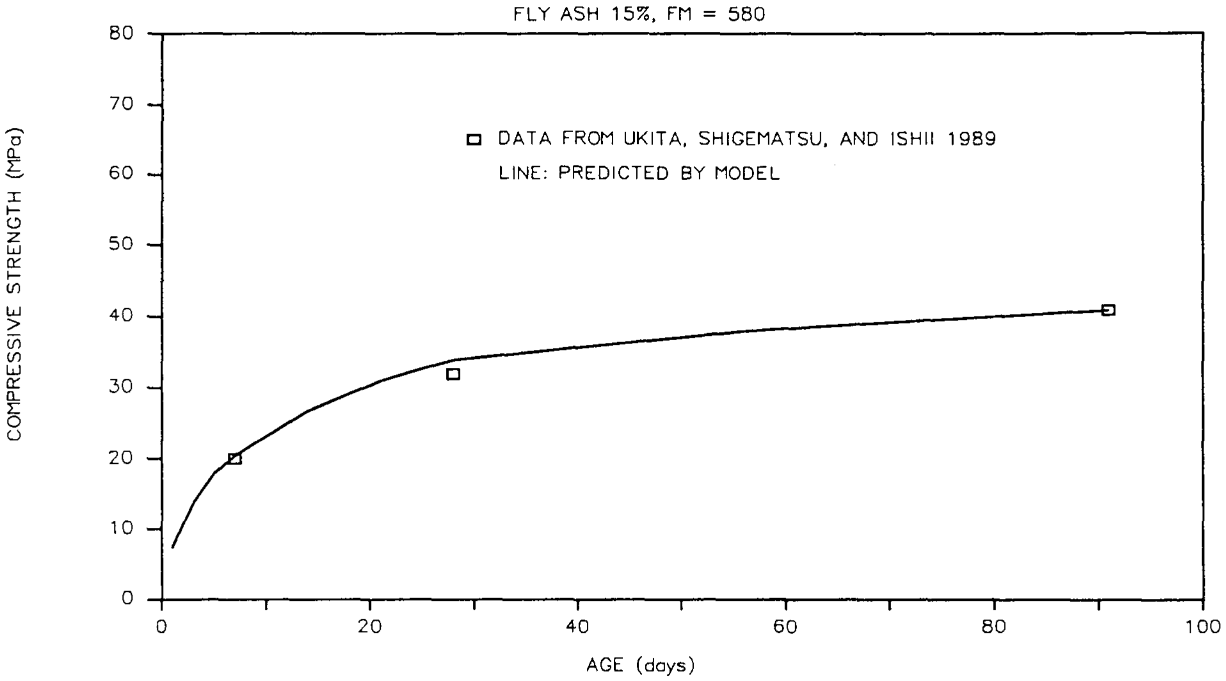

Figure A 59 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 15%, FM = 580)

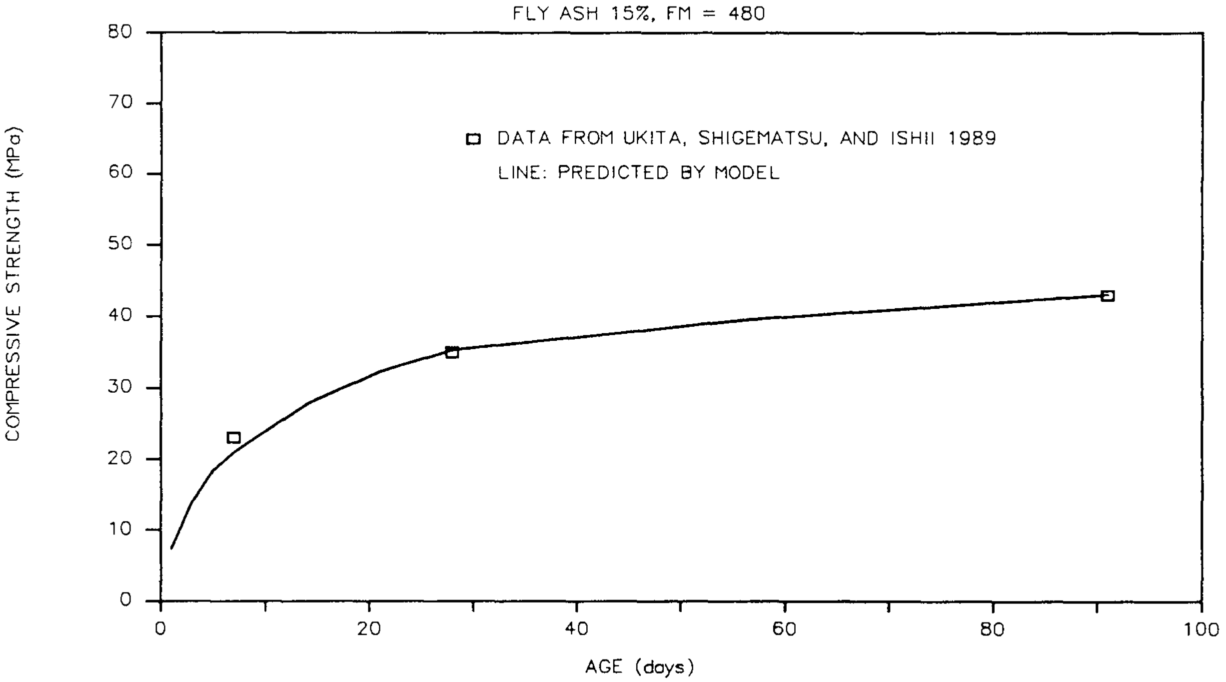

Figure A 60 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 15%, FM = 480)

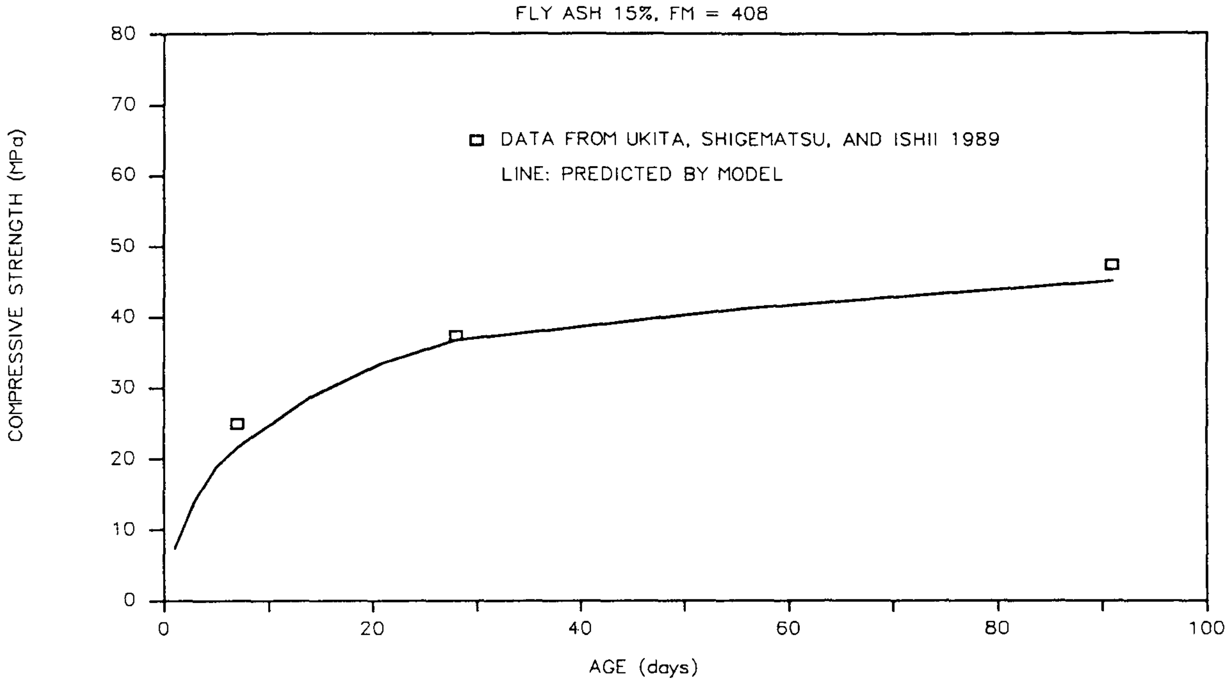

Figure A 61 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 15%, FM = 408)

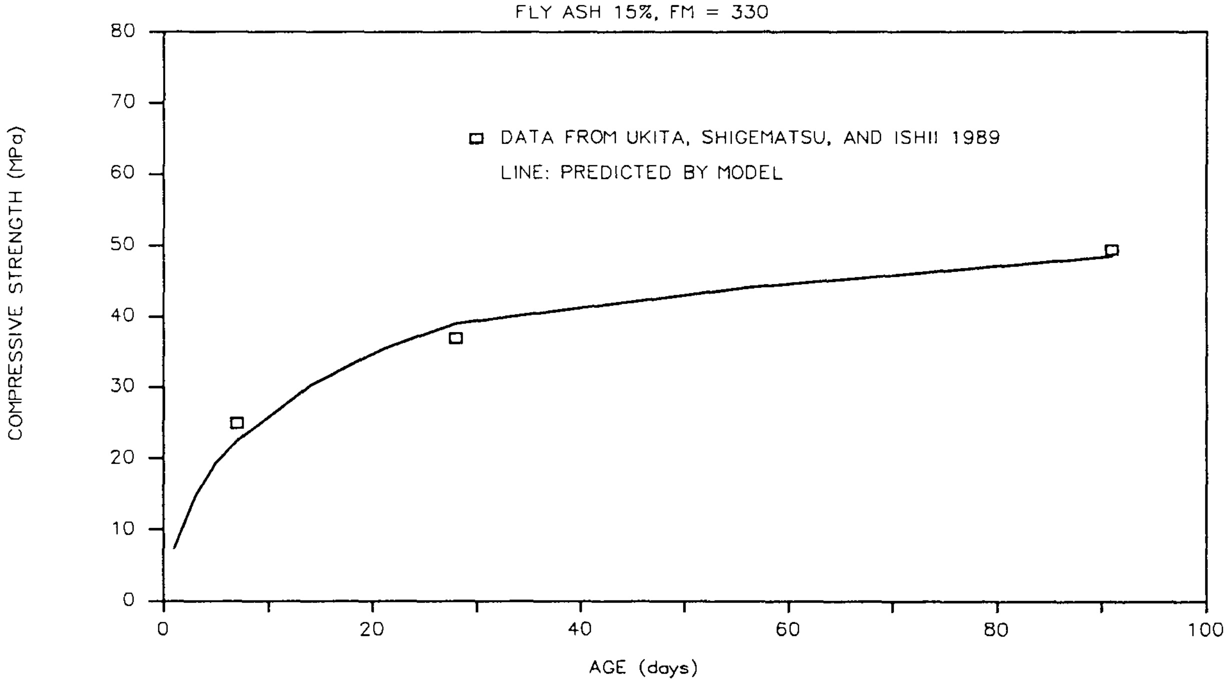

Figure A 62 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 15%, FM = 330)

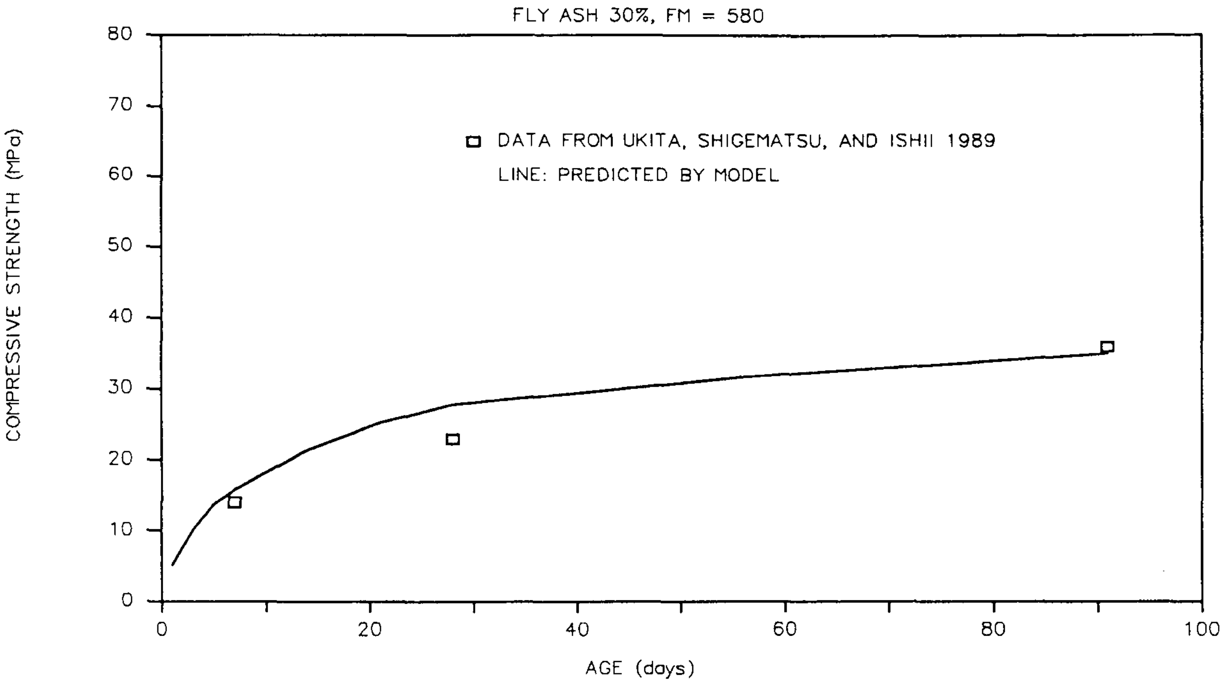

Figure A 63 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 30%, FM = 580)

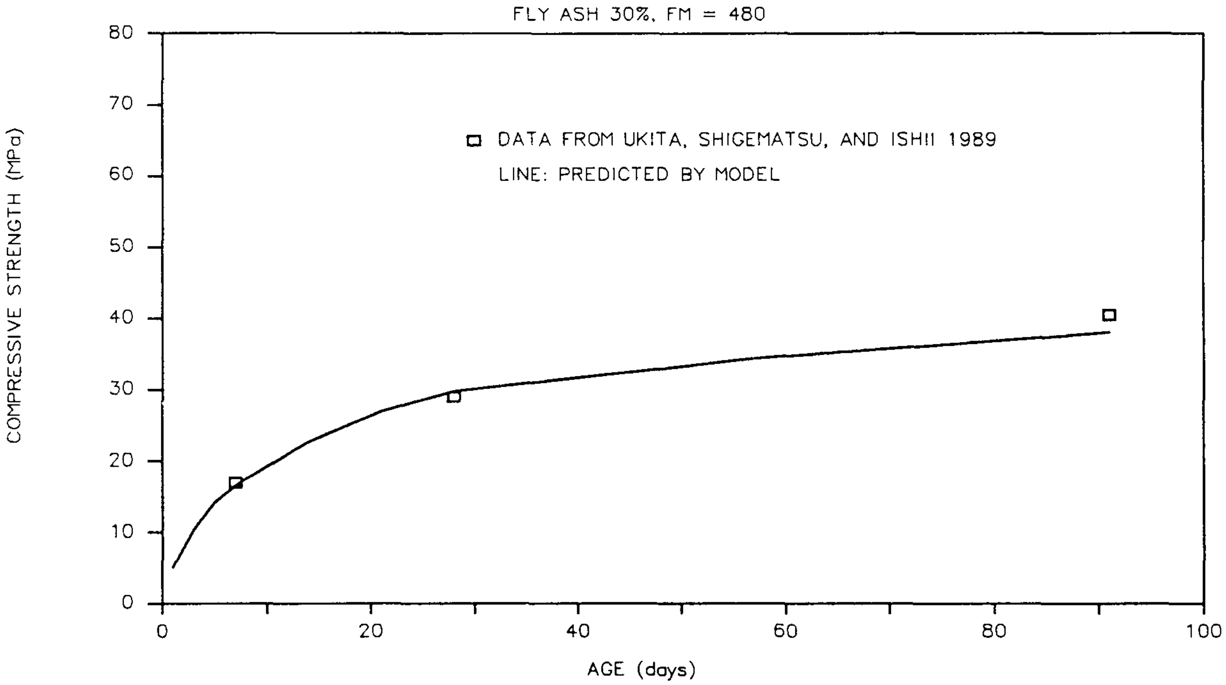

Figure A 64 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 30%, FM = 480)

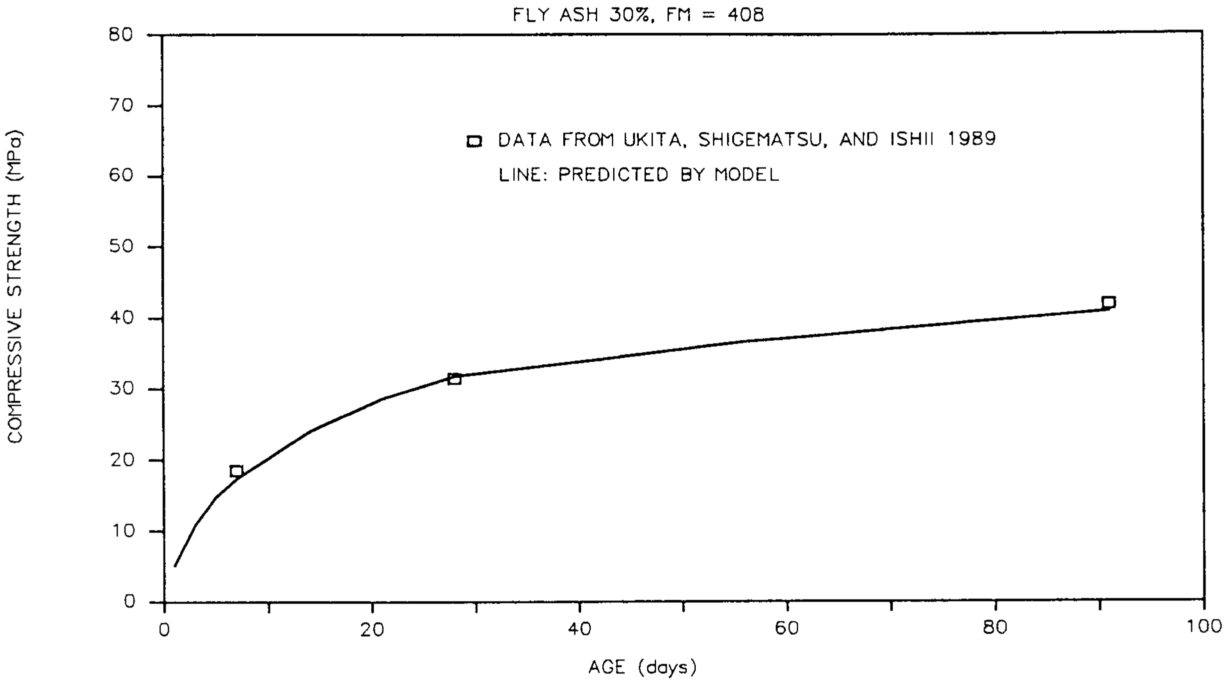

Figure A 65 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 30%, FM = 408)

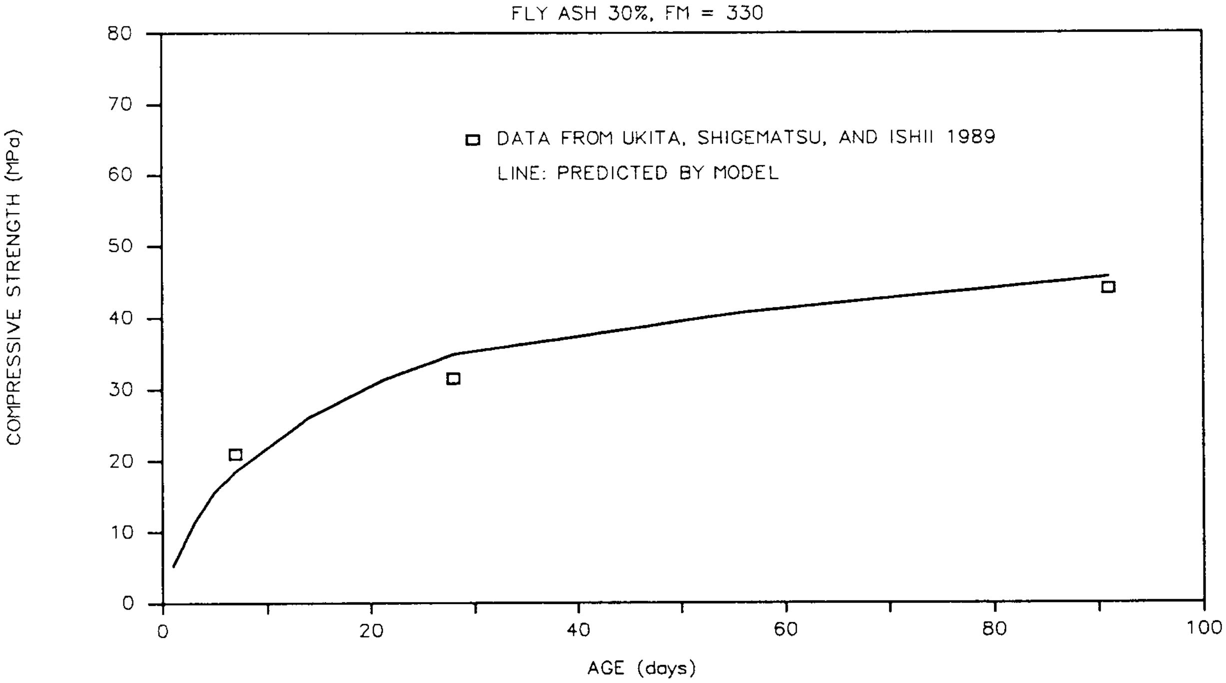

Figure A 66 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Ukita, Shigematsu, and Ishii (1989) and from the Proposed Model (Fly Ash 30%, FM = 330)

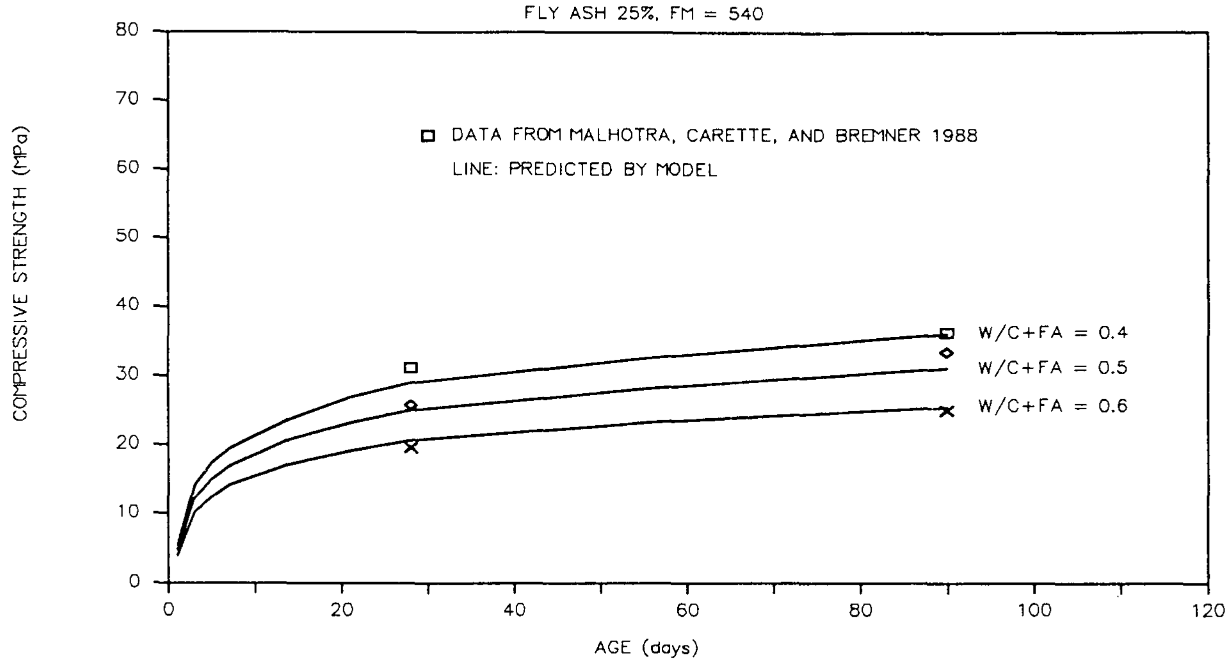

Figure A 67 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Malhotra, Carette, and Bremner (1988) and from the Proposed Model (Fly Ash 25%, FM = 540)

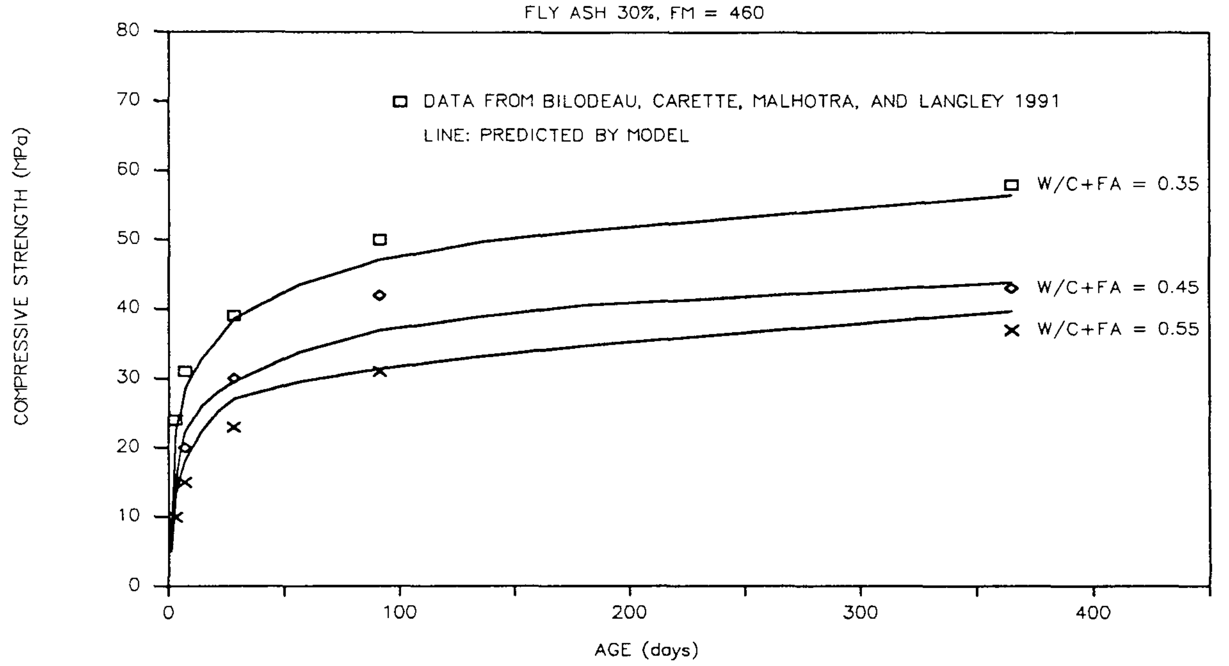

Figure A 68 Comparison between the Compressive Strength of Fly Ash Concrete Obtained from Bilodeau, Carette, Malhotra, and Langley (1991) and from the Proposed Model (Fly Ash 30%, FM = 460)

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