A STUDY ON RATE OF STRENGTH GAIN OF CONCRETE MIX PREPARED WITH LOCALLY AVAILABLE COMPOSITE CEMENTS

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by

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DECLARATION

It is hereby certified that the work presented in this project has been carried out by the author under the supervision of Dr. Khan Mahmud Amanat, Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka. This work has not been submitted elsewhere for any other purpose, except for publication.

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Md. Shahinul Islam

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ABSTRACT

In building construction sector, there is a common complain that concrete made with Portland composite cement (PCC) does not gain target strength within specified period (28 days). There is another argument found that the quality of this cement productions are not properly controlled by the cement industry of Bangladesh. This study is conducted to find out the fact on strength gain characteristics of concrete made with Portland composite cements (PCC) that are locally available. For this, concrete have been made with Portland composite cement (PCC) of four different brands (brand-A, brand-B, brand-C and brand-D) and one ordinary Portland cement (brand-E) for the target strength of 2500 psi, 4000 psi and 6000 psi where mix design procedure of concrete of ordinary Portland cement has been followed. The compressive strength of concrete cylinders have been tested at 3 days, 7 days, 14 days, 28 days, 3 months, 6 months and 1 year of age of concrete. Concrete have been cured in two different ways, one set of concrete cylinders have been cured continuously until they are tested while the other set of concrete cylinders have been cured only 14 days under water.

Compressive strength of concrete is taken as a measure to determine the rate of strength gain of concrete with age. Comparison of compressive strength gain of concrete made with Portland composite cement and ordinary Portland cement have been performed. Also the effect of curing on the strength development has been investigated.

From the experimental observation, it is found that the early age strength of concrete made with Portland composite cement (PCC) is lower in magnitude than that of concrete made with ordinary Portland cement (OPC) due to the presence of fly ash in Portland composite cement (PCC) which is responsible for the pozzolanic reaction. The continued pozzolanic activity of fly ash contributes to increased strength gain at later ages at continued curing condition. It is also found that drying ambient conditions reduce the strength potential of concrete made with Portland composite cements (PCC) because the secondary (pozzolanic) reaction fails to contribute to the development of strength.

It is found that concrete made with Portland composite cement (PCC) for the target strengths of 2500 psi, 4000 psi and 6000 psi gains 55 to 60 percent of its target strength at 7 days of age and 80 to 85 percent of its target strength at 28 days of age at continuous curing condition. At 14 days curing condition, it gains 75 to 80 percent of its target strength at 28 days of age. It requires 50 to 70 days, 80 to 100 days and 180 to 200 days to gain the target strengths of 2500 psi, 4000 psi, and 6000 psi respectively at continuous curing condition. At 14 days curing condition, it requires 90 days, 180 days and more than a year to gain the target strength of 2500 psi, 4000 psi and 6000 psi respectively.

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NOTATIONS

A	Cross sectional area of concrete sample
C_3A	Tricalcium aluminate.
C_4AF	Tetracalcium alumino ferrite
C_2S	Dicalcium silicate
C_3S	Tricalcium silicate
f_c	Flexural strength of concrete
P	Load applied to the sample
w/c	Water/Cement ratio
w/(c+p)	Water to cementitious material ratio
w	Water content
p	Fly ash content
c	Cement content
•	Unit weight of concrete

ABBREVIATION

AASHTO	American association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BDS	Bangladesh Standards
BS	British Standard Specification
CA	Coarse aggregate
CEM	Cement
EN	European Norms
FA	Fine aggregate
FM	Fineness modulus
ICI	Indian Concrete Institute
IS	Indian Standard Specification
LOI	Loss on Ignition
NRMCA	National Ready Mixed Concrete Association
OPC	Ordinary Portland cement
PCC	Portland Composite Cement
PFA	Pulverized Fuel Ash
PPC	Portland Pozzolana Cement

CHAPTER- 1

INTRODUCTION

1.1 General

Concrete is one of the most widely used manmade construction materials in the world. It is composed of cement as well as other cementitious materials such as fly ash and slag, aggregate (generally a coarse aggregate such as gravel, limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures. It is used to make a variety of structures such as pavements, building structures, foundations, footings for gates, fences poles, motorways or roads, bridges or overpasses, parking structures, and brick or block walls etc. The popularity of the concrete is due to the fact that from the common ingredients, it is possible to tailor the properties of concrete to meet the demands of any particular situation.

1.2 Background and Present State of the Problem

The principal ingredients of concrete are gravel, sand, water and cement, of which cement is the most cost and energy intensive components of concrete. Its production is a major contributor to greenhouse gas emissions that are implicated in global warming and climate change. The cement composed of lime and silica (sourced from limestone, clay, and sand), is fired in a rotary kiln at 1400°C, consuming enormous quantities of fossil fuels and thereby producing high amounts of CO_2. The global cement industry contributes around 1.35 billion tons of the greenhouse gas emissions annually, or about 7% of the total man-made greenhouse gas emissions to the earth's atmosphere (Malhotra, 2002; McCaffrey, 2002).

The concrete industry consumes portland and modified portland cements at an annual rate of about 1.6 billion metric tons and the production of Portland cement consume vast amount of virgin materials such as limestone, silica clay, iron ore etc. Though the raw materials needed for manufacture of cement are available in most parts of the world, many countries have severe shortage of cement, although their needs are vast. The search for suitable substitute for cement, either partially or fully, has thus become a challenge for planning the development of many of third world countries like Bangladesh.

Achieving a dramatic improvement in resource productivity through durability enhancement of products is, of course, a long-term solution for sustainable development. That is why, the practice of reclamation and reuse of its own waste products and, to the extent possible, the waste products of other industries which are unable to recycle them in their own manufacturing process have started. Use of reclaimed and recyclable industrial by-products, such as supplementary cementing materials (SCMs), fly ash from coal-fired power plants, can provide excellent example of industrial ecology because they offer a holistic solution for reducing the environmental impact of several industries. Additional benefits include minimization of waste disposal for these industrial by-products and lessened pressure on natural resources (such as limestone and iron ore). Incorporation of fly ash in concrete improves workability and thereby reduces the water requirement with respect to the conventional concrete. Among numerous other beneficial effects are reduced bleeding, reduced segregation, reduced permeability, increased plasticity, lowered heat of hydration, and increased setting times (ACI Committee 226, 1987, supra).

Even though the use of fly ash in concrete has increased in the last 20 years, less than 20% of the fly ash collected is used in the cement and concrete industries (Helmuth 1987). A critical drawback of the use of fly ash in concrete is that the rate of strength gain of fly ash concrete is slower but it is sustained for longer periods than the rate of the strength increase of Portland cement concrete (Chindaprasirt, Jaturapitakkul, 2005; Hwang, 2004).

During the last several years, price of raw materials of cement has not only increased but also become unavailable because of extra demand for these items in countries such as China and India where the raw materials are produced. This ultimately increased the production cost of cement in Bangladesh. To minimize the rising production cost of cement, cement manufacturing companies of Bangladesh have been using fly ash in cement for the last several years. These fly ash containing cement are available in the market named as “Portland Composite Cement”. It is found that the proportion of different ingredients of these Portland composite cements (PCC) vary among different cement manufacturing companies. These composite cements are being used frequently in building construction woks in Bangladesh. While using this cement, mix design procedure of concrete of ordinary Portland cement is followed. In this situation, there is a common complain from building construction sector that concrete made with Portland composite cement (PCC) does not gain target strength within specified period (28 days). Since some important decision related to the construction works depends on the time required by the concrete to gain full target strength as well as the maximum strength which can concrete attain. It should be ensured while removing formwork that the concrete has reached a minimum strength to prevent any movement or damage of the structure. Moreover the concrete should attain the minimum strength within short time so that the entire construction time of structure is not delayed.

That is why, it is necessary to investigate the strength gaining property of concrete made with Portland composite cement (PCC) both at early ages and later ages. Kaosar (2006) has made a study on brick aggregate concrete with varying amount of fly ash content where fly ash are added directly at the time of mixing. Then compressive strength and two types of durability such as chloride resistance and sulfate resistance tests have been performed. This study evaluated the effects of fly ash on strength and durability of brick aggregate concrete.

1.3 Research Significance

Findings of the study will give a general scenario of the strength gain characteristics of concrete made with locally available Portland composite cements (PCC) both at earlier ages and later ages which will be useful for design and construction planning of building construction including formwork removal time of concrete. This can give an idea about the quality of locally available Portland composite cements (PCC) also. The work is performed using locally available materials such as stone chips, sand (Sylhet Sand) and locally available Portland composite cements to know the response of fly ash with these locally available materials. The concrete have been cured in two different ways, one set of concrete specimens have been cured continuously until they are tested while the other set of concrete specimens have been cured only 14 days under water to know effect of continuous curing over 14 days curing.

1.4 Objectives with Specific Aims

The objectives are as follows:

a) To study the variation of compressive strength of concrete with time made with locally available Portland composite cement (PCC).
b) To compare compressive strength of concrete made from locally available Portland composite cement (PCC) with ordinary Portland Cement (OPC).
c) To study and compare the effect of continuously curing and only 14 days curing on strength development of concrete made with Portland composite cement (PCC) and ordinary Portland cement (OPC).
d) To show the response of compressive strength of concrete made with Portland composite cement (PCC) which is designed by ACI mix design method of ordinary Portland cement.

1.5 Outline of the Methodology

The properties of different ingredients of concrete (coarse aggregate, fine aggregate, cement) would be tested. Then the amount of different ingredients of concrete for the target compressive strength of 2500 psi, 4000 psi and 6000 psi would be calculated by ACI mix design method of concrete of type-1 ordinary Portland cement. A total number of 495 concrete cylinders would be cast using Portland composite cement (PCC) of four different brands and one ordinary Portland cement (OPC) for three different target design strengths. Samples would be cured in two different ways; one set of concrete samples would be cured continuously until they are tested while the other set of concrete samples would be cured for only 14 days under water. The compressive strength of concrete samples would be tested at 3 days, 7 days, 14 days, 28 days, 3 months, 6 months and 1 year of age of concrete. Bar charts would be plotted showing Compressive strength of concrete with age which would represent the comparison of compressive strength variation of concrete made with Portland composite cement (PCC) and ordinary Portland cement (OPC). Also the compressive strength variations of continuous cured concrete samples and only 14 days cured concrete samples would be studied.

1.5.1 Properties of Coarse and Fine Aggregate

Different physical properties of both fine and coarse aggregate would be tested according to ASTM codes.

Fineness modulus, unit weight and specific gravity of coarse aggregate would be performed according to ASTM C136, ASTM C29, ASTM C127 respectively.

Fineness modulus, bulk specific gravity and absorption capacity of fine aggregate would be performed according to ASTM C136, ASTM C128 respectively.

1.5.2 Properties of Cement

Normal consistency, Initial and final setting time, Direct compressive strength of cement mortar would be tested according to C187, C191 and C109 respectively.

1.5.3 Method of Mix Design of Concrete

Mix design is defined as the process of selecting suitable ingredients of concrete and determining their relative quantities with the purpose of producing an economical concrete which has certain minimum properties, notably workability, strength and durability. Thus selection of better mix design method is vital to obtain desired strength of concrete. For this project, ACI mix design method of concrete of ordinary Portland cement would be used, considering all design standards.

1.5.4 Determination of Rate of Strength Gain of Concrete

There are various factors which affect the rate of strength gain of concrete. That’s why all properties of concrete ingredients would be kept unchanged and only cement type would be changed with different cement brand names.

Compressive strength of concrete would be taken as a measure to determine the rate of strength gain of concrete. It is one of the most important and useful properties of concrete. It usually gives an overall picture of the quality of concrete because it is directly related to the structure of the hardened cement paste. This test method would be conformed to the ASTM standard requirements of specification C 39.

CHAPTER-2

LITERATURE REVIEW

2.1 Generals

Fly ash, a by-product of coal combustion, is widely used as a cementitious and pozzolanic ingredient in portland cement concrete. It may be introduced either as a separately batched material or as a component of blended cement. The use of fly ash in concrete is increasing because it improves some properties of concrete and often results in lower cost concrete.

According to ACI 116R, fly ash is "the finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases; known in UK as pulverized fuel ash (PFA)."

ACI 116R defines "pozzolan" as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties."

Fly ash possesses pozzolanic properties similar to the naturally occurring pozzolans of volcanic or sedimentary origin found in many parts of the world. It is mixed with Portland cement (which releases lime during hydration), aggregate and water to produce mortar and concrete. All fly ashes contains pozzolanic materials, however some fly ashes possess varying degrees of cementitious value without the addition of calcium hydroxide or portland cement because they contain some lime.

2.2 History of Fly Ash Use

The term fly ash was first used in the electrical power industry around 1930. The first comprehensive data on the use of fly ash in concrete in North America were reported by Davis et al. (1937). The first major practical application was reported in 1948 with the publication of the U.S. Bureau of Reclamation's data on the use of fly ash in the construction of the Hungry Horse Dam, utilizing 120,000 metric tons of fly ash. This decision by the U.S. Bureau of Reclamation paved the way for using fly ash in concrete constructions. Worldwide acceptance of fly ash as a component of concrete slowly followed these early efforts, but interest was particularly noticeable in the wake of the rapid increases in energy costs (and hence cement costs) that occurred during the 1970s.

2.3 Source of Fly Ash

Due to the increased use of pulverized coal as fuel for electric power generation, fly ash is now available in most areas of the United States, Canada and in many other parts of the world. Fly ash is produced as a by-product of burning coals which have been crushed and ground to a fineness of 70 to 80 percent passing a 75μm (No. 200) sieve. Approximately 45,000 Gg (50 million tons) of fly ash is produced annually in the United States (American Coal Ash Association, 1992).

2.4 Composition of Fly Ash

Fly ash is a complex material consisting of heterogeneous combinations of amorphous (glassy) and crystalline phases. The largest fraction of fly ash consists of glassy spheres of two types, solid and hollow (cenospheres). These glassy phases are typically 60 to 90 percent of the total mass of fly ash with the remaining fraction of fly ash made up of a variety of crystalline phases. These two phases are not completely separate and independent of one another. Rather, the crystalline phases may be present within a glassy matrix or attached to the surface of the glassy spheres. This union of phases makes fly ash a complex material to classify and characterize in specific terms.

2.4.1 Chemical Composition

The bulk chemical composition has been used by ASTM C 618 to classify fly ash into two types, Class C and Class F. Wide ranges exist in the amounts of the four principal constituents, SiO_2 (35 to 60 percent), Al_2O_3 (10 to 30 percent), Fe_2O_3 (4 to 20 percent), CaO (1 to 35 percent). The sum of the first three constituents (SiO_2, Al_2O_3, and Fe_2O_3) is required to be greater than 70 percent to be classified as an ASTM Class F fly ash, whereas their sum must only exceed 50 percent to be classified as an ASTM Class C fly ash. Class C fly ashes generally contain more than 20 percent of material reported as

CaO; therefore the sum of the SiO_2, Al_2O_3, and Fe_2O_3 may be significantly less than the 70 percent Class F minimum limit.

2.4.2 Physical Properties

Fly ashes produced at different power plants or at one plant with different coal sources may have different colors. Fly ash color and the amount used can influence the color of the resulting hardened concrete in the same way as changes in cement or fine aggregate color. Fly ash color is generally not an engineering concern, unless aesthetic considerations relating to the concrete require maintaining a uniform color in exposed concrete. However, a change in the color of an ash from a particular source may be an indicator of changed properties due to changes in coal source, carbon content, iron content, or burning conditions.

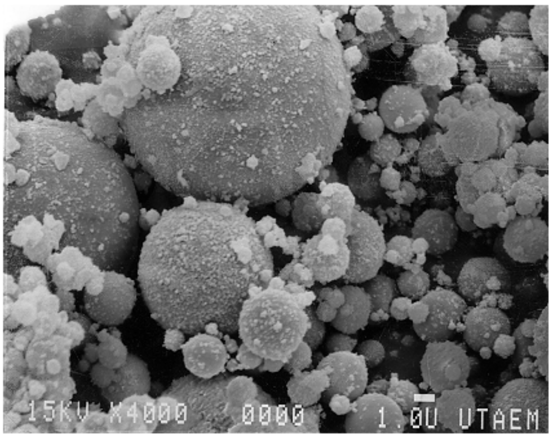

Figure 2.1 Fly ash at 4000 magnification (ACI 232.2 R-1996)

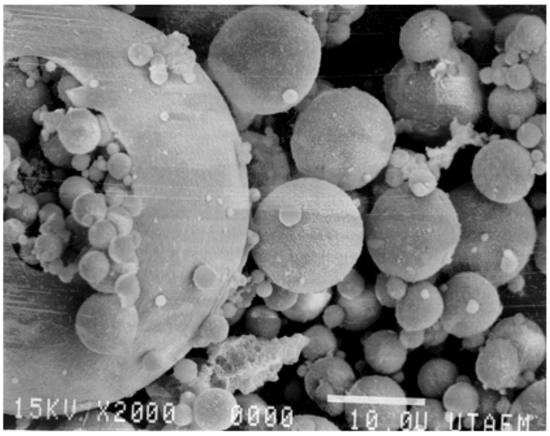

Figure 2.2 Fly ash showing plerospheres at 2000 magnification (ACI 232.2 R-1996)

2.4.2.1 *Particle shape*

Particle size and shape characteristics of fly ash are dependent upon the source and uniformity of the coal, the degree of pulverization prior to burning, the combustion environment (temperature level and oxygen supply), uniformity of combustion, and the type of collection system used (mechanical separators, baghouse filters, or electrostatic precipitators). Lane and Best (1982) reported that the shape of fly ash particles is also a function of particle size. The majority of fly ash particles are glassy, solid, or hollow, and spherical in shape. Examples of fly ash particle shapes are shown in Fig. 2.1 and 2.2. Fly ash particles that are hollow are translucent to opaque, slightly to highly porous, and vary in shape from rounded to elongated.

2.4.2.2 *Fineness*

Individual particles in fly ash range in size from less than 1µm to greater than 1 mm. In older plants where mechanical separators are used, the fly ash is coarser than in more modern plants which use electrostatic precipitators or bag filters. In fly ash suitable for use in concrete, ASTM C 618 states that not more than 34 percent of the particles should be retained on the 45-µm (No. 325) sieve. The 45-µm (No. 325) sieve analysis of fly ash from a particular source will normally remain relatively constant, provided there are no major changes in the coal source, coal grinding, process operations, and plant load. Minor variations may be expected due to sampling techniques.

Fineness of a specific fly ash may have an influence on its performance in concrete. Lane and Best (1982) used results of tests by ASTM C 430, 45-µm (No. 325) sieve fineness, as a means to correlate the fineness of Class F fly ash with certain concrete properties.

2.4.2.3 *Density*

According to Luke (1961), the density of solid fly ash particles ranges from 1.97 to 3.02 Mg/m^3 (123 to 188 lb/ft^3), but is normally in the range of 2.2 to 2.8 Mg/m^3 (137 to 175 lb/ft^3). Some fly ash particles, such as cenospheres, are capable of floating on water. High density is often an indication of fine particles. Roy, Luke, and Diamond (1984) indicate that fly ashes high in iron tend to have higher densities and that those high in carbon have lower densities. ASTM Class C fly ashes tend to have finer particles and fewer cenospheres; thus their densities tend to be higher, in the range of 2.4 to 2.8 Mg/m^3 (150 to 175 lb/ft^3).

2.4.2.4 *Specific Gravity*

The specific gravity of different fly ashes varies over a wide range. In the CANMET investigation of 11fly ashes (Care tte and Malhotra, 1986), the specific gravity ranged from a low value of 1.90 for a subbituminous ash to a high value of 2.96 for an iron-rich bituminous ash. Three subbituminous ashes had a comparatively low specific gravity of

2.0, and this suggested that hollow particles, such as cenospheres or plerospheres, were present in significant proportions in the three ashes.

2.5 Microscopy of Fly Ash Particle

Electron microscopes can reveal information about the microinhomogeneities and their distribution, including the formation of reaction products. A number of workers Ghose, 1981, Cabrera, 1982 have studied the microstructure of fly-ash-cement pastes. There is general agreement that fly ash reacts with lime in the alkaline environment of hydrating cement. However, different reports quote highly divergent time scales at which the pozzolanic reaction products are detected, varying from 3 days to 28 days. It is difficult to draw general conclusions. Generally, the microstructural development takes more than a year. However, the most significant morphology is developed during the first 6 months.

Figure 2.3 Cement + fly-ash paste after 1 hour

Figure 2.4 Cement + fly-ash paste after 4 hours

Studies of pastes made from 70 % Ordinary Portland Cement and an (ASTM) class F fly ash with water to solid ratios of 0.5 and 0.385 show that noticeable bonding may start to develop 12 to 18 hours after mixing, while from 18 hours onwards specimens may normally be fractured without crumbling.

After as little as 1 hour, there may be evidence of reaction on the cement grains (Fig. 2.3) in the form of AFt needles and small granular products of early hydration together with larger crystals of secondary gypsum. Some of the fly-ash spheres may also have hydration products on them. After 4 hours, some of the fly ashes may show definite signs of surface pitting with granular hydration products growing at the pits (Fig. 2.4), in addition to the CH and AFt seen lying on the surface; this is even more pronounced at 8 hours (Fig. 2.5). By this time, the cement grains are covered with reaction products including C-S-H and AFt with some large CH crystals (Fig. 2.6) and after 12 hours this type of coating may envelop even fly-ash spheres as shown in Fig. 2.7. This resembles the duplex coating found by Diamond et al. (1980) on fly ash.

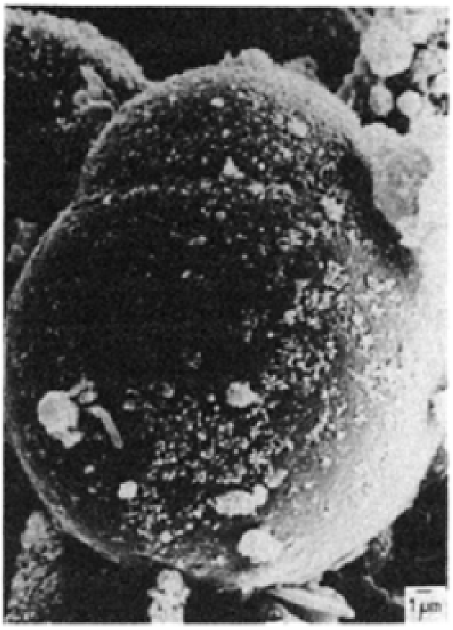

Figure 2.5 Cement + fly-ash paste after 8 hours

Figure 2.6 Cement grain in fly-ash paste after 8 hours

After 18 hours, the paste may acquire some cohesion, the AFt rods being better crystallized, and Hadley grains being more numerous (Fig. 2.8). Large CH crystals may also start to grow (Fig. 2.9), while some of the fly-ash grains show very different morphologies of the coating on different parts of their surface (Fig. 2.10). These coatings are generally found to be intact over the entire grain surface.

In 1-day old specimens, AFt phases may be found to grow longer and interlock in some of the void spaces. In general, the fly-ash particles are found to be coated but some appeared to have reacted. Flocculation of the fly ash may be evident in places. Cleavage through CH crystals may first be seen at this age and few spheres may be embedded in the CH (Fig.2.11). These fly ashes do not have any coating and appear to have been etched in the pore solution. In some regions, large well-formed crystals of CH may be found in intimate contact with big fly-ash spheres, and reactions may take place at the interface (Fig. 2.12).

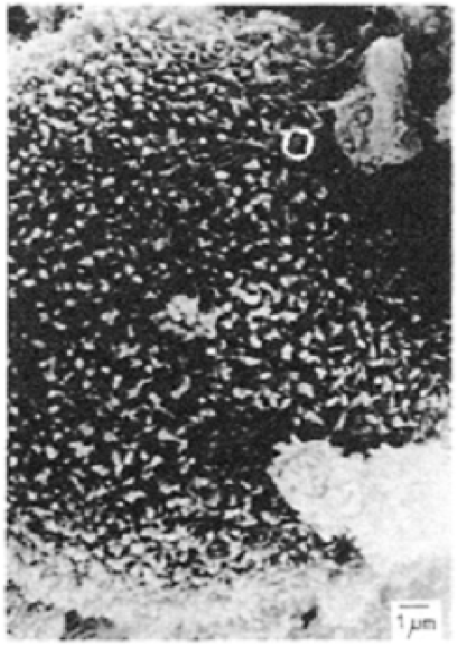

Figure 2.7 Fly-ash sphere with duplex film after 12 hours

Figure 2.8 Hadley grain and AFt rods in cement + fly-ash paste after 18 hours

The growth of massive CH in the form of stacked platelets which cleave during fracture will be much more pronounced at 3 days. Most of the fly-ash spheres embedded in this CH growth again looks etched rather than reacted on the surface. Heavily coated fly ashes may also be observed, but not in the vicinity of these massive CH deposits. Some of these may show reaction coating or product over part of the surface (Fig. 2.13) and this can also be evident at longer ages. It is difficult to imagine part of the coating tearing off during fracture in this particular case. This sphere may be partly glassy and partly crystalline, the glass in the fly ash being the reactive component according to Kokubu, (1974); the demarcation of surface products may reveal the glass/crystal interfaces. In resin impregnated, cut, polished and etched sections of 2-month old specimens, this may sometimes be evident after differential etching of the fly ash.

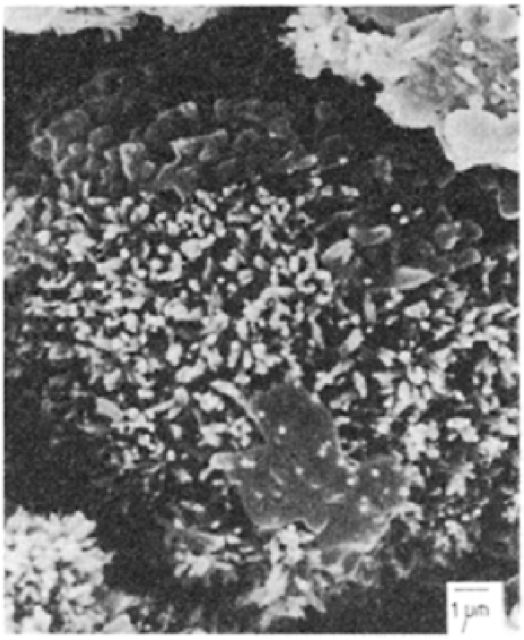

Figure 2.9 Large CH crystal in cement + fly-ash paste after 18 hours

Figure 2.10 Fly-ash sphere in the paste after 18 hours

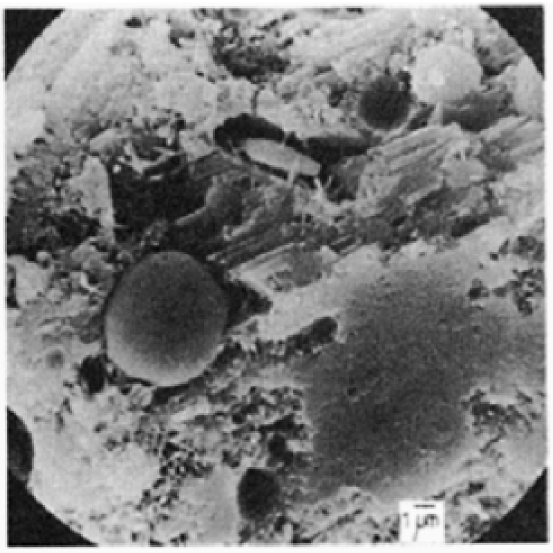

Figure 2.11 Uncoated fly ash after 1 day

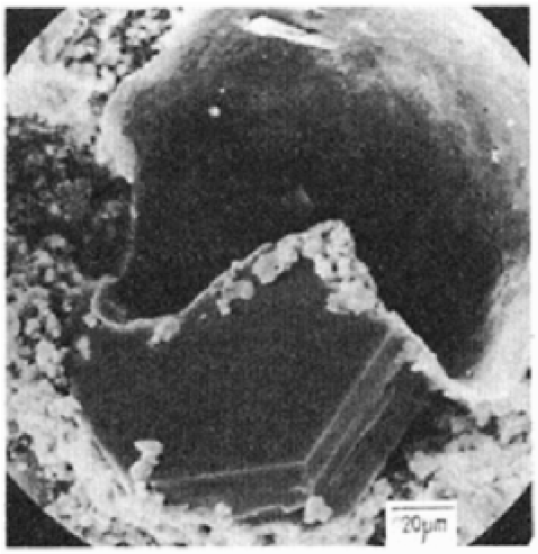

Figure 2.12 Reacted fly ash after 1 day

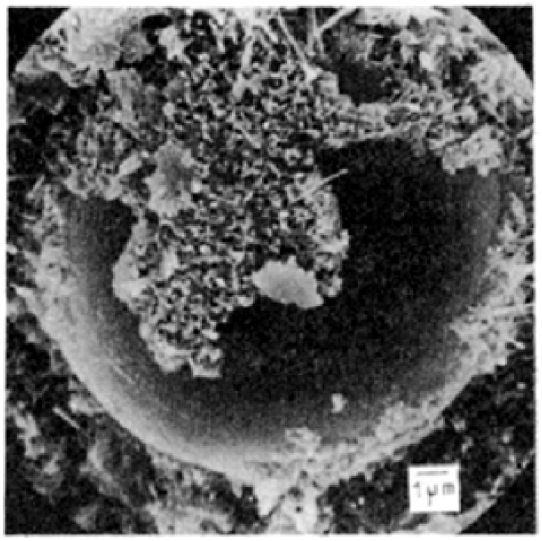

Figure 2.13 Partly coated fly-ash sphere after 3 days

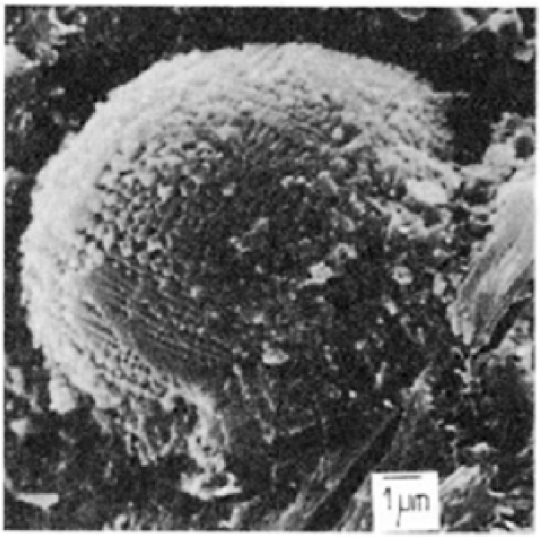

Figure 2.14 Etched fly ash after 2 months

Figure 2.15 Reacted fly ash after 5 months

Figure 2.16 Heavily reacted fly-ash sphere after 5 months

Up to 14 days, the structure becomes denser with continuing infilling from CH and C-S-H; Hadley grains disappear, probably being engulfed in the developing structure, and evidence of AFt-AFm conversion may be seen in open places. Sometimes fly-ash spheres are seen to be encapsulated by the reaction products. Between 3 days and 2 months, fly-ash spheres with a variety of reaction and etch patterns are found (Fig. 2.13 and 2.14), the extent of the attack increasing with the time. At longer times of up to 5 months, some of the fly-ash spheres have reacted significantly (Fig. 2.15) and some have been eaten away (Fig. 2.16), while at the same time, some spheres which have not reacted very much are found. Microanalysis in fracture faces is not always very convincing, but there appears to be some indication from micro analytical studies on these cement fly-ash pastes that the reacted fly ashes are generally richer in alumina and poorer in silica than non-reacted ashes.

The SEM images (Figures 2.3 to 2.16) were supplied by Prof. P.L.Pratt, Imperial College of Science and Technology, Dept. of Materials, London, United Kingdom (Ghose, 1981).

2.6 Effects of Fly Ash on Concrete

The shape, fineness, particle-size distribution and density of fly ash particles influence the properties of freshly mixed, unhardened concrete and the strength development of hardened concrete. This is primarily due to the particle influence on the water demand of the concrete mixture.

2.6.1 Effects on Properties of Fresh Concrete

One of the most important aspects of the use of fly ash in concrete is the fact that, in general, the use of fly ash markedly improves the properties of freshly mixed concrete.

2.6.1.1 *Workability*

The small size and the essentially spherical form of low-calcium fly -ash particles influence the rheological properties of cement pastes, causing a reduction in the water required or an increase in workability compared with that of an equivalent paste without fly ash. As Davis et al. (1937) noted, fly ash differs from other pozzolans that usually increase the water requirement of concrete mixtures. The improved workability allows a reduction in the amount of water used in concrete. According to Owens (1979), the major factor influencing the effects of ash on the workability of concrete is the proportion of coarse material (>45 mm) in the ash. Owens (1979) has reported that substitution of 50% by mass of the cement with fine particulate fly ash can reduce the water requirement by 25%. A similar substitution using ash with 50% of the material larger than 45 mm has no effect on the water requirement.

2.6.1.2 *Temperature reduction*

The chemical reaction of cement with water generates heat, which has an important bearing on the rate of strength development and on early stress development due to differential volume change in concrete. Most of this heat is generated during the early stages of hydration of the alite (substituted C_3S) and C_3A phases of the cement. The temperature rise can be reduced by using fly ash as a portion of the cementitious material in concrete, as shown in Fig. 2.17 (Samarin, Munn and Ashby, 1983; Mehta, 1983). As the amount of cement is reduced the heat of hydration of the concrete is generally reduced (Mather, 1974). However, some Class C fly ashes do contribute to early temperature rise in concrete (Dunstan, 1984). When heat of hydration is of critical concern, the proposed concrete mixture should be tested for temperature rise.

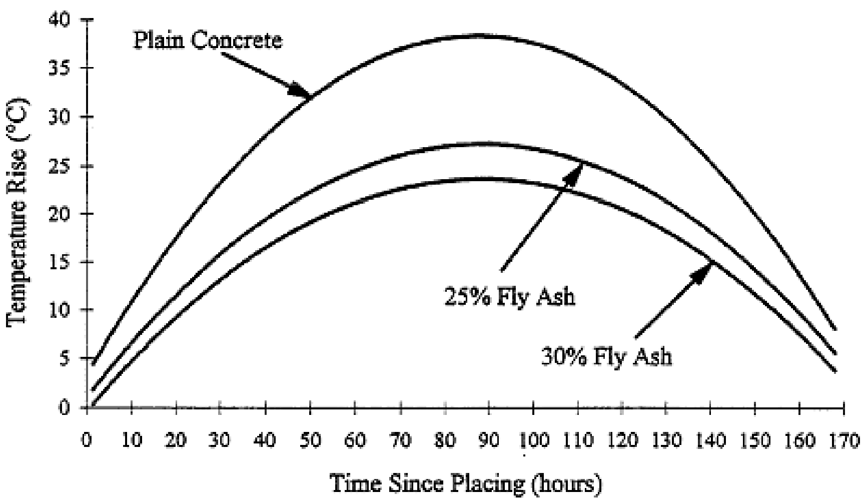

Figure 2.17 Variation of temperature with time at the center of 15 cubic meter concrete blocks (Samarin, Munn and Ashby, 1983)

2.6.1.3 *Time of Setting*

The use of fly ash may extend the time of setting of concrete if the portland cement content is reduced. Jawed and Skalny (1981) found that Class F fly ashes retarded early C_3S hydration. Grutzeck, Wei and Roy (1984) also found retardation with Class C fly ash. The setting characteristics of concrete are influenced by ambient and concrete temperature, cement type, source, content and fineness, water content of the paste, water soluble alkalies, use and dosages of admixtures, the amount of fly ash and the fineness and chemical composition of the fly ash (Plowman and Cabrera, 1984). When these factors are given proper consideration in the concrete mixture proportioning, an acceptable time of setting can usually be obtained. The actual effect of a given fly ash on time of setting may be determined by testing when a precise determination is needed or by observation when a less precise determination is acceptable. Pressures on form work may be increased when fly ash concrete is used if increased workability, slower slump loss or extended setting characteristics are encountered (Gardner, 1984).

2.6.1.4 *Bleeding*

Using fly ash in air-entrained and non-air-entrained concrete mixtures usually reduces bleeding by providing greater surface area of solid particles and a lower water content for a given workability (Idorn and Henriksen, 1984).

2.6.1.5 *Air entrainment*

The use of fly ash in air-entrained concrete will generally require a change in the dosage rate of the air-entraining admixture. Some fly ashes with LOI values (Loss on Ignition) less than 3 percent require no appreciable increase in air-entraining admixture dosage. The LOI is determined by the mass loss of fly ashes heated at a temperature of 750 ± 25°C; unburned carbon is the largest component of LOI. Some Class C fly ashes may reduce the amount of air-entraining admixture required, particularly for those with significant water-soluble alkalies in the fly ash (Pistilli, 1983). To maintain constant air content, admixture dosages must usually be increased, depending on the carbon content as indicated by LOI, fineness and amount of organic material in the fly ash. When using a fly ash with a high LOI, more frequent testing of air content at the point of placement is desirable to maintain proper control of air content in the concrete.

2.6.2 Effects on Properties of Hardened Concrete

2.6.2.1 *Compressive strength*

The main factors determining strength in concrete are the amount of cement used and the water/cement ratio. In practice, these are established as a compromise between the need for workability in the freshly mixed state, strength and durability in the hardened state and cost. The degree and manner in which fly ash affects workability are major factors in its influence on strength development. Fly ash that permits a reduction in the total water requirement in concrete will generally present no problems in selection of mixture proportions and permit any rate of strength development.

2.6.2.2 *Modulus of elasticity*

Lane and Best (1982) reported that the modulus of elasticity of Class F fly ash concrete, as well as its compressive strength, is somewhat lower at early ages and a little higher at later ages than similar concretes without fly ash. The effects of fly ash on modulus of elasticity are not as significant as the effects of fly ash on strength. Fig.2.18 shows a comparative stress-strain relationship for fly ash and non-fly ash concrete with 19.0-mm (3/4-in.) nominal maximum size aggregate. The increase in modulus of elasticity under these conditions with Class F fly ash is small. The study concludes that cement and aggregate characteristics will have a greater effect on modulus of elasticity than the use of fly ash (Cain, 1979).

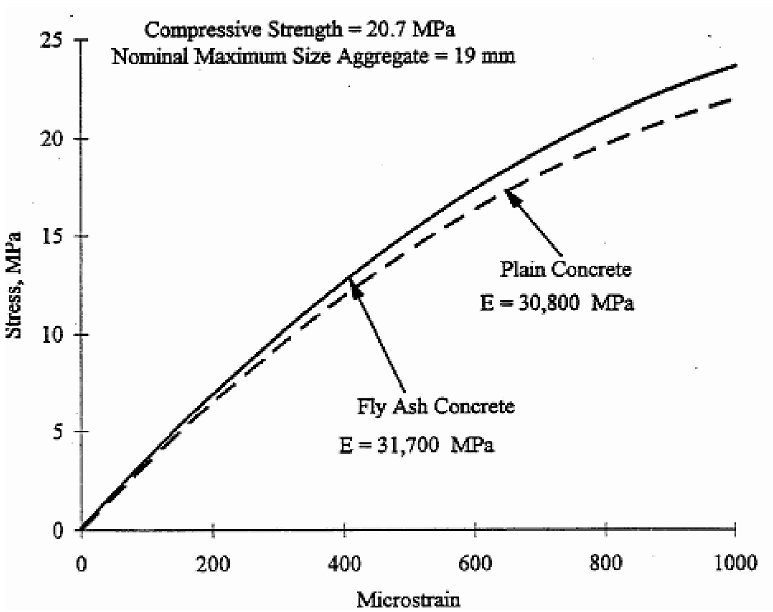

Figure 2.18 Stress-strain relationship at 90 days (TVA Technical Report CR-81-1)

2.6.2.3 *Creep*

The effects of fly ash on creep strain of concrete are limited primarily to the extent to which fly ash influences the ultimate strength and the rate of strength gain. Concrete with a given volume of cement plus fly ash loaded at ages of 28 days or less to a constant stress will normally exhibit higher creep strain than concrete having an equal volume of cement only, due to the lower strength of fly ash concrete at the time of loading (Lane and Best, 1982). However, both Lane and Best (1982) showed that concrete with fly ash proportioned to have the same strength at the age of loading as concrete without fly ash produced less creep strain at all subsequent ages. When specimens with and without fly ash are sealed to prevent moisture losses, simulating conditions in mass concrete, creep strain values are essentially equal after loading at an age of 1 year (Ghosh and Timusk, 1981). When unsealed specimens of equal strength were also loaded at 1 year, creep strain values for concrete containing fly ash were only half those measured for concrete without fly ash.

Most investigations have shown that if concretes with and without Class F fly ash having equivalent 28-day strengths are equally loaded at the same age, the fly ash concrete will exhibit lower long-term creep due to the greater rate of late age strengths gain common to most fly ash concrete. Yuan and Cook (1983) investigated the creep of concretes with Class C fly ash. With 20 percent replacement, creep was about the same; at above 20 percent, creep increased with increasing fly ash content.

2.6.2.4 *Drying shrinkage*

Drying shrinkage of concrete is a function of the fractional volume of paste, the water content, cement content and type and the type of aggregate. In those cases where the addition of fly ash increases the paste volume, drying shrinkage may be increased slightly if the water content remains constant. If there is a water-content reduction, shrinkage should be about the same as concrete without fly ash. Davis et al., (1937) studied different fly ash cement mixtures and found no apparent differences in drying shrinkage between concrete with up to 20 percent fly ash content and non-fly ash concrete. Dunstan (1984) and Symons and Fleming (1980) found that increased fly ash content resulted in slightly less drying shrinkage.

2.6.3 Durability Characteristics

The durability of concrete is defined as its ability to resist weathering action, chemical action or any other process of deterioration.

2.6.3.1 *Abrasion Resistance*

Compressive strength, curing, finishing and aggregate properties are the major factors controlling the abrasion resistance of concrete (ACI 201.2R, 210R). At equal compressive strengths, properly finished and cured concretes with and without fly ash will exhibit essentially equal resistance to abrasion.

2.6.3.2 *Resistance to High Temperatures*

With respect to the exposure of concrete to sustained high temperatures, Carette, Painter, and Malhotra (1982) indicated that the use of fly ash in concrete does not change the mechanical properties of concrete in relation to similar concrete containing only portland cement when exposed to sustained high-temperature conditions ranging from 75 to 600 C (170 to 1110 F).

2.6.3.3 *Permeability and Corrosion Protection*

Calcium hydroxide liberated by hydrating cement is water-soluble and may leach out of hardened concrete, leaving voids for the ingress of water. Through its pozzolanic properties, fly ash chemically combines with calcium hydroxide and water to produce C-S-H, thus reducing the risk of leaching calcium hydroxide. Additionally, the long-term reaction of fly ash refines the pore structure of concrete to reduce the ingress of chloride ions. As a result of the refined pore structure, permeability is reduced (Manmohan and Mehta, 1981; and EPRI CS-3314).

2.6.3.4 *Reduction of Expansion Caused by Alkali-Silica Reaction (ASR)*

The reaction between the siliceous glass in fly ash and the alkali hydroxides in the Portland-cement paste consumes alkalies, which reduces their availability for expansive reactions with reactive aggregates. The use of adequate amounts of some fly ashes can reduce the amount of aggregate reaction and reduce or eliminate harmful expansion of the concrete (Farbiarz and Carrasquillo, 1987).

2.6.3.5 *Sulfate Resistance*

As a general rule, Class F fly ash can improve the sulfate resistance of concrete mixtures. The increase in sulfate resistance is believed to be due in part to the continued reaction of fly ash with hydroxides in concrete to continue to form additional calcium silicate hydrate (C-S-H), which fills in capillary pores in the cement paste, reducing permeability and the ingress of sulfate solutions.

2.6.3.6 *Efflorescence*

Efflorescence is caused by leaching of water soluble calcium hydroxide and other salts to external concrete surfaces. The leached calcium hydroxide reacts with carbon dioxide in air to form calcium carbonate, the source of the white discoloration on concrete. The use of fly ash in concrete can be effective in reducing efflorescence by reducing permeability. This reduced permeability helps maintain the high alkaline environment in hardened concrete. However, certain Class C fly ashes of high alkali and sulfate contents may increase efflorescence.

2.7 Use of Fly Ash as a Supplementary Cementing Material

2.7.1 General

Fly ash may be used in concrete either as a constituent of an ASTM C 1157 blended cement or as specified in ASTM C 595 for Portland pozzolan cement, Type IP, pozzolan modified Portland cement, Type I (PM), or it may be introduced separately at the concrete mixer. It can be incorporated in the raw mix for the production of Portland clinker (low-quality fly ash) as a raw material and as replacement for Portland clinker for the production of Portland fly-ash cement (low-carbon, high-quality fly ash). In the case of Portland clinker production, fly ash is used as an alternative to clay, shale etc (Cook, James E., 1983).

Fly ash is normally used at the rate of 15 to 35 percent by mass of total cementitious material. Larger proportions of fly ash may be used for mass concrete to reduce the likelihood of cracking upon cooling, to improve sulfate resistance, to control alkali-aggregate reaction, or they may be used in other special applications (Malhotra, 1984; Haque et al., 1984).

The addition of fly ash to the mix is sometimes preferred to the use of fly-ash cement, for the simple reason that any loss in strength may be corrected by changing the fly-ash content (Cook, James E., 1983). Intergrinding of fly ash with cement in the production of blended cement has improved its contribution to strength (EPRI SC-2616-SR). However, the following advantages are claimed in the literature.

i. By treating the fly ash (screening, homogenization, etc.), the variability in its composition can be reduced.
ii. By grinding the clinker (and possibly also the fly ash) to a higher degree of fineness, it is possible to compensate for the loss of early strength development which occurs when only a part of the clinker is replaced by fly ash.
iii. Gypsum anhydrite addition can be adjusted to give the desired setting time.

2.7.2 Portland Composite Cement (PCC)

Portland Composite cements are cements in which a proportion of the Portland cement clinker is replaced by industrial by-products, such as granulated blastfurnace slag (gbs) and power station fly ash (also known as pulverized fuel ash or PFA), certain types of volcanic material (natural pozzolanas) or limestone. The gbs, fly ash and natural pozzolanas react with the hydration products of the Portland cement, producing additional hydrates, which make a positive contribution to concrete strength development and durability. (Massazza, 1988; Moranville-Regourd, 1988). In general, the fly-ash content is 30 % at the most. In principle, the effects of this fly ash on concrete properties are similar to those of the fly ash added to the mixer as a partial Portland cement replacement.

Portland composite cement has some beneficial properties such as workability, lower concrete temperature, reduce cracking, smooth surface of concrete, waterproof, sulphate resistance, high strength and durability. Portland composite cement (PCC) follows European Standard of Cement (EN 197-1: 2000) CEM II.

Table 2.1 summarizes the range of cement compositions permitted by EN 197-1. Table 2.2 summarizes the mechanical and physical requirements for the strength classes permitted by EN 197-1. Compressive strength is determined using the EN 196-1 mortar prism procedure. Setting times are determined by the almost universally applied Vicat needle procedure and soundness by the method first developed by Le Chatelier in the nineteenth century. These methods are described in EN 196-3.

Table 2.1 Cement types and compositions permitted by EN 197-1

Cement type	Notation	Clinker %	Addition %
CEM I	Portland cement CEM I	95–100	–
CEM II	Portland-slag cement II/A-S	80–94	6–20
	II/B-S	65–79	21–35
	Portland-silica fume cement II/A-D	90–94	6–10
	Portland-pozzolana cement II/A-P	80–94	6–20
	II/B-P	65–79	21–35
	II/A-Q	80–94	6–20
	II/B-Q	65–79	21–35
	Portland-fly ash cement II/A-V	80–94	6–20
	II/B-V	65–79	21–35
	II/A-W	80–94	6–20
	II/B-W	65–79	21–35
	Portland-burnt shale cement II/A-T	80–94	6–20
	II/B-T	65–79	21–35
	Portland-limestone cement II/A-L	80–94	6–20
	II/B-L	65–79	21–35
	II/A-LL	80–94	6–20
	II/B-LL	65–79	21–35
	Portland-composite cement II/A-M	80–94	6–20
	II/B-M	65–79	21–35
CEM III	Blastfurnace cement III/A	35–64	36–65
	III/B	20–34	66–80
	III/C	5–19	81–95
CEM IV	Pozzolanic cement IV/A	65–89	11–35
	IV/B	45–64	36–55
CEM V	Composite cement V/A	40–64	36–60
	V/B	20–38	61–80

Notes:
All cements may contain up to 5% minor additional constituent (mac)
CEM V/A Composite cement contains 18–30% blastfurnace slag
CEM V/B Composite cement contains 31–50% blastfurnace slag
Proportions are expressed as % of the cement nucleus (excludes calcium sulfate)

S – blastfurnace slag, D – silica fume, P – natural pozzolana, Q – natural calcined pozzolana, V – siliceous fly ash (e.g. pfa), W – calcareous fly ash (e.g. high-lime fly ash); L and LL – limestone; T – burnt shale, M – two or more of the above.

Table 2.2 Strength setting time and soundness requirements in EN 197-1

Strength class	Compressive strength MPa (EN 196-1 method)				Initial setting time (mm)	Soundness (expansion) (mm)
	Early strength		Standard strength			
	2 days	7 days	28 days			
32,5 N	–	≥16,0	≥32,5	≤52,5	≥75	≤10
32,5 R	≥10,0	–				
42,5 N	≥10,0	–	≥42,5	≤62,5	≥60	
42,5 R	≥20,0	–				
52,5 N	≥20,0	–	≥52,5		≥45	
52,5 R	≥30,0	–				

Figure 2.19 compares the strength development properties of cement prepared by blending a Portland cement with 20% ground limestone, granulated slag, natural pozzolana and fly ash (Moir and Kelham, 1997).

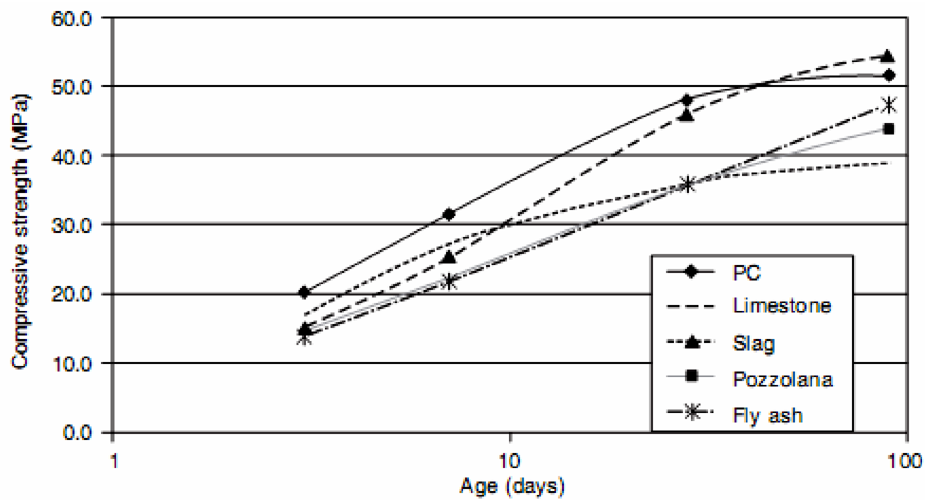

Figure 2.19 Comparative strength growths at 20°C of cements containing 20% limestone, slag, fly ash and pozzolana (BS 4550 concrete, w/c 0.60)

2.8 Strength Development of Concrete of Fly Ash Cement

Although a great deal of information on fly ash and its use in concrete is available, very little of it contributes to an understanding of the interactions between portland cement and fly ash during the hydration and the hardening process which could provide a basis for predicting and improving the performance of fly ash in concrete. Strength at any given age and rate of strength gain of mortars and concretes containing fly ash will depend on the pozzolanic reactivity of the fly ash, the richness of the mix, the character and grading of the aggregate, the water content of the mix and the curing conditions (Hobbs D.W., 1983).

2.8.1 Pozzolanic Reactivity of Fly Ash

The strength of fly ash concrete will depend on whether a water reduction is achieved, plus the pozzolanic performance of the cement/fly ash combination. It is generally accepted that in the pozzolanic reaction of fly ash, the $Ca(OH)_2$ produced during cement hydration reacts with the silicate and aluminate phases of fly ash to produce calcium silicate and aluminate hydrates .The pozzolanic reaction is, Calcium hydroxide + silica = Tricalcium silicate + water

$$3Ca(OH)_2 + SiO_2 = 3CaO \cdot SiO_2 + 3H_2O$$

The hydration products produced fill the interstitial pores reducing the permeability of the matrix. Roy (1987) states ‘the reaction products are highly complex involving phase solubility, synergetic accelerating and retarding effects of multiphase, multi-particle materials and the surface effects at the solid liquid interface’. The reaction products formed differ from the products found in Portland cement only concretes. A very much finer pore structure is produced with time presuming there is access to water to maintain the hydration process. Dhir et al. (1986) have also demonstrated that the addition of fly ash improves the dispersion of the Portland cement particles, improving their reactivity.

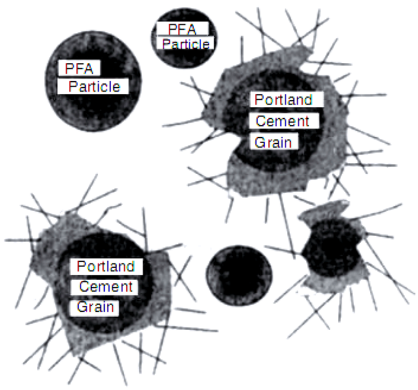

Figure 2.20 Hydration products of Portland cement (Dhir et al., 1986)

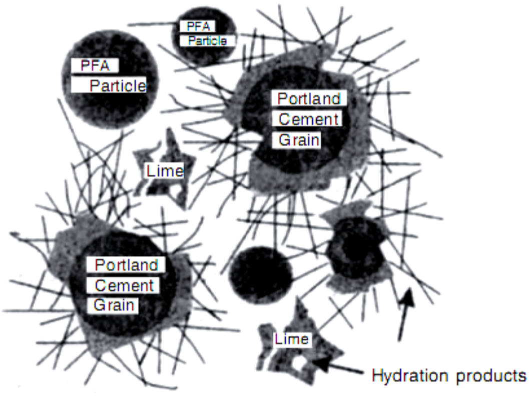

Figure 2.21 Lime is formed as a by- product of hydration (Dhir et al., 1986)

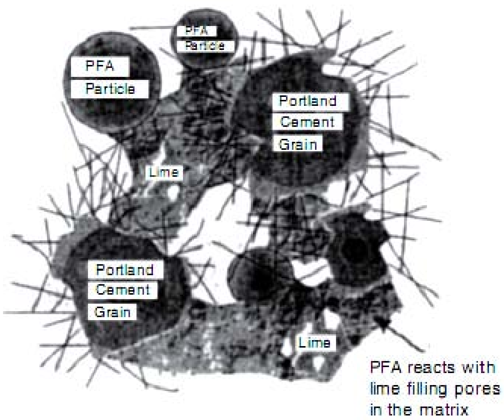

Figure 2.22 The pozzolanic reaction products fill the interstitial spaces (Dhir et al., 1986)

Figures 2.20 to 2.22 show that $Ca(OH)_2$ (hydrated lime) is produced by the reaction of the Portland cement and water. Due to its limited solubility, particles of hydrated lime form within interstitial spaces. With a continuing supply of moisture, the lime reacts with the fly ash pozzolanically, producing additional hydration products of a fine pore structure.

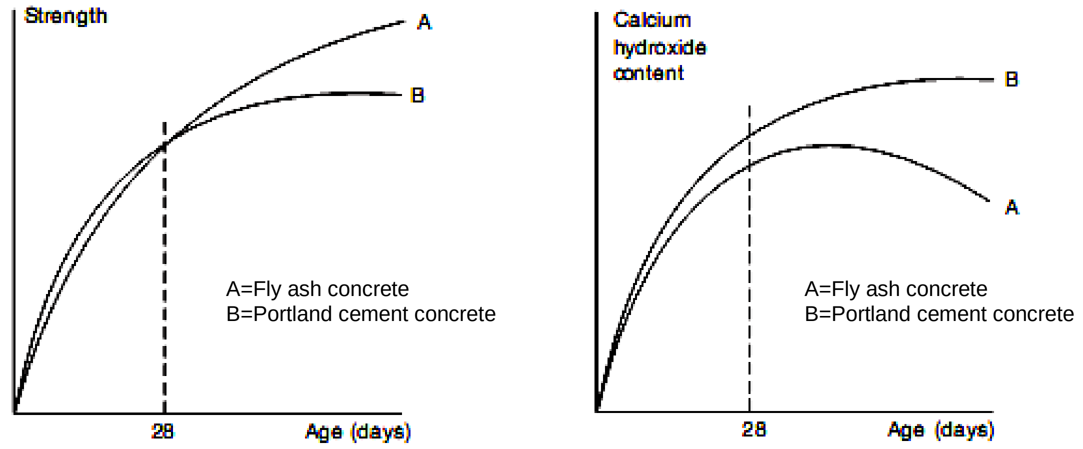

Figure 2.23 Influence of calcium hydroxide on strength development (Cabrera and Flowman, 1981)

Figure 2.23, from Cabrera and Plowman (1981), shows the depletion of calcium hydroxide (lime) with time and how this reaction affects the long-term gain in strength of fly ash concrete (A) compared to a PC concrete control (B). The reaction takes place both within the pores of the cement paste and on the surface of fly ash particles. Despite the pozolanic reaction reducing the available hydrated lime in the pore solution, there is sufficient remaining to maintain a high pH.

Little pozzolanic reaction occurs during the first 24 hours at 20°C. This reaction is much slower than the hydration of the clinker silicates and the strength development of pozzolanic cements is slower than that of 'pure' Portland cements. Thus for a given cementitious content, with increasing fly ash content, lower early strengths are achieved. After the rate of strength contribution of portland cement slows, the continued pozzolanic activity of fly ash contributes to increased strength gain at later ages if the concrete is kept moist; therefore, concrete containing fly ash with equivalent or lower strength at early ages may have equivalent or higher strength at later ages than concrete without fly ash. This higher rate of strength gain will continue with time and result in higher later age strengths than can be achieved by using additional cement (Berry and Malhotra, 1980).

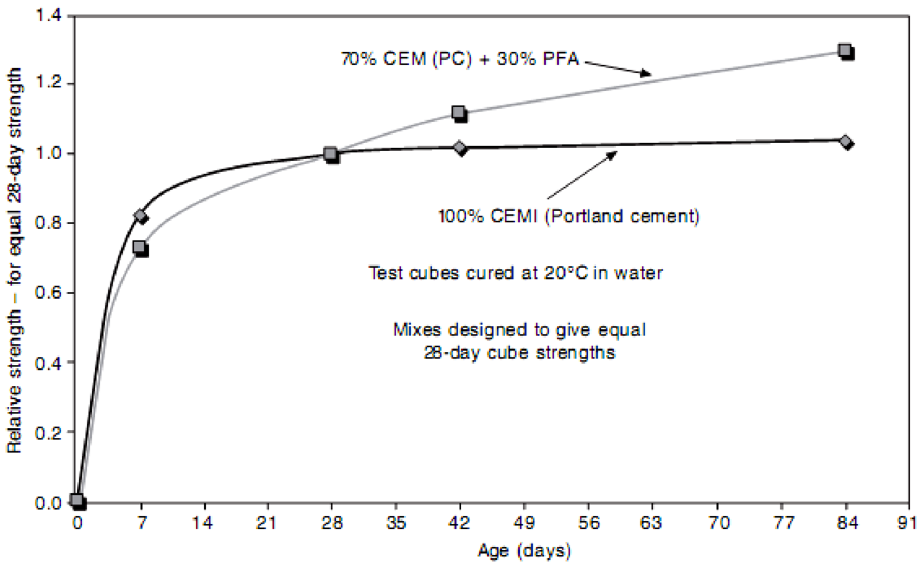

Figure 2.24 At 20°C concrete containing 30 percent fly ash continues to gain significant strength (Brown, 1980)

Using 28-day strengths as a reference, Lane and Best (1982) reported strength increases of 50 percent at one year for concrete containing fly ash, as compared with 30 percent for concrete without fly ash. Other tests, comparing concrete with and without fly ash showed significantly higher performance for the concrete containing fly ash at ages up to 10 years (Mather, 1965). The ability of fly ash to aid in achieving high ultimate strengths has made it a very useful ingredient in the production of high-strength concrete (Blick, Peterson, and Winter, 1974; Schmidt and Hoffman, 1975; Joshi, 1979).

Typically, strength development graphs of standard cubes with and without fly ash are shown in Figure 2.24 (Brown, 1980). The graph also clearly illustrates what effect inclusion of fly ash in concrete has on the development of strength at early ages. Where higher curing temperatures are encountered, as in thick sections, significantly higher in-situ strength can be achieved than in test cubes cured at 20°C. Figure 2.25 (Concrete Society, 1998), shows 30 MPa grade, 1.5 m cubic concrete specimens that have achieved considerably higher in-situ strengths than the 28-day, 20°C cube strengths. These were insulated on five sides to recreate thick concrete sections.

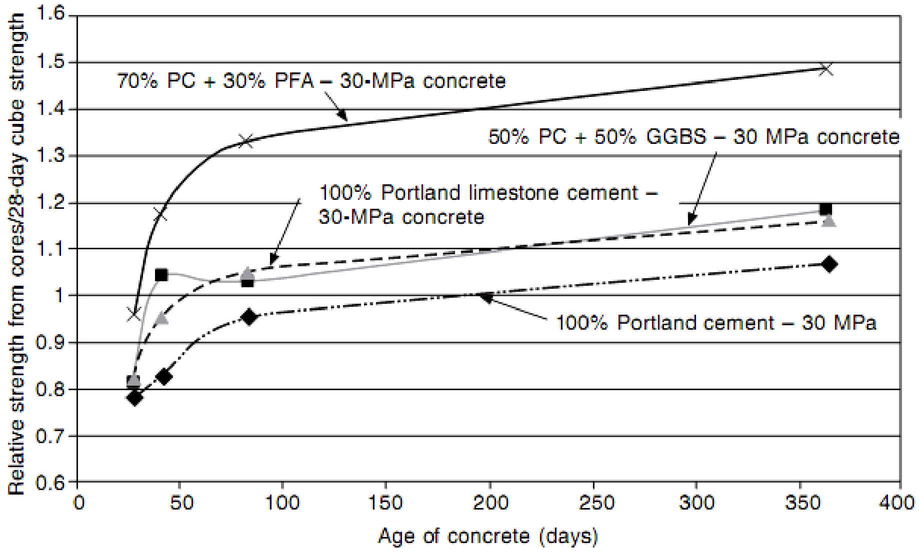

Figure 2.25 30 percent PFA can significantly improve the in-situ strength of concrete in the longer term (Concrete Society, 1998)

2.8.2 Effect of Fineness of fly ash

The fineness of fly ash, particularly of its glassy phase, is considered to be more important than its chemical composition in determining its reactivity and improving the strength characteristics of mortars and concretes. Finer material will dissolve and react faster in the liquid phase of the hydrating system.

Many authors have reported a direct correlation between the fineness of fly ash and its reactivity and effect on the strength development of mortar and concretes, although the effect of fineness may not be evident at the early ages (Costa, 1983). The lower the residue above 45 µm sieve, the greater is the reactivity. Krueger et al. (1982) reported that the fly-ash reactivity correlated better with the 45 µm residue than with the specific surface of fly ash whereas Ravina (1980) found the reverse to be true. Some authors, however, noted only a limited effect of the specific surface or particle size distribution of fly ash on the strength development of concrete (Montgomery, 1981). The coarse fraction of fly ash contributes significantly to early concrete strength only under thermal curing (Ravina, 1981).

Grinding of fly ash increases its fineness and reduces its porosity, both of which have a positive effect on fly-ash reactivity and strength development of concrete (Shen, 1982). However, it is also found to increase the water requirement in the concrete mix, possible entailing an adverse effect on strength development (Entin, 1982).

The particle density of fly ash is typically 2300 kg/m^3, significantly lower than for Portland cement at 3120 kg/m^3. Therefore, for a given mass of Portland cement a direct mass substitution of fly ash gives a greater volume of cementitious material. The mix design for the concrete should be adjusted in comparison to a Portland cement of the same binder content to allow for the increased volume of fine material.

2.8.3 Water Reduction

Dewar's (1986) mix design system correlates with the water reductions found in practice when using fly ash. Where a water reduction is found this partially contributes to the relative strength performance of the cement/fly ash combination by acting as a solid particulate plasticizer. At a fixed water/cement ratio, the range of strengths found indicates coefficients of variation of 17 percent at 365 days and 9 percent at 28 days. With a single source of fly ash, the strength performance can be related to water demand and fineness as in Figure 2.26, from Owens (1979).

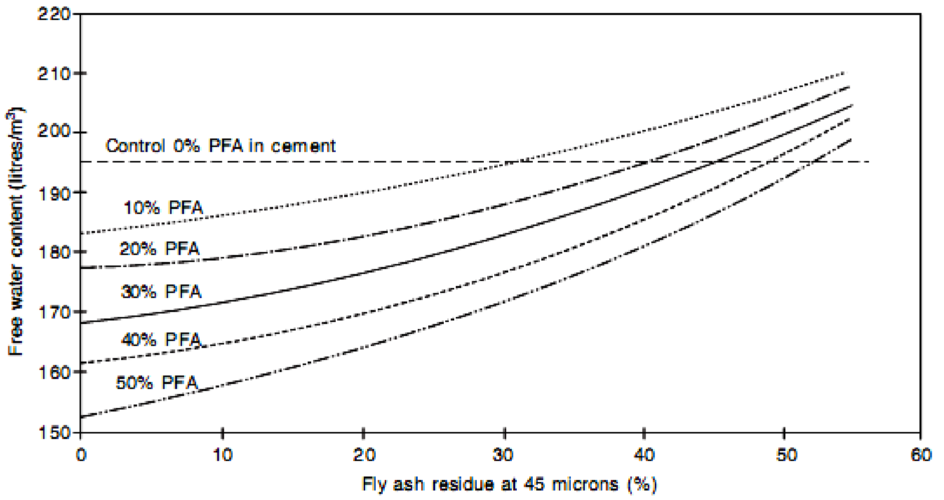

Figure 2.26 Finer fly ash and/or more fly ash reduces water content (Owens, 1979)

The particle shape and finer fractions of fly ash are capable of reducing the water content needed for a given workability. When relatively coarse fly ash, i.e. 45 µm residue >12 percent, is interground with clinker or ground separately, the water requirement of concrete is markedly reduced according to Monk (1983). These effects are felt to be due to void filling on a microscopic scale replacing water within the concrete mix.

2.8.4 Effect of Fly-Ash Type on Concrete Strength

Class C fly ashes often exhibit a higher rate of reaction at early ages than Class F fly ashes (Smith, Raba, and Mearing 1982). Even though Class C fly ash displays increased early age activity, strength at later ages in high-strength concrete appears to be quite acceptable. (Cook, 1982) with Class C fly ash and (Brink and Halstead, 1956) with Class F fly ash showed that, in most cases, the pozzolanic activity increased at all ages proportionally with the percent passing the 45-mm (No. 325) sieve. Class C fly ashes typically give very good strength results at 28 days. (Cook, 1981 and Pitt and Demirel, 1983) reported that some Class C fly ashes were as effective as portland cement on an equivalent-mass basis. However, certain Class C fly ashes may not show the later-age strength gain typical of Class F fly ashes.

The effect of Australian Class F fly ash on strength development with different cements was demonstrated by (Samarin, Munn, and Ashby, 1983) and is shown in Fig. 2.27. Strength development for Class C fly ash is shown in Fig. 2.28.

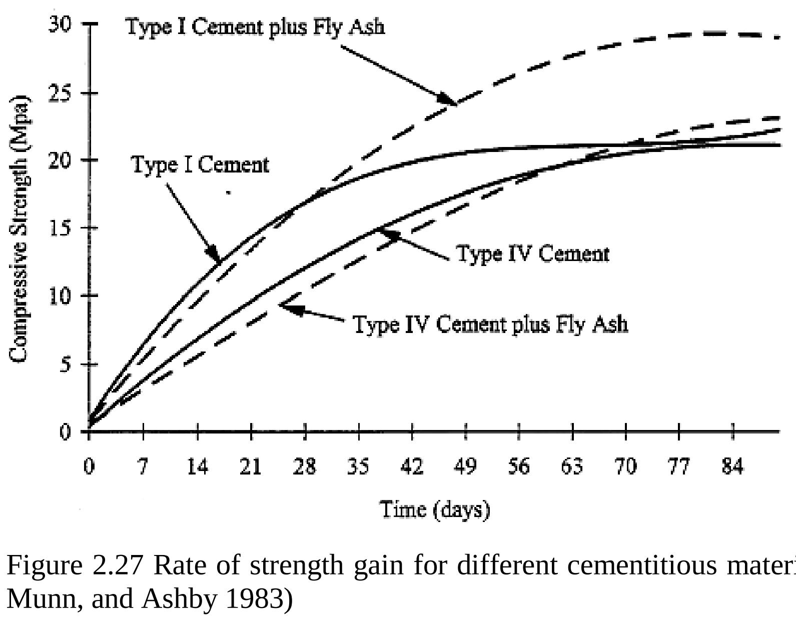

Figure 2.27 Rate of strength gain for different cementitious materials: Class Ffly ash (Samarin, Munn, and Ashby 1983)

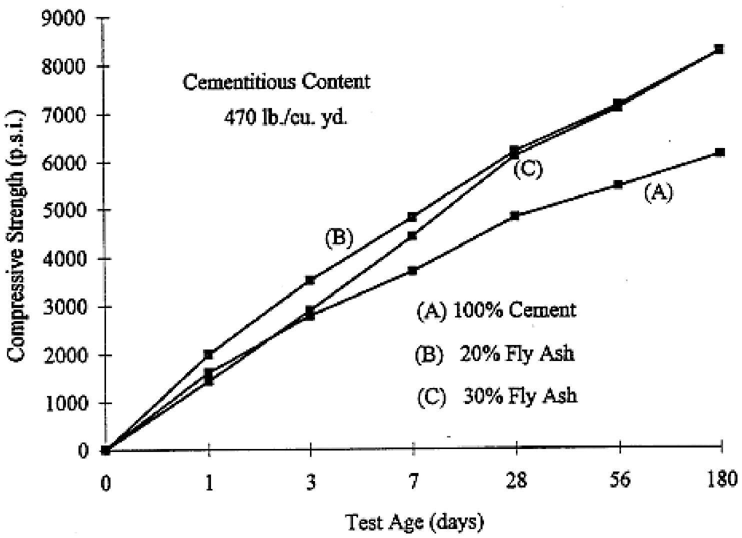

Figure 2.28 Rates of strength gain of Portland cement concrete and concrete in which part of the cement is replaced pound-for-pound with a Class C fly ash (Cook, 1983)

2.8.5 Effects of Temperature and Curing on Strength Development in Fly-Ash Concrete

Several investigations have reported that the strength development and durability of concrete containing fly ash is related to the extent and degree of curing. It has also been substantiated that drying ambient conditions greatly reduce the strength potential of fly ash concrete because the secondary (pozzolanic) reaction fails to contribute to the development of the strength. Given adequate curing the strength development of cement-fly ash paste was superior to plain cement paste. Moist or wet curing is found to be beneficial for the strength development of fly-ash concretes (Matthews, 1978).

Curing and sealing compounds that meet ASTM C-1315 should be used, because this specification requires more moisture retention for curing than ASTM C-309, more in line for concrete containing fly ash.

When concrete made with Portland cement is cured at temperatures greater than 30°C, an increase in strength occurs at early ages but a marked decrease in strength in the mature concrete. Concretes containing fly ash and control concretes behave significantly differently. Figure 2.29 shows the general way in which the temperature maintained during the early ages of curing influence s the 28-day strength of concrete (Williams and Owens, 1982).

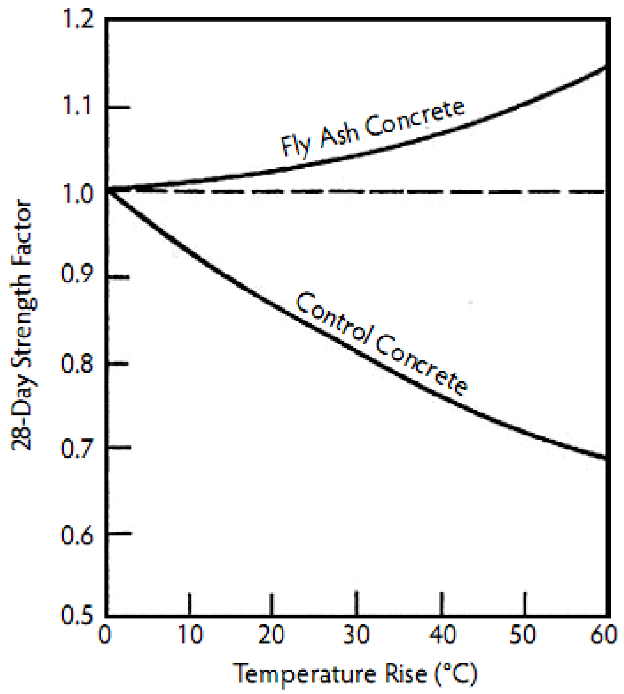

Figure 2.29 Effect of temperature rise during curing on the compressive strength development of concretes. (From Williams, J.T. and Owens, P.L., in Proceedings of International Symposium on the Use of PFA in Concrete, Cabrera, J.G. and Cusens, A.R., Eds., Department of Civil Engineering, University of Leeds, Leeds, U.K., 1982, pp. 301–313.

2.8.6 Effect of Mixture Proportioning

Apart from the quality of fly ash and cement, the method of mix design is the single most important factor influencing the properties of fly-ash concrete. A substantial amount of work in the literature suggests that the partial replacement of cement (either by weight or by volume) in mortar or concrete by fly ash results in lower compressive strength at early ages (about 3 to 6 months), with development of greater strength as compared to control concrete at and beyond 6 months (Fig. 2.29).

An increased amount of fly ash in the mix delays setting and may slow down strength development at the early ages (Samarin, 1983). High-calcium fly ashes develop better early strength than low-calcium fly ashes, although they may cause false setting (Yuan, 1983). Faster strength development is achieved by reducing water content and raising curing temperature (Ravina, 1981). However, (Butler et al. 1982) have reported lower ultimate strengths for mortars cured at higher temperatures.

Partial replacement of cement and fine aggregate by fly ash in the concrete mix results in a concrete with early strengths usually comparable to those of control mixes, but with higher strengths at later ages. Partial replacement of aggregate, whether fine or both fine and coarse, by fly ash generally produces concrete with increased strength at all ages as compared to control mixes. These observations obviously result from the fact that there is no reduction in cement content in the mix, and that there is increased cement hydration after one day.

2.8.7 Achievement of Early Strength of Fly Ash Concrete by Admixture

Compared with concrete without fly ash proportioned for equivalent 28-day compressive strength, concrete containing a typical Class F fly ash may develop lower strength at 7 days of age or before when tested at room temperature (Abdun-Nur, 1961). If equivalent 3-day or 7-day strength is desired, it may be possible to provide the desired strength by using accelerators or water-reducers, or by changing the mixture proportions (Bhardwaj, Batra and Sastry, 1980; Swamy, Ali and Theodor-Akopoulos, 1983).

Test results indicate that silica fume can be used, for example, in fly ash concrete to increase the early-age strength; simultaneous use of silica fume and fly ash resulted in a continuing increase in 56 and 91 day strengths indicating the presence of sufficient calcium ion for both the silica-fume reaction and the longer term fly-ash reaction to continue (Carette and Malhotra, 1983). Also, (Mukherjee, Loughborough and Malhotra, 1982) have shown that increased early strengths can be achieved in fly ash concrete by using high-range water reducing admixtures to reduce the water to cementitious material ratio to at least as low as 0.28.

2.9 Fly Ash Concrete Mixture Proportioning

The total mass of the cementitious material and the optimum proportion of fly ash selected depend on the class and quality of fly ash; the type, quality, and alkali content of the portland cement; the presence of chemical admixtures; placement conditions and parameters such as strength requirements, curing conditions, and weather conditions at the time of placement (Prusinski, Fouad and Donovan (1993); Majko and Pistilli, 1984).

2.9.1 Considerations in Mixture Proportioning

Following considerations can be followed while making mixture proportion of fly ash concrete (ACI 232.2R-96).

a) When fly ash is used, indications are that the total volume of cementitious material used (cement plus fly ash) must exceed the volume of cement used in cement-only mixtures to produce equal early strength and equal slump.
b) The optimum use of fly ash and chemical admixtures often requires that adjustments be made in the ratio of cement to fly ash between winter and summer conditions. For example, in cold weather, a reduction in the fly ash percentage of the cementitious material may be prudent or a change in the type of chemical admixture or dosage rate may be indicated to permit earlier finishing or form removal. Conversely, hot weather concreting provides greater opportunities for using high proportions of fly ash since higher curing temperatures tend to increase the relative strength of fly-ash concrete compared to non-fly ash concrete at all ages, especially if long term curing is provided.
c) Because use of fly ash normally contributes additional volume to the concrete, certain adjustments must be made to proportions. When following ACI 211.1, the volume of fine aggregates should be adjusted to compensate for this increase and for any change in volume of mixing water and air void system. Generally, a small reduction in the mixing water demand can be expected when fly ash is used.

Most specifying agencies and concrete producers compute an equivalent water-cement ratio (w/c) for fly ash concrete by adding the cement + pozzolan by mass to get a water to total cementitious material ratio by mass. This ratio is sometimes called the water to binder ratio (ACI 363R). This is a consistent approach since the fly ash in a blended cement meeting ASTM C 595 will be counted as part of the cement. In those cases where a maximum water-cement ratio or a minimum cement content is specified or recommended, it is generally accepted practice to count the mass of the fly ash as part of the amount of cementitious material required when separately batched fly ash is used.

The most effective method for evaluating the performance of a given fly ash in concrete and establishing proper mixture proportions for a specific application is by use of a trial batch and testing program (ACI 211.1). Because different fly ashes have different properties and concrete requirements differ, proportions for a given fly ash and cement cannot be prescribed for all materials combinations and requirements. Therefore, a series of mixtures should be prepared and tested to determine the required total amount of cementitious materials to obtain a specified strength with various percentages of fly ash (Ghosh, 1976; Cook, 1983).

2.10 Fly Ash: A Raw Material of Cement in Bangladesh

Bangladesh's cement industry totally depends on imported raw materials, of which clinker is the main one. About 5-6 million tones of clinker is imported annually from Thailand, Indonesia, Malaysia and the Philippines. Clinker is also imported in small quantity from India by railway.

The price of raw materials, especially clinker (major component for cement manufacturing), has gone up by about 30 percent in recent years. Market players believe international prices of clinker and other raw materials will not go down soon as the demands in China and India for these raw materials are rising rapidly. In this situation most of the factories in Mongla, Khulna, Jessore and North Bengal areas have been shut down because of their financial inability to compete with big market players in the face of rising production cost. Even Meghna cement, produced by Bashundhara, one of the largest business conglomerates in the country, also reduced its production capacity recently.

To minimize the rising production cost of cement and to make the cement industry stable, cement manufacturing companies of Bangladesh have been using fly ash, slag in cement as a partial replacement of clinker for past several years. Since 2002, a joint venture cement grinding company introduced cement, which is mixed with fly ash, now mostly used by most of the cement grinding companies in the country. Bangladesh spent hundreds of millions of dollars for past several years in importing fly ash from India, thus mixing it with clinker, as such productions are much cheaper compared to clinker-gypsum mixing formula. Most of the cement grinding companies in the country are selling this fly ash mixed cement as Portland composite cement (PCC) in the local market.

In the regular method of producing ordinary Portland cement, 95 percent clinker is mixed with 5 percent gypsum while in the production of Portland composite cement 65-80 percent clinker is mixed with 20-35 percent fly ash. The replacement of 20-30 percent clinker with fly ash effect the strength gain properties of concrete. That is why it is necessary to find out the fact of strength gain property of concrete made with Portland composite cements (PCC).

CHAPTER- 3

PREPARATION, MAKING AND TESTING OF CONCRETE

3.1 General

ACI mix design method is used to determine the amount of concrete ingredients for making concrete. This method requires knowing several properties of concrete ingredients. That is why properties of cement, coarse aggregate and fine aggregate have been determined with due care. The methods of determination of the properties of concrete ingredients and preparation, making and testing of concrete specimens are described in this chapter.

3.2 Properties of Coarse Aggregate

Aggregate act as an inert filler in the concrete providing improved volume stability. Crushed stone of maximum size ¾ in. has been used in this project. Following tests have been performed to determine the properties of coarse aggregate.

3.2.1 Bulk Specific Gravity and Absorption Capacity of Coarse Aggregate

This test method covers the determination of specific gravity and absorption capacity of coarse aggregate. This test method confirms to the ASTM standard requirements of specification C127.

Bulk Specific gravity (saturated surface dry) = $\frac{B}{B-C}$

Absorption capacity, % = $\frac{B-A}{A} \times 100$

Where, A=Weight of oven dry test sample in air, g

B= Weight of saturated surface dry test sample in air, g and

C=Weight of saturated test sample in water, g

Bulk Specific gravity and absorption capacity of coarse aggregate are found 2.71 and 0.45% respectively.

3.2.2 Unit Weight of Coarse Aggregate

This test method covers the determination of unit weight of coarse aggregate. This test method confirms to the ASTM standard requirements of specification C 29.

Unit weight, $M = \frac{G-T}{V}$

Where, M=Unit of the aggregate, lb/ft^3

G=Mass of the aggregate plus the measure, lb

T=Mass of the measure, lb

V=Volume of the measure, ft^3

Unit weight of coarse aggregate is found 97 lb/ft^3

3.2.3 Sieve Analysis of Coarse Aggregate

The term sieve analysis is given to the simple operation of dividing a sample of aggregate into fraction each consisting of particles between specific limits. The analysis is conducted to determine the grading of materials proposed for use as an aggregate or being used as aggregate. This test method confirms to the ASTM standard requirements of specification C 136.

Sieve analysis of coarse aggregate shows that the value of fineness modulus is 7.4

3.3 Properties of Fine Aggregate

In this project, Sylhet sand has been used as most of the construction works in Bangladesh is done using this sand. Following tests have been performed to determine the properties of fine aggregate.

3.3.1 Bulk Specific Gravity and Absorption Capacity of Fine Aggregate

Bulk specific gravity is defined as the ratio of the weight of the aggregate (oven dry or saturated surface dry) to the weight of the water occupying a volume equal to that of the solid.

A absorption value is used to calculate the change in the weight of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition. For an aggregate that has been in contact with water and that has free moisture on the particle surfaces, the percentage of free moisture can be determined by deducting the absorption from the total moisture content. This test method confirms to the ASTM standard requirements of specification C 128.

Bulk Specific gravity (saturated surface dry) = $\frac{B}{B+S-C}$

Absorption, % = $\frac{S-A}{A} \times 100$

Where, A=Weight of oven dry specimen in air, g

B=Weight of pycnometer filled with water, g

S= Weight of saturated surface dry specimen, g and

C=Weight of pycnometer with specimen and water to calibration mark, g

Bulk Specific gravity and absorption capacity of fine aggregate is 2.56 and 1.21% respectively.

3.3.2 Sieve Analysis of Fine Aggregate

The term fineness modulus (F.M.) is a ready index of coarseness or fineness of the material. It is an empirical factor obtained by adding the cumulative percentages of aggregates retained on each of the standard sieves and dividing this sum arbitrarily by 100. No. 100, No. 50, No.30, No.16, No.8, No.4, 3/8 in, 3/4 in, 1.5 in are the ASTM standard sieves. This test method confirms to the ASTM standard requirements of specification C 136.

Sieve analysis of fine aggregate shows that the value of fineness modulus is 2.56

3.4 Properties of Cement

In this project Portland composite cement (PCC) of four different brands and one ordinary Portland cement (OPC) have been used in making concrete.

Portland Composite cements (PCC): Brand -A, Brand -B, Brand –C and Brand -D

Ordinary Portland cement (OPC): Brand –E

Table 3.1 Proportions of ingredients in cements

	Brand-A	Brand-B	Brand-C	Brand-D	Brand-E
Clinker	65%~79%	70%~79%	65%~ 79%	80%~94%	95%~100%
Gypsum	0%~5%	0% ~ 5%	0% ~ 5%	0% ~ 5%	0% ~ 5%
Slag, Fly Ash, Limestone	21%~ 35%	21%~30%	21%~ 35%	06%~ 20%	-

3.4.1 Normal Consistency of Cement with Vicat's Apparatus

The amount of water content that brings the cement paste to standard condition of wetness is called "normal consistency". It has a marked effect upon the time of set as well as upon other properties. The paste at normal consistency is fairly stiff and is used only for the determination of time of set and soundness.

The test method conforms to the ASTM standard requirements of specification C187.The usual range of values being between 22 to 30 percent by weight of dry cement. Test results for normal consistency of the tested cements are plotted in table 3.2

3.4.2 Initial and Final Setting Time of Cement

The term "initial setting time" indicates the beginning of the setting process of cement paste when cement paste starts losing its plasticity. The "final setting time" is the time elapsed between the moment the water is added to cement and the time when completely lost its plasticity and attained sufficient stability to resist certain definite pressure.

This test method conforms to the ASTM standard requirements of specification C191. As per ASTM C150, Ordinary Portland cement should have initial setting time not less than 45 minutes and final setting time not more than 375 minutes. Test results for initial and final setting time of the cement are plotted in table 3.2

3.4.3 Direct Compressive Strength of Cement Mortar

The mechanical strength of hardened cement is the property of this material which is, perhaps, the most important one for its structural use. Tests for strength are not made on a neat cement paste because of difficulties in moulding and testing with a consequent large variation in results.

Compression strength tests of cement is done by preparing mortar cubes, typically 2 in. x 2 in. x 2 in. then curing them for 28 days. The curing temperature is typically 20 degrees centigrade. After reaching the required age for testing, the cubes are crushed in a large press. This test method conforms to the ASTM standard requirements of specification C109. Test results for direct compressive strength of the tested cement mortar are plotted in table 3.2

Table 3.2 Test result of cement

Properties of cement		Standard requirements (OPC)	Brand A	Brand B	Brand C	Brand D	Brand E
Compressive strength, psi (ASTM C109)	3 days	1740	3200	2450	3120	2920	3018
	7days	2760	3550	3810	4120	4030	4326
	28days	4060	4540	5480	5470	4920	5681
Initial setting time, min. (ASTM C191)		Not less than 45 min.	89	90	124	116	79
Final setting time, min. (ASTM C191)		Not more than 375 min.	332	305	390	294	296
Water for normal consistency(ASTM C187)		(22-30) %	24.5%	26.5%	26%	25%	23%

3.5 Determination of Rate of Strength Gain of Concrete

As the target of this project is to find out the strength gain rate of concrete made with locally available Portland composite cements (PCC). That is why, the properties of concrete ingredients (coarse aggregate, fine aggregate, water) have been kept unchanged, only the cement type has been changed. Portland composite cement (PCC) of four different brands and one ordinary Portland cement have been used in making concrete. Portland composite cements (PCC) are: cement brand-A, brand-B, brand-C and brand-D and ordinary Portland cement is cement brand-E.

3.5.1 Mixture Proportion of Concrete

Amount of concrete ingredients have been calculated for target strength of 2500 psi, 4000 psi and 6000 psi by ACI mix design method of concrete of ordinary Portland cement. This method has been followed to keep in similarity with local practice. According to ACI mix design method, the required quantity of concrete ingredients for casting concrete is listed in table 3.3. One sample mix design calculation has been shown in Appendix-A.

Table 3.3 Amount of ingredients required for making concrete

Target strength psi	Slump, (in.)	Cement, kg	Water, kg	Fine aggregate, kg	Coarse aggregate, kg
2500	(3–4)	24.70	18.52	75.67	93.16
4000	(1–2)	30.13	17.16	74.75	93.16
6000	(1–2)	41.86	17.16	65.07	93.16

3.5.2 Casting of Concrete

Concrete have been cast for the target strength of 2500 psi, 4000 psi and 6000 psi using Portland composite cement (PCC) of four different brands and one ordinary Portland cement. Compaction of concrete specimens has been done by table vibrator.

In this project, the mould that has been used is cylindrical in shape with 4 inch diameter and 8 inch height in size. Number of specimens is;

- Curing type: 2 (continuously curing and only 14 days curing)
- Concrete cylinder of same property tested at each testing period : 3 Nos
- Total number of cement type: 5 Nos (4 PCC + one OPC)
- Number of different target strength: 3 Nos (2500 psi, 4000 psi and 6000 psi)
- Period of concrete testing: 7 Nos (3 days,7 days, 14 days, 28 days, 3 months, 6 months and 1 year)

So, total number of concrete specimens required = (7x3x3x5) + (4x3x3x5) = 495 Nos.

3.5.3 Curing of Concrete

Concrete have been cured two different ways, one set of concrete specimens have been cured continuously until they are tested while the other set of concrete specimens have been cured only 14 days under water. These 14 days cured specimens have been kept in air until they are tested. A curing tank has been constructed for curing the concrete specimens properly. The temperature of the curing water varies from 20 to 25 degree celsius.

3.5.4 Compressive Strength Test of Concrete

Compressive strength of concrete is taken as a measure to determine the rate of strength gain with age of concrete made with Portland composite cement (PCC). It is one of the most important and useful properties of concrete. It usually gives an overall picture of the quality of concrete because it is directly related to the structure of the hardened cement paste. This test method conforms to the ASTM standard requirements of specification C 39.

Compressive strength test of moist cured concrete specimens has been made as soon as practicable after removal from moist storage. The compressive strength of concrete cylinders have been tested at 3 days, 7 days, 14 days, 28 days, 3 months, 6 months and 1 year of age of concrete.

3.5.5 Calculation of Compressive Strength of Concrete

The compressive strength of the concrete specimen is calculated by dividing the maximum load gained by the specimen during the test by the average cross-sectional area of the specimen.

Load has been applied until the concrete specimen fails. The maximum load carried by the concrete specimen during the test has been recorded and the compressive strength has been calculated as follows:

$$f_m = \frac{P}{A}$$

Where, f_m = Compressive strength in psi

P = Total maximum load in psi

A = Area of loaded surface in in^2

3.5.6 Analysis of Test Result

Bar charts have been plotted for percent of target Compressive strength gain with age of concrete which shows a comparison of compressive strength gain of concrete made with Portland composite cement and ordinary Portland cement. The time required by the concrete made with Portland composite cement to gain full target strength relative to that of ordinary Portland cement has been estimated. Also the strength variation of concrete made with Portland composite cement at different ages have been investigated for continuously curing condition and only 14 days curing condition.

3.6 Procedure of Concrete Making and Testing

Procedure of making and testing of concrete specimens has been shown in the following figures.

Figure 3.1 Pouring of concrete ingredients into the mixer machine

Figure 3.2 Mixing of concrete ingredients in the mixer machine

Figure 3.3 Adding water into the mixture machine

Figure 3.4 Formation of concrete paste in the mixer machine

Figure 3.5 Removing concrete from the mixer machine

Figure 3.6 Filling the cone sampler with concrete for slump test

Figure 3.7 Measuring the slump value of the prepared concrete

Figure 3.8 Filling the cylindrical mold with concrete

Figure 3.9 Placing the cylinder on the vibration table for compaction

Figure 3.10 Compaction of concrete by the vibration machine

Figure 3.11 Leaving the concrete specimens for hardening for 24 hours

Figure 3.12 Placing of concrete specimens into the curing tank

Figure 3.13 Capping of concrete cylinders before compressive strength test

Figure 3.14 Applying load on the concrete cylinder by compression test machine

Figure 3.15 Formation of cracks at the concrete cylinder

Figure 3.16 Failure surface of the crushed concrete cylinder

CHAPTER-4

RATE OF STRENGTH GAIN OF CONCRETE

4.1 General

Compressive strength of concrete is taken as a measure to determine the rate of strength gain of concrete. It gives an overall picture of the quality of concrete because it is directly related to the structure of the hardened cement paste. Concrete have been made with Portland composite cement (PCC) of four different brands (brand-A, brand-B, brand-C and brand-D) and one ordinary Portland cement (brand-E) for the target strength of 2500 psi, 4000 psi and 6000 psi where mix design procedure of ordinary Portland cement have been followed. The compressive strength of concrete cylinders has been tested at 3 days, 7 days, 14 days, 28 days, 3 months, 6 months and 1 year of age of concrete. Concrete have been cured two different ways, one set of concrete cylinders have been cured continuously until they are tested while the other set of concrete cylinders have been cured only 14 days under water to know the effect of curing on strength development of concrete.

4.2 The Relative Strength Gain Properties of Concrete

The relative strength gain of concrete made with Portland composite cements (PCC) and ordinary portland cement (OPC) for target strength of 2500 psi is shown in fig.4.1, fig.4.2, fig.4.3 and fig.4.4 for cement brand-A, brand-B, brand-C and brand-D respectively. The common characteristics of these figures is that the percentage of target compressive strength gain at early ages (3 days, 7 days, 14 days) of concrete made with Portland composite cement (PCC) is lower in magnitude than that of concrete made with ordinary portland cement (OPC). But at later ages (180 days, 365 days), the percentage of target strength of concrete made with portland composite cements and ordinary portland cement is almost same. The only exception is found in case of cement brand-D where the percentage of target compressive strength gain of concrete at early age (3 days) is higher in magnitude than that of concrete made with other portland composite cement brands (brand-A, brand-B, brand-C) since brand-D contains higher percentage of clinker (80%-94%) thus lower percentage of fly ash whereas cement brand A and C contain 65% to 79% clinker and brand-B contains 70% to 79% clinker.

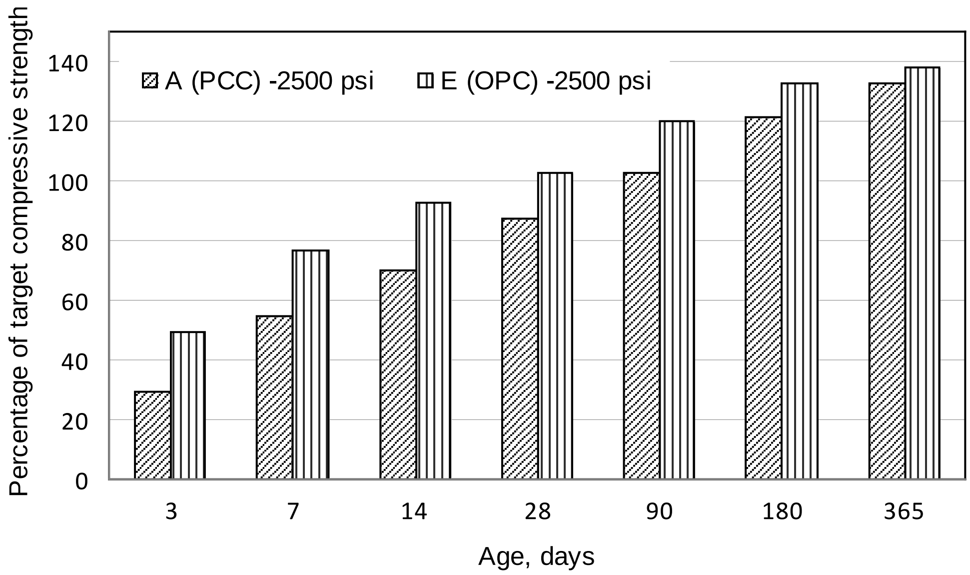

Fig: 4.1 Comparison of compressive strength gain with age of concrete made with cement brand-A and brand-E for 2500 psi

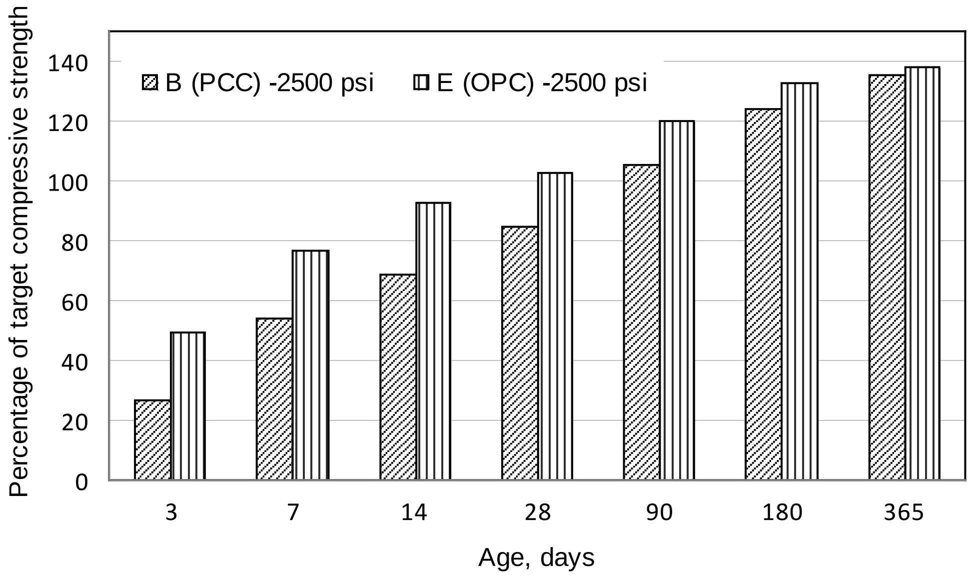

Fig: 4.2 Comparison of compressive strength gain with age of concrete made with cement brand-B and brand-E for 2500 psi

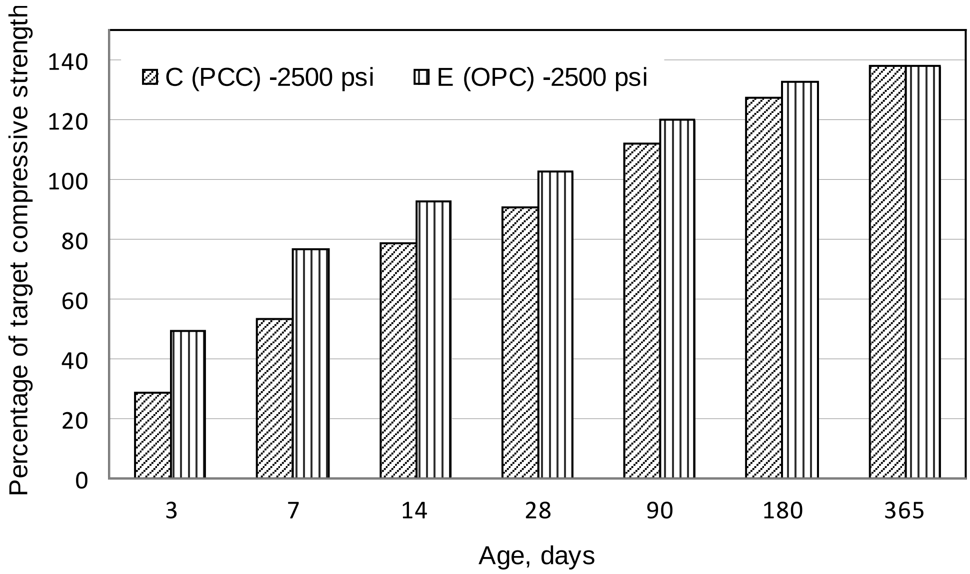

Fig: 4.3 Comparison of compressive strength gain with age of concrete made with cement brand-C and brand-E for 2500 psi

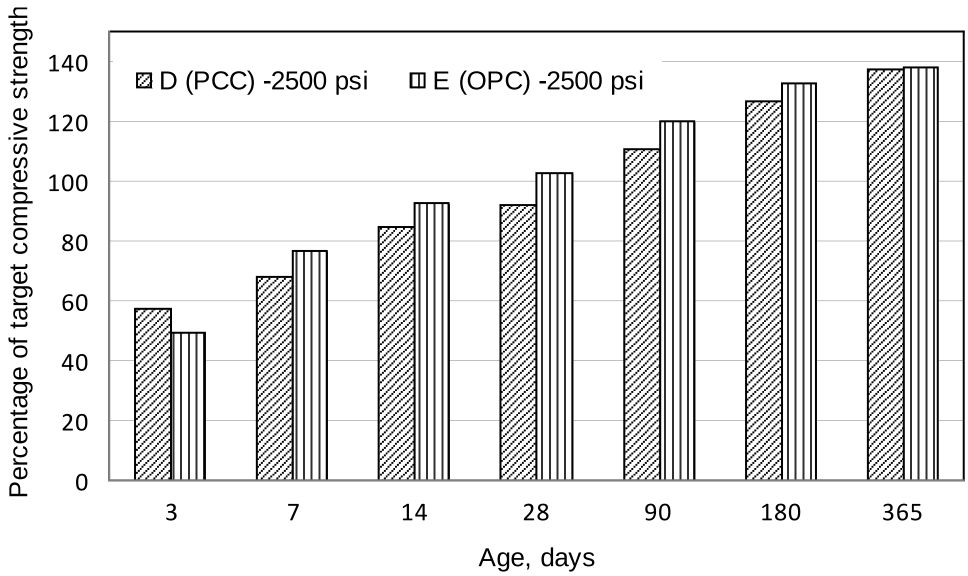

Fig: 4.4 Comparison of compressive strength gain with age of concrete made with cement brand-D and brand-E for 2500 psi

The relative strength gain of concrete made with Portland composite cements (PCC) and ordinary portland cement (OPC) for target strength of 4000 psi is shown in fig.4.5, fig.4.6, fig.4.7 and fig.4.8 for cement brand-A, brand-B, brand-C and brand-D respectively. Figures show that concrete made with portland composite cement have gained 15 percent less strength at 14 days of age than that of conrete made with ordinary portland cement. But at the end of 1 year, they have gained similar percentage of target strength at continuous curing condition.

The only exception is found in case of cement brand-D where the percentage of target compressive strength gain of concrete at early age (3 days) is higher in magnitude than that of concrete made with other composite cement brands (brand-A, brand-B, brand-C) since brand-D contains higher percentage of clinker thus lower percentage of fly ash.

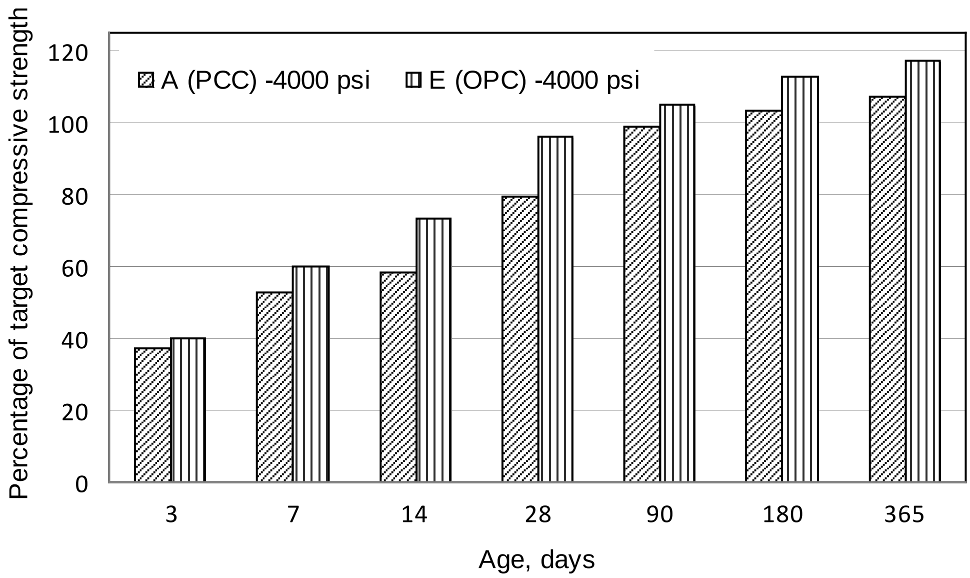

Fig: 4.5 Comparison of compressive strength gain with age of concrete made with cement brand-A and brand-E for 4000 psi

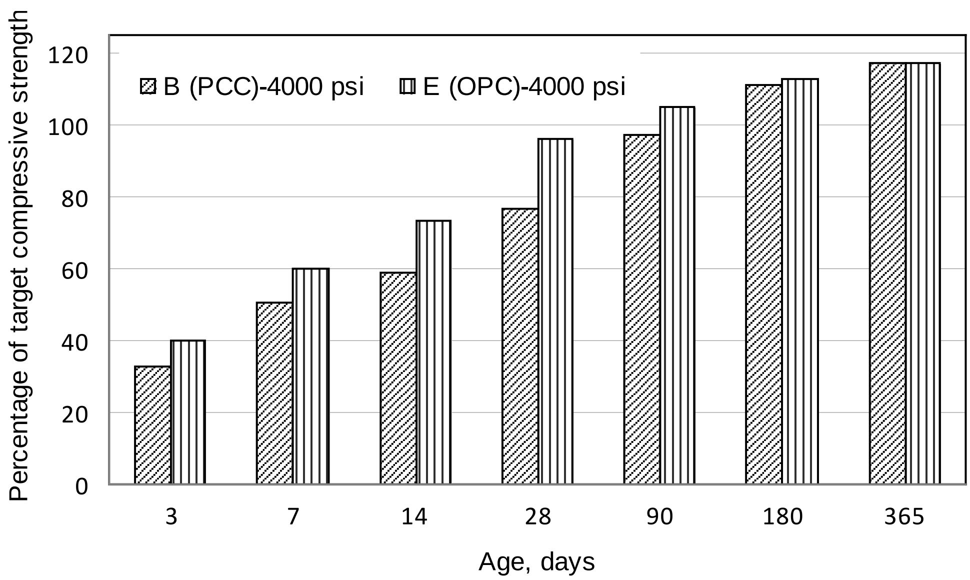

Fig: 4.6 Comparison of compressive strength gain with age of concrete made with cement brand-B and brand-E for 4000 psi

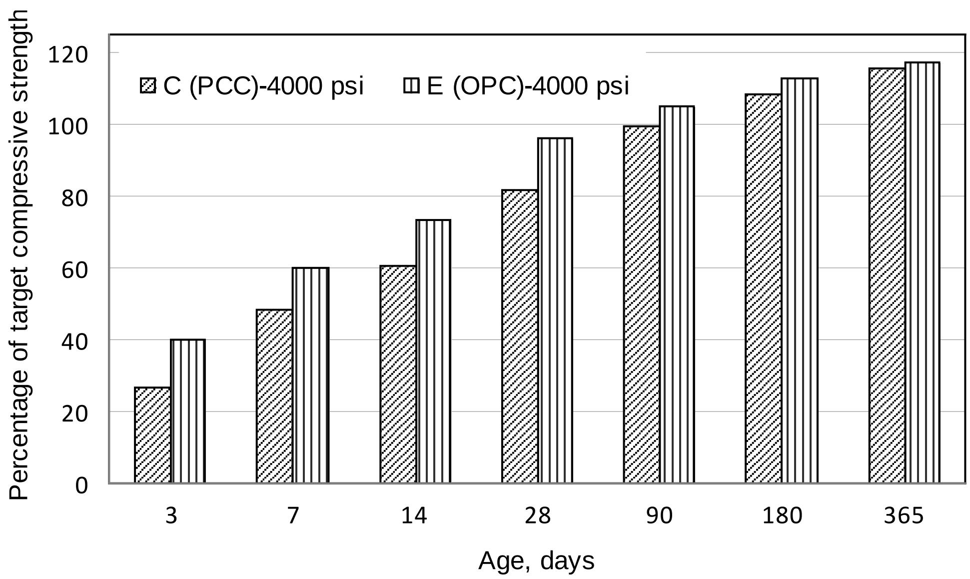

Fig: 4.7 Comparison of compressive strength gain with age of concrete made with cement brand-C and brand-E for 4000 psi

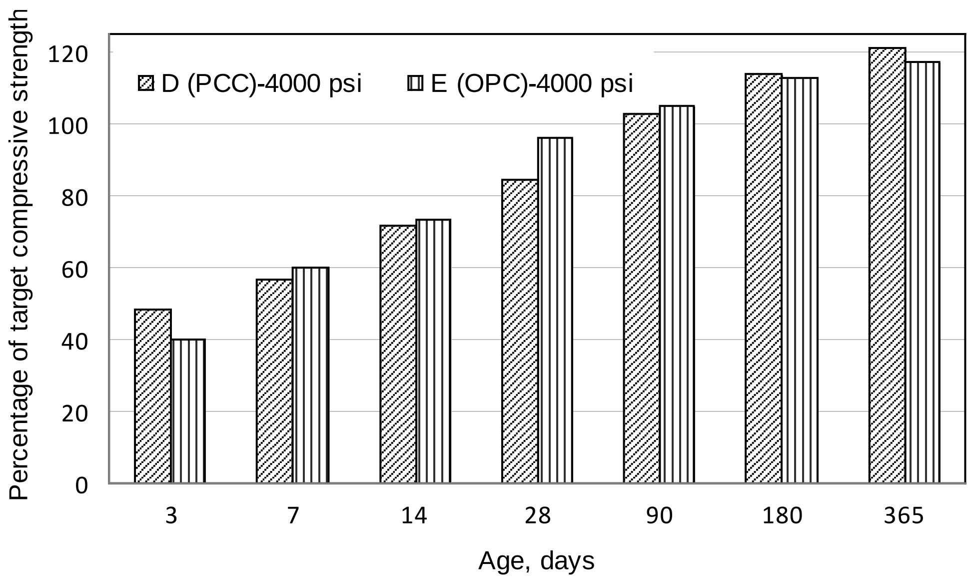

Fig: 4.8 Comparison of compressive strength gain with age of concrete made with cement brand-D and brand-E for 4000 psi

The relative strength gain of concrete made with Portland composite cements (PCC) and ordinary portland cement (OPC) for target strength of 6000 psi is shown in fig.4.9, fig.4.10, fig.4.11 and fig.4.12 for cement brand-A, brand-B, brand-C and brand-D respectively. It is found that concrete made with portland composite cement gains 15 to 20 percent less strength at early ages (3 days, 7 days, 14 days) than that of concrete made with ordinary portland cement. But at later ages (180 days, 365 days), concrete made with portland composite cement have gained only 5 percent less strength than that of concrete made with ordinary portland cement at continuous curing condition.

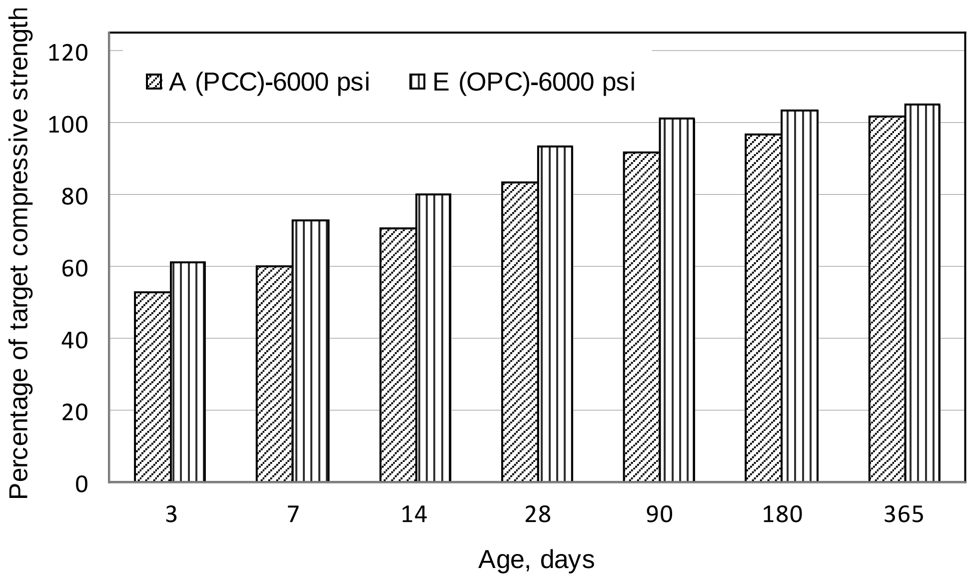

Fig: 4.9 Comparison of compressive strength gain with age of concrete made with cement brand-A and brand-E for 6000 psi

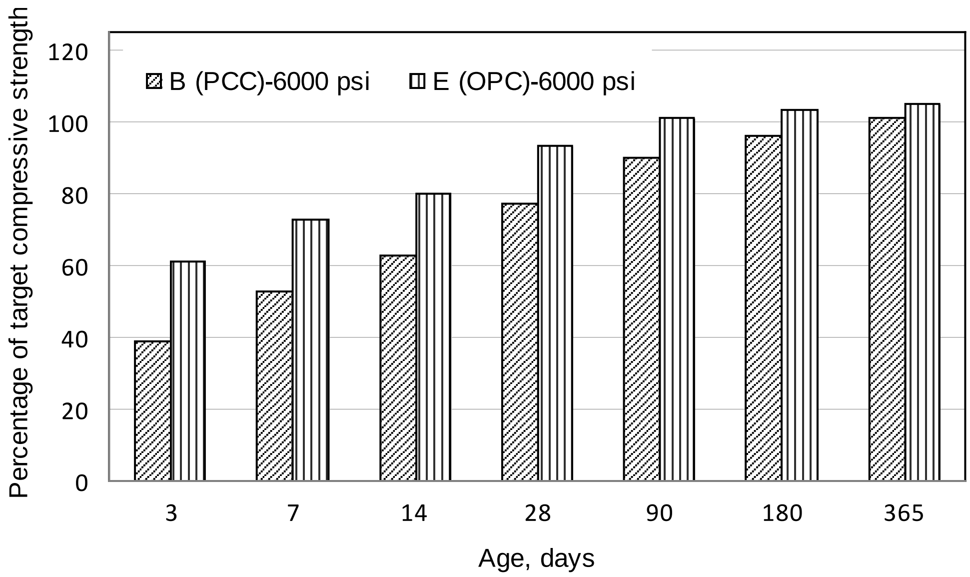

Fig: 4.10 Comparison of compressive strength gain with age of concrete made with cement brand-B and brand-E for 6000 psi

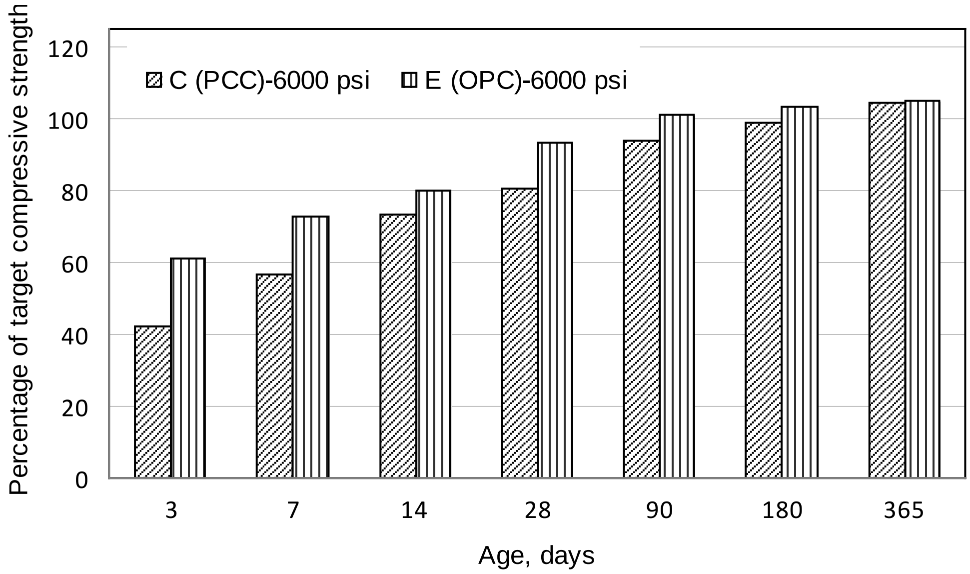

Fig: 4.11 Comparison of compressive strength gain with age of concrete made with cement brand-C and brand-E for 6000 psi

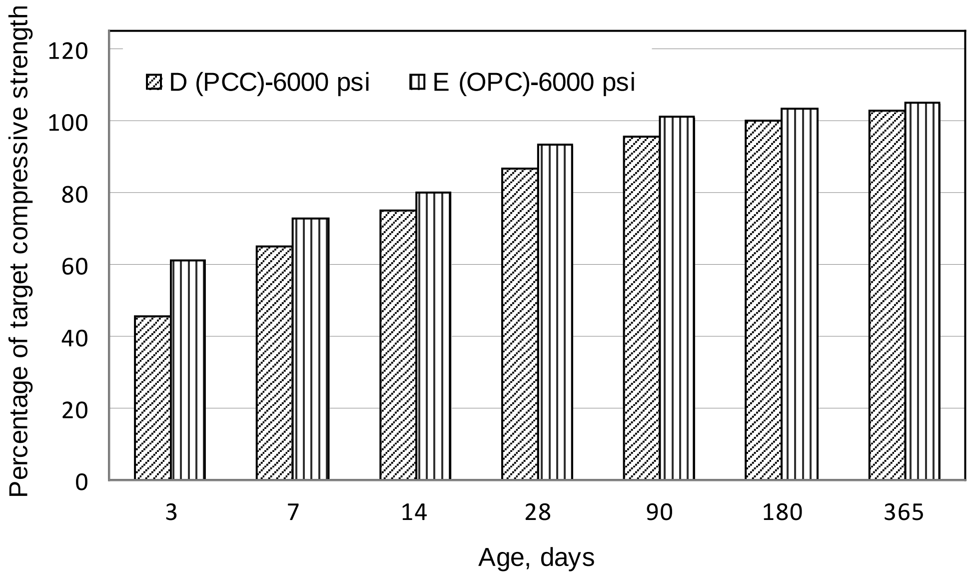

Fig: 4.12 Comparison of compressive strength gain with age of concrete made with cement brand-D and brand-E for 6000 psi

4.3 Development of Compressive Strength of Concrete at Early Ages

Concrete made with Portland composite cement (PCC) and ordinary portland cement (OPC) show different characteristics in strength development at early ages. Fig.4.13, Fig.4.14 and Fig.4.15 show the variation of strength gain characteristics of concrete at early ages with cement type at continuous curing condition that have been designed for target strengths of 2500 psi, 4000 psi and 6000 psi respectively.

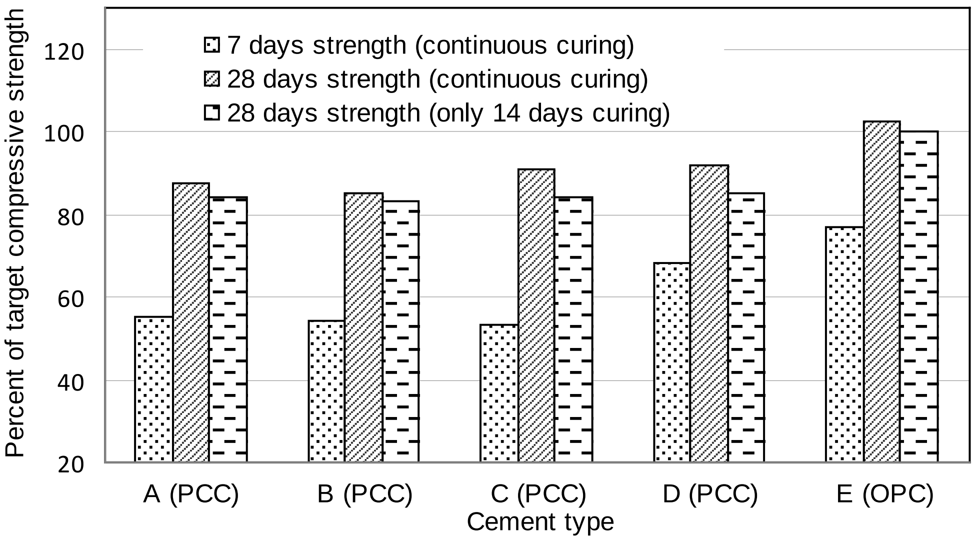

Fig: 4.13 Variation of target strength at 7 and 28 days with cement type for 2500 psi target strength.

Fig. 4.13 shows that concrete made with Portland composite cement (PCC) brand A, B, C and D for target strength of 2500 psi has gained 55 to 60 percent and 80 to 85 percent of target strength at 7 days and 28 days of age at continuous curing condition. At 14 days curing condition, it has gained 80 percent of its target strength at 28 days of age. On the other hand, concrete made with ordinary portland cement (E) has gained 75 percent and 100 percent of the target strength at 7 days and 28 days of age of concrete at continuous curing condition and 95 percent of target strength at 28 days of age at 14 days curing condition.

Fig. 4.14 shows that concrete made with Portland composite cement (PCC) brand A, B, C and D for target strength of 4000 psi has gained 50 to 60 percent and 80 percent of target strength at 7 days and 28 days of age at continuous curing condition. At 14 days curing condition, it has gained 75 to 80 percent of its target strength at 28 days of age. On the other hand, concrete made with ordinary portland cement (E) has gained 60 percent and 95 percent of the target strength at 7 days and 28 days of age of concrete at continuous curing condition and 90 percent of target strength at 28 days of age at 14 days curing condition.

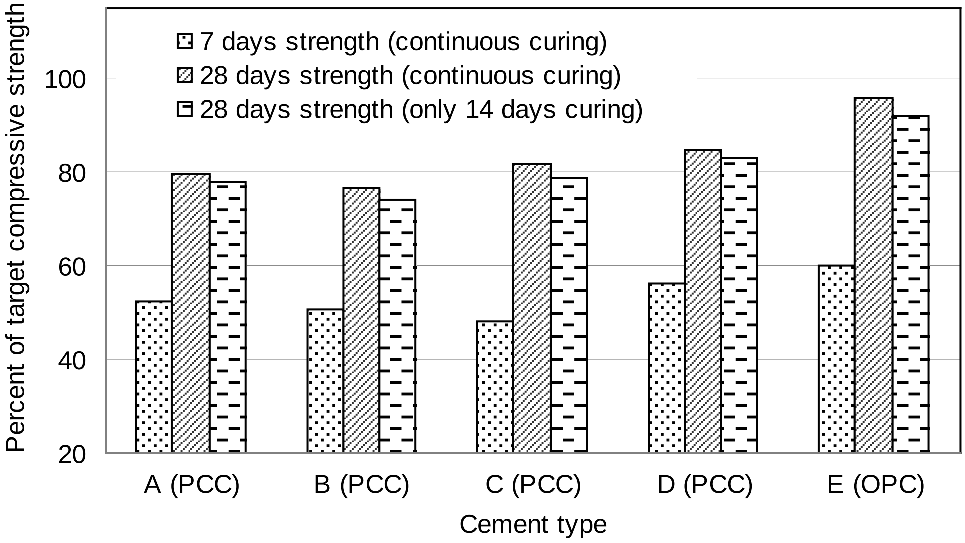

Fig: 4.14 Variation of target strength at 7 and 28 days with cement type for 4000 psi target strength.

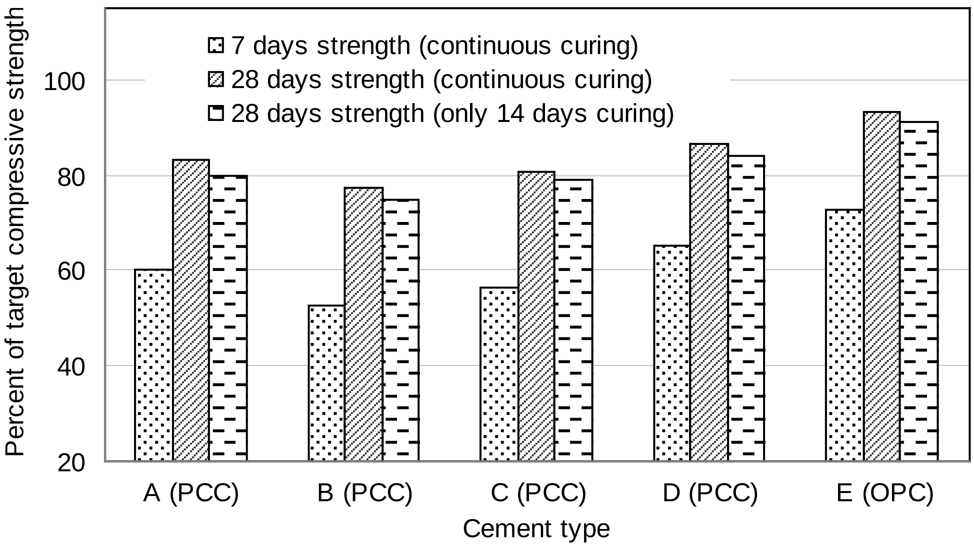

Fig: 4.15 Variation of target strength at 7 and 28 days with cement type for 6000 psi target strength.

Fig. 4.15 shows that concrete made with Portland composite cement brand A, B, C and D for target strength of 6000 psi has gained 55 to 60 percent and 80 percent of target strength at 7 days and 28 days of age at continuous curing condition. At 14 days curing condition, it has gained 75 to 80 percent of its target strength at 28 days of age. On the other hand, concrete made with ordinary portland cement (E) has gained 70 percent and

95 percent of the target strength at 7 and 28 days of age of concrete at continuous curing condition and 90 percent of target strength at 28 days of age at 14 days curing condition.

4.4 Time Required to Gain Full Target Strength

The time required to gain the full target strength of concrete made with portland composite cements (PCC) and ordinary portland cement (OPC) have been estimated when they are cured at continuous curing condition.

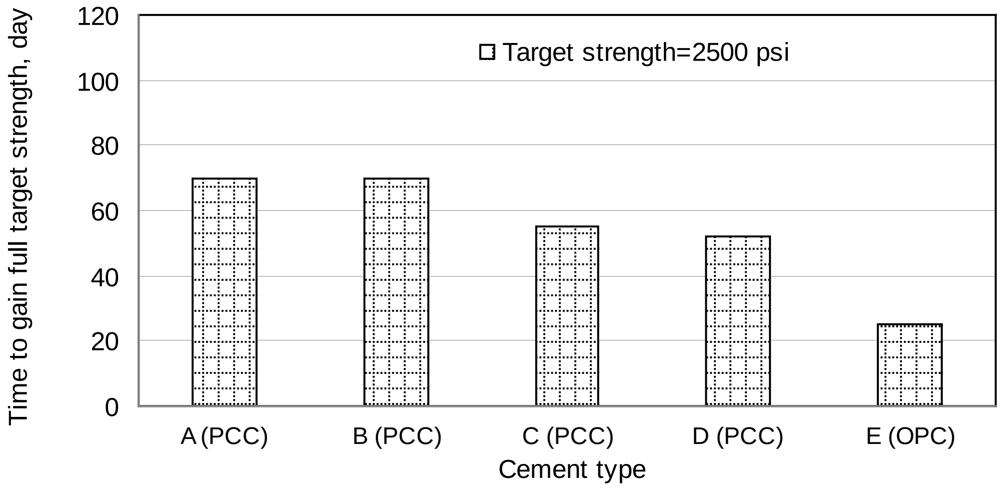

Fig: 4.16 Time required by concrete to gain full target strength at different cement type at continuous curing condition.

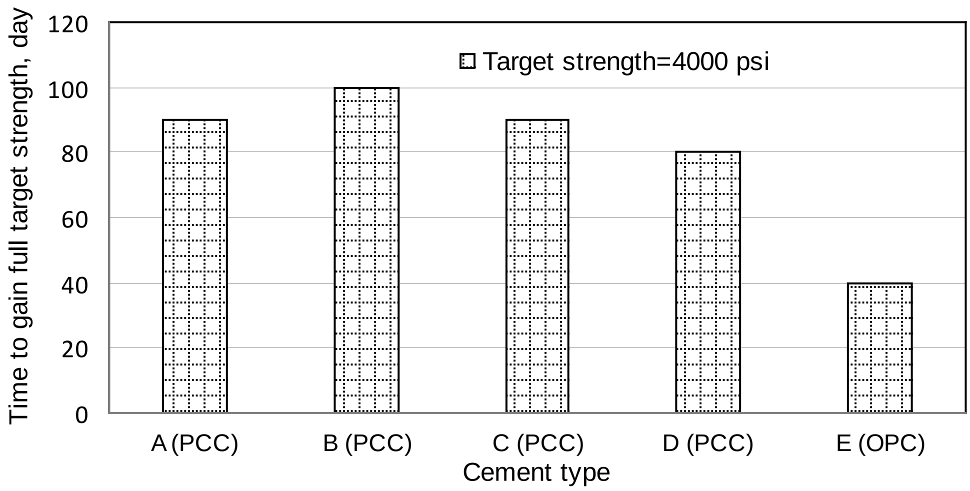

Fig: 4.17 Time required by concrete to gain full target strength at different cement type at continuous curing condition.

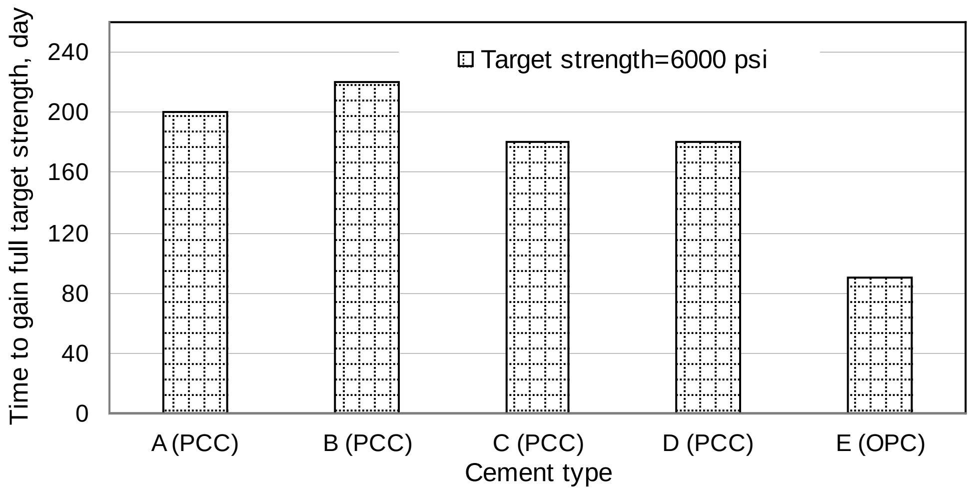

Fig: 4.18 Time required by concrete to gain full target strength at different cement type at continuous curing condition .

Fig 4.16, fig 4.17 and fig 4.18 show the time required by concrete made with Portland composite cements (PCC) relative to ordinary portland cement (OPC) to gain full target strengths of 2500 psi, 4000 psi and 6000 psi respectively. It is found that concrete made with portland composite cement (PCC) for target strengths of 2500 psi, 4000 psi and 6000 psi required 50 to 70 days, 80 to 100 days and 180 to 200 days respectively to gain full target strength. At the same condition, concrete made with ordinary portland cement for target strengths of 2500 psi, 4000 psi and 6000 psi required 30 days, 40 days and 90 days respectively to gain full target strength.

4.5 Effect of Curing on Strength Development of Concrete

Concrete properties are significantly influenced by curing since it greatly effects the hydration of cement. A proper curing maintains a suitably warm and moist environment for the development of hydration products and thus reduces the porosity in hydrated cement paste and increases the density of microstructure in concrete.

Fig.4.19, fig.4.20, fig.4.21, fig.4.22 and fig.4.23 are plotted for concrete of 2500 psi target compressive strength made with cement brand-A, brand-B, brand-C, brand-D and brand-E respectively. Figures show that concrete specimens made with portland composite cement have gained full target strength within 90 days at 14 days curing condition. Concrete specimens have gained 130 to 140 percent and 120 percent of target strength after 1 year at continuous curing condition and 14 days curing condition respectively. Concrete made with ordinary portland cement have gained 140 percent and 125 percent of target strength at continuous curing condition and 14 days curing condition respectively after 1 year.

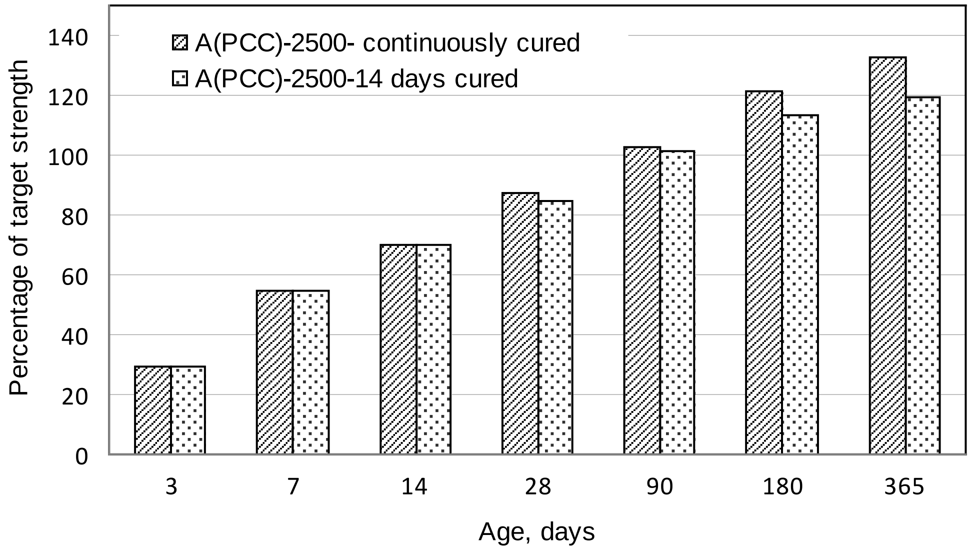

Fig: 4.19 Compressive strength gain with age of concrete made with cement brand-A for 2500 psi

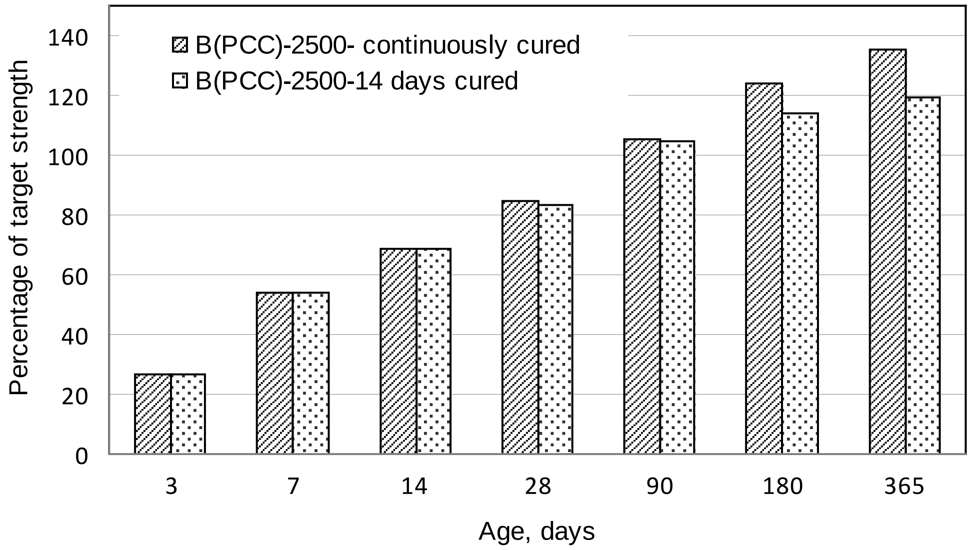

Fig: 4.20 Compressive strength gain with age of concrete made with cement brand-B for 2500 psi

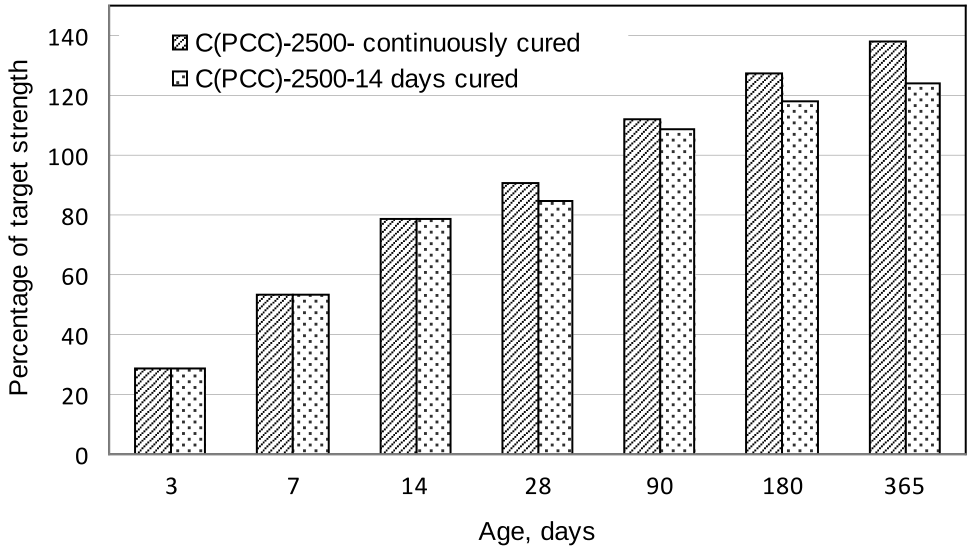

Fig: 4.21 Compressive strength gain with age of concrete made with cement brand-C for 2500 psi

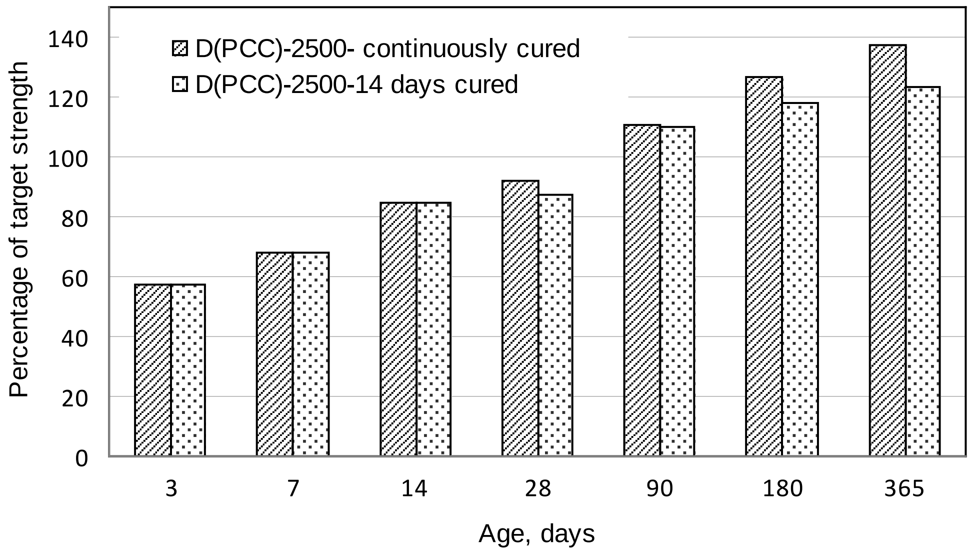

Fig: 4.22 Compressive strength gain with age of concrete made with cement brand-D for 2500 psi

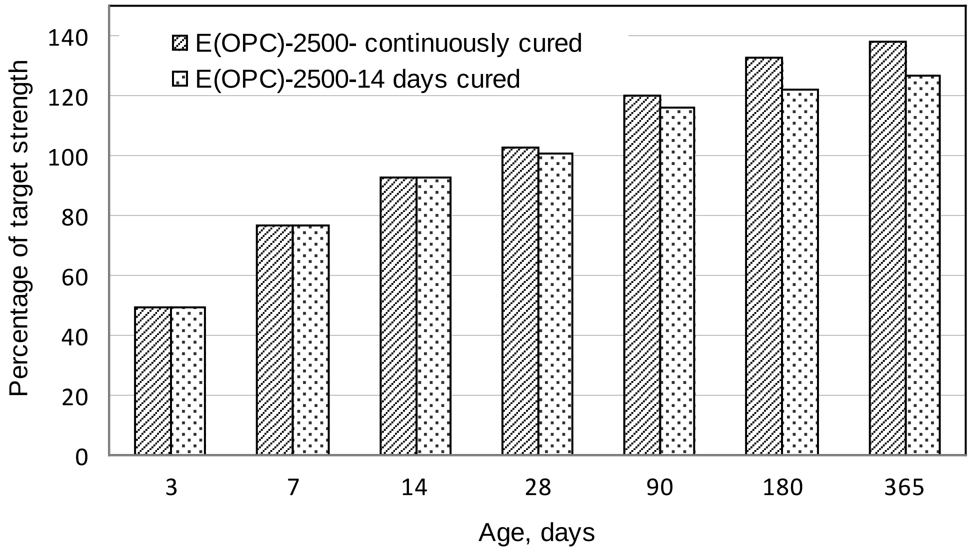

Fig: 4.23 Compressive strength gain with age of concrete made with cement brand-E for 2500 psi

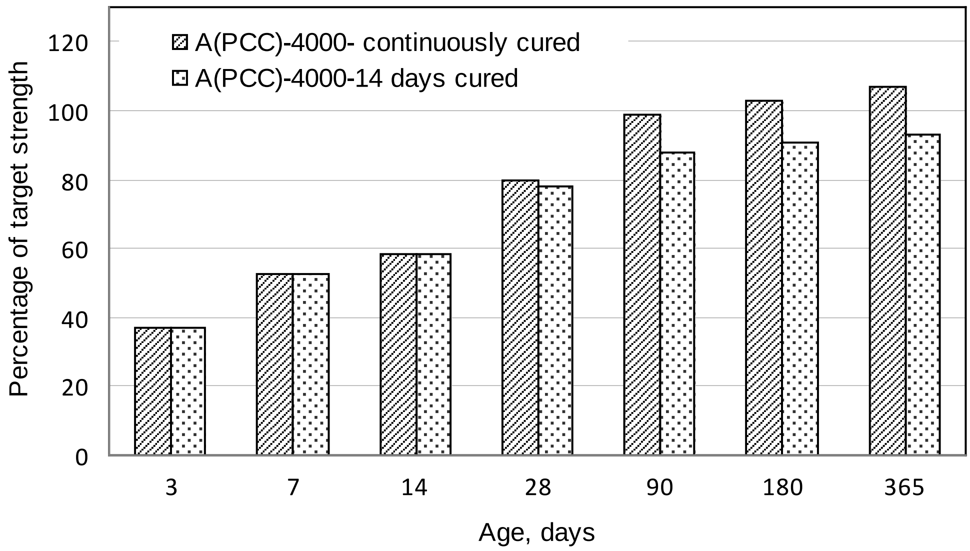

Fig: 4.24 Compressive strength gain with age of concrete made with cement brand-A for 4000 psi

Fig.4.24, fig.4.25, fig.4.26, fig.4.27 and fig.4.28 are plotted for concrete of 4000 psi target compressive strength made with cement brand-A, brand-B, brand-C, brand-D and brand-E respectively. Figures show that concrete specimens made with portland composite cement have gained full target strength within 180 days at 14 days curing condition. Concrete specimens have gained 110 to 120 percent and 95 to 105 percent of target strength after 1 year at continuous curing condition and 14 days curing condition respectively. Concrete made with ordinary portland cement have gained 120 percent and 110 percent of target strength at continuous curing condition and 14 days curing condition respectively after 1 year.

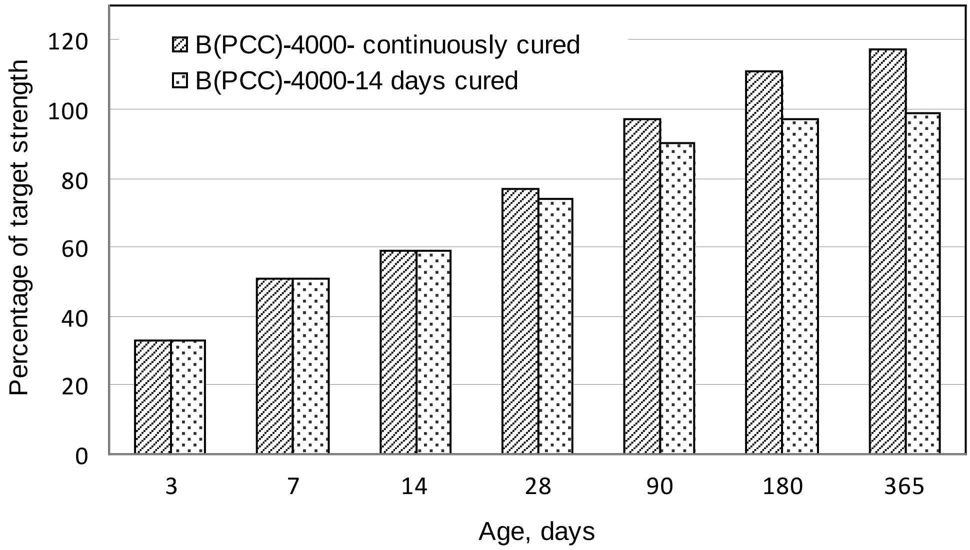

Fig: 4.25 Compressive strength gain with age of concrete made with cement brand-B for 4000 psi

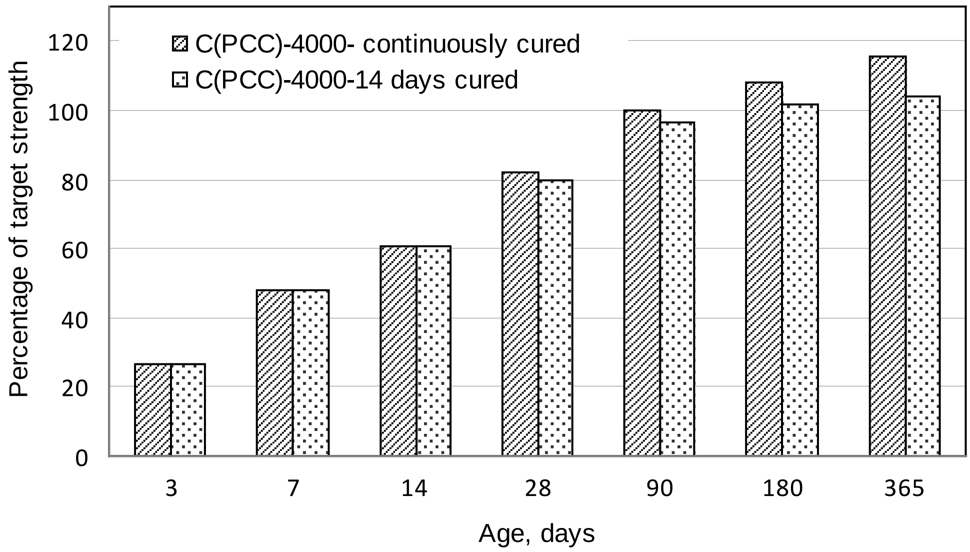

Fig: 4.26 Compressive strength gain with age of concrete made with cement brand-C for 4000 psi

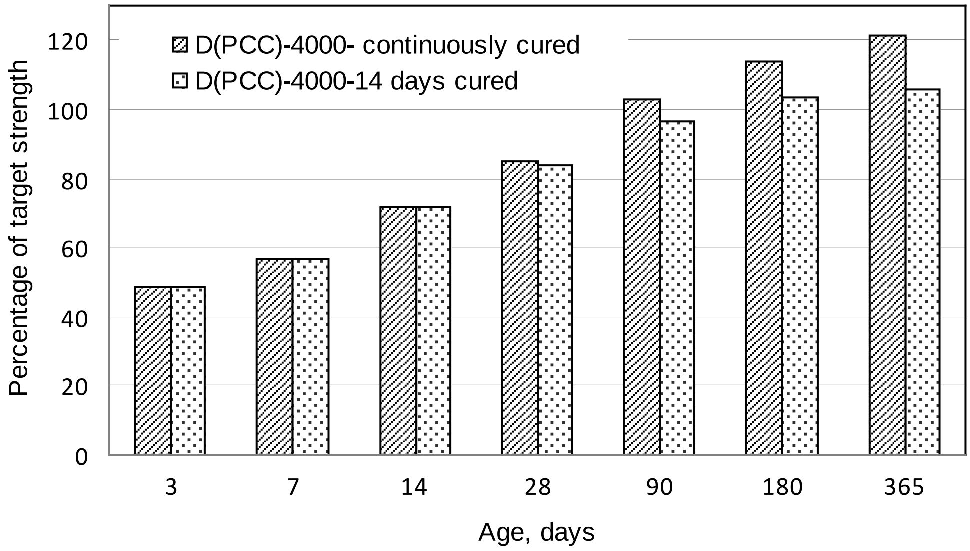

Fig: 4.27 Compressive strength gain with age of concrete made with cement brand-D for 4000 psi

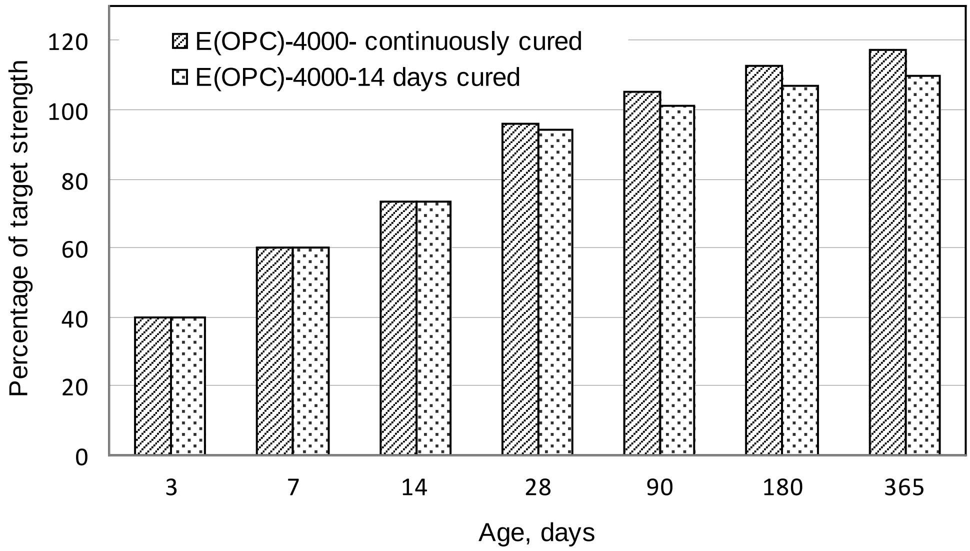

Fig: 4.28 Compressive strength gain with age of concrete made with cement brand-E for 4000 psi

Fig.4.29, fig.4.30, fig.4.31, fig.4.32 and fig.4.33 are plotted for concrete of 6000 psi target compressive strength made with cement brand-A, brand-B, brand-C, brand-D and brand-E respectively. Figures show that concrete specimens made with portland composite cement have failed to gain full target strength within 1 year at 14 days curing condition. Concrete specimens have gained 100 percent and 90 percent of target strength after 1 year at continuous curing condition and 14 days curing condition respectively. Concrete made with ordinary portland cement have gained 105 percent and 95 percent of target strength at continuous curing condition and 14 days curing condition respectively after 1 year. This suggest that adequate curing at early ages as well as later ages is essential to continue the pozzolanic reaction in concrete which contribute to the development of strength of concrete made with portland composite cement (PCC).

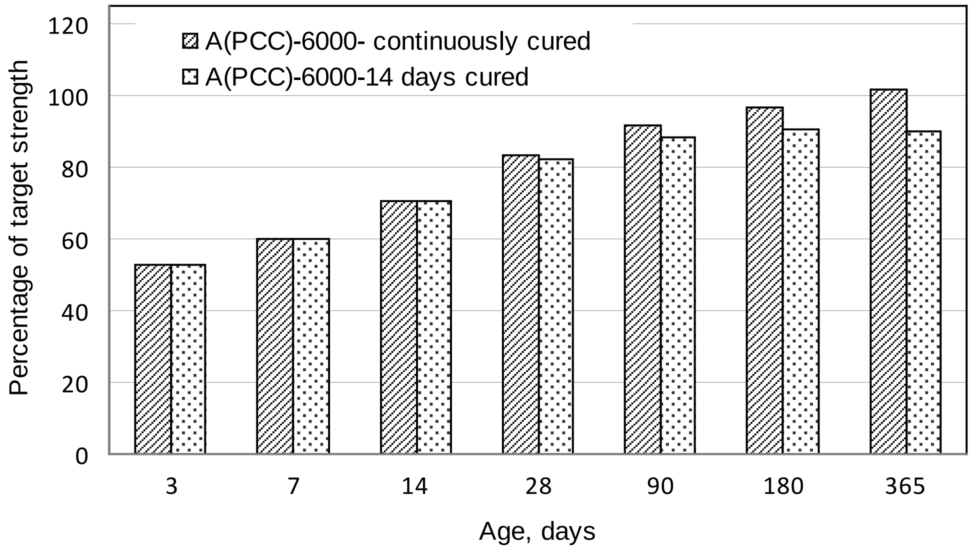

Fig: 4.29 Compressive strength gain with age of concrete made with cement brand-A for 6000 psi

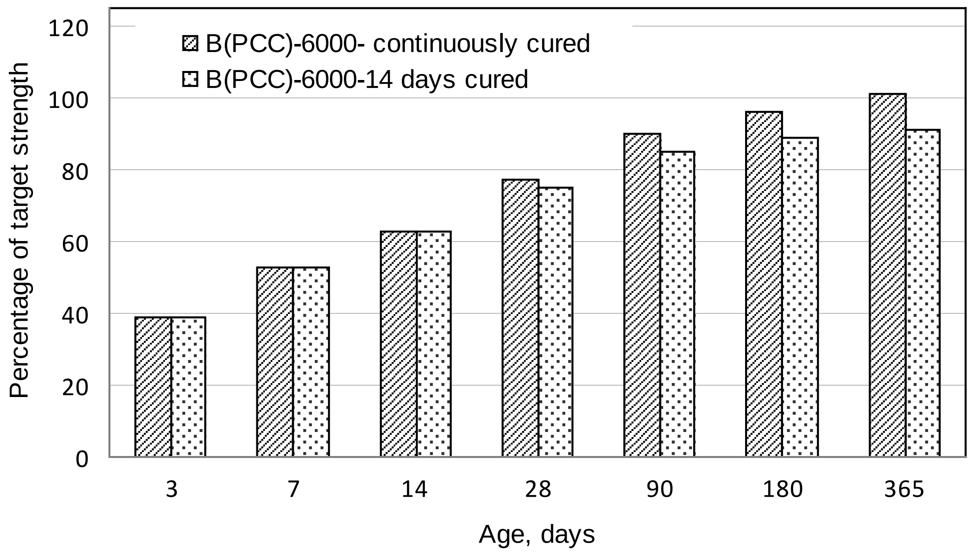

Fig: 4.30 Compressive strength gain with age of concrete made with cement brand-B for 6000 psi

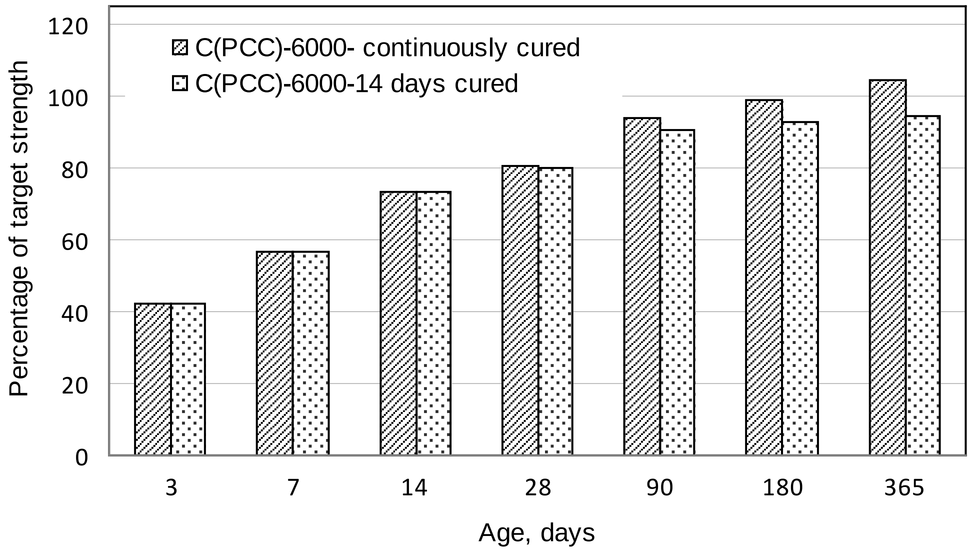

Fig: 4.31 Compressive strength gain with age of concrete made with cement brand-C for 6000 psi

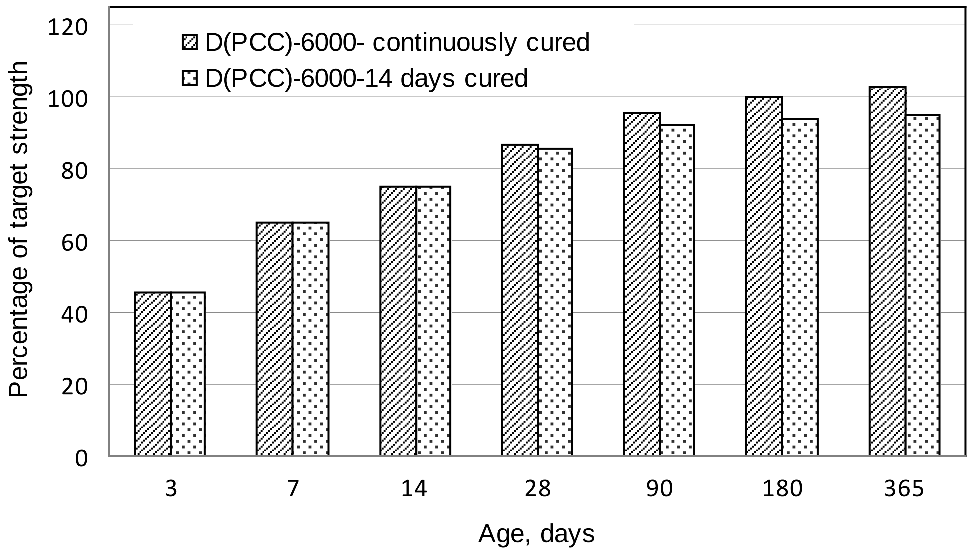

Fig: 4.32 Compressive strength gain with age of concrete made with cement brand-D for 6000 psi

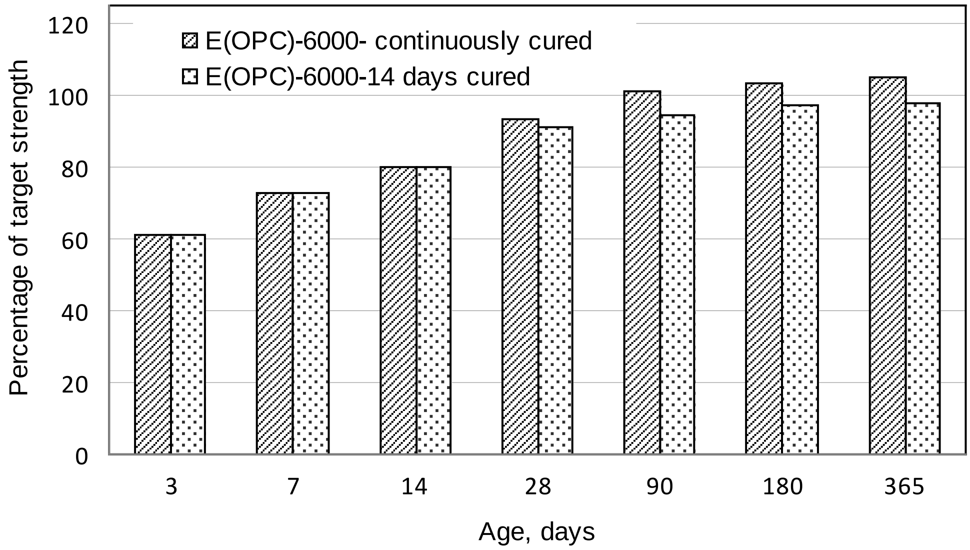

Fig: 4.33 Compressive strength gain with age of concrete made with cement brand-E for 6000 psi

CHAPTER-5

CONCLUSION AND RECOMMENDATION

5.1 General

Findings of the study give a general scenario of the strength development characteristics of concrete made with locally available Portland composite cements (PCC) where mix design procedure of concrete of type-I ordinary Portland cement has been followed. These findings will be useful for design and construction planning of concrete structures to be made with Portland composite cements. It gives some ideas about adequate curing period as well as safe removal period of formwork of concrete made with Portland composite cements.

5.2 Conclusion

Based on the comparative study of cylinder strengths at different ages as described in the previous chapters, following conclusions can be drawn.

Compressive strength at early ages (3 days, 7 days, 14 days) of concrete made with portland composite cement is lower in magnitude than that of concrete made with ordinary portland cement. But at later ages (180 days, 365 days), the strength of concrete made with portland composite cements and ordinary portland cement is almost same.

At continuous curing condition, concrete made with portland composite cements (PCC) for the target strengths of 2500 psi, 4000 psi, and 6000 psi requires 50 to 70 days, 80 to 100 days and 180 to 200 days respectively to gain full target strength and at 14 days curing condition, it requires 90 days and 180 days to gain the target strength of 2500 psi and 4000 psi respectively. But it fails to gain the target strength of 6000 psi within 1 year at 14 days curing condition.

Concrete made with portland composite cement (PCC) for the target strengths of 2500 psi, 4000 psi and 6000 psi gains 55 to 60 percent of its target strength at 7 days of age and 80 to 85 percent of its target strength at 28 days of age at continuous curing condition and at 14 days curing condition, it gains 75 to 80 percent of its target strength at 28 days of age.

At continuous curing condition, concrete made with portland composite cement for the target strengths of 2500 psi, 4000 psi and 6000 psi gains 140 percent, 120 percent and 100 percent of its target strength respectively after 1 year.

At 14 days curing condition, concrete made with portland composite cement for the target strengths of 2500 psi, 4000 psi and 6000 psi gains 120 percent, 100 percent and 90 percent of its target strength respectively after 1 year.

Adequate curing at early ages as well as at later ages is essential in the strength development of concrete made with portland composite cements (PCC). It has been found that drying ambient conditions reduce the strength potential of concrete made with portland composite cement. This characteristics of strength development can significantly increase the use of portland composite cement in construction of mass concrete to be used in water related structure.

5.3 Recommendations

From the analysis and discussion of the test results of the present study the following further investigations are recommended —

a) Since Portland composite cement contains supplementary cementitious materials, a water to cementitious material ratio may be considered in place of the traditional water to cement ratio during mix design of concrete. The water to cementitious material ratio like the water to cement ratio should be calculated on a weight basis.

b) Further investigation can be performed by using high-range water reducing admixtures in concrete made with Portland composite cement to achieve increased early strength by reducing the water to cementitious material ratio.

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APPENDIX-A

PROPERTIES OF FINE AND COARSE AGGREGATE

A-1: Absorption Capacity and Specific Gravity of Fine Aggregate

Results of Absorption capacity and Specific Gravity of fine aggregate (Sylhet Sand) are follows:

Table: Absorption capacity and specific gravity of fine aggregate

Sample no.	Oven dry sample (gm)	Pycno meter +Water (gm)	Pycnometer + Water + Sample (gm)	SSD Sample (gm)	Absorption capacity (%)	Specific Gravity		
						Bulk	Bulk (SSD)	Appa-rent
	A	B	C			A/(B+500-C)	500/(B+500-C)	A/(B+A-C)
1.	494.02	1299	1606	500	1.21	2.56	2.59	2.64

A-2: Sieve Analysis of Fine Aggregate

Coarse aggregate are sieved to obtain fineness modulus and gradation chart. Test method used for this purpose is ASTM C 136.Sample used is Sylhet sand.

Table: Sieve analysis of fine aggregate

Sieve Size (ASTM)	Sieve Size (mm)	Wt. of the materials retained (gms)	% of the materials retained (rounded)	Cumulative retained (%)	% finer
No.8	2.36	16.02	3.2	3.2	96.8
No.16	1.18	103.87	20.8	24	76
No.30	.0006	168.11	33.6	57.6	42.4
No.50	.0003	160.19	32.0	89.6	10.4
No.100	.00015	44.85	9	98.6	1.4
No.200	.000075	4.27	0.9	99.5	0.5
Pan		2.65	0.5		
TOTAL		500			

Fineness Modulus, FM= (3.2+24.0+57.6+89.6+98.6+99.5)/100 =2.56

A-3: Sieve Analysis of Coarse Aggregate

Coarse aggregate are sieved to obtain fineness modulus and gradation chart. Test method used for this purpose is ASTM C 136.

Table: Sieve analysis of coarse aggregate

Sieve Size	Sieve Size (mm)	Wt. of the materials retained (gms)	Percent of materials retained (rounded)	Cumulative % retained	% Finer
$2\frac{1}{2}$”	63.5	0	0	0	100
2”	50.8	0	0	0	100
$1\frac{1}{2}$”	38.1	0	0	0	100
1”	25.4	0	0	0	100
$\frac{3}{4}$”	19.05	1994	40	40	60
$\frac{1}{2}$”	12.7	2824	57	97	3
$\frac{3}{8}$”	9.525	162	3	100	0
$\frac{1}{4}$”	6.25	15	0	100	0
No.4	5	4	0	100	0
No.8	2.36	0	0	100	0
No.16	1.18	0	0	100	0
No.30	0.0006	0	0	100	0
No.50	0.0003	0	0	100	0
No.100	0.0002	0	0	100	0
PAN		1			
TOTAL		5000	100		

Fineness Modulus, F.M. = (40+97+100+100+100+100+100+100)/100 =7.4

A-4: Absorption Capacity and Specific Gravity of Coarse Aggregate

For the purpose of testing ASTM C127 method is used. Specimen for the test is crushed stone.

Table: Absorption capacity of coarse aggregate

Serial no	Oven dry wt. (gm)	S.S.D .wt. (gm)	Wt. of saturated specimen in water (gm)	Absorption capacity (%)
	A	B	C	(B-A)/Ax100
1.	3149	3163	1995	0.45

Table: Bulk specific gravity of coarse aggregate

Serial No.	Bulk specific gravity A/(B-C)	Bulk specific gravity (Saturated surface dry) B/(B-C)	Apparent Specific Gravity A/(A-C)
1.	2.70	2.71	2.73

A-5: Unit Weight of Coarse Aggregate

Unit weight of the coarse aggregate is tested by the test method ASTM C29. Tested sample is crushed stone chips. Nominal volume is ¼ ft^3. Weight of the sample taken is 10.963 kg. Factor for the measure is 141.64 for the test.

Unit weight: (10.63x2.204)/ (1/4) = 97 lb/ft^3

A-6: Mix design of Concrete of 4000 psi Target Strength

Properties of material:

Cement : Type-1, Specific gravity = 3.15

Coarse aggregate: Bulk Specific gravity (SSD) = 2.71, Absorption capacity = 0.45%, Dry rodded unit weight = 97 $\frac{lb}{ft^3}$

Fine aggregate : Bulk Specific gravity (SSD) = 2.59, Fineness modulus = 2.56

Step-1: Estimation of mixing water and air content

Table: For non air Entrained concrete

Maximum aggregate size (in.)								
Slump(in.)	0.375	0.5	0.75	1.0	1.5	2.0	3.0	6.0
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	---
Air content	3.0%	2.5%	2.0%	1.5%	1.0%	0.5%	0.3%	0.2%

For slump value (1-2) and aggregate size = $\frac{3}{4}$ inch, the recommended air content = 2.0% and water required = 315 $\frac{lb}{yd^3}$

Step-2: Determination of w/c ratio

28 day compressive strength (psi)	Non air Entrained	Air Entrained
2000	0.82	0.74
3000	0.68	0.59
4000	0.57	0.48
5000	0.48	0.40
6000	0.41	---

For 4000 psi compressive strength and non air entrained concrete, w/c = 0.57

Step-3: Estimation of cement content

Weight of cement = $\frac{315\frac{lb}{yd^3}}{0.57} = 553\ \frac{lb}{yd^3}$

Step-4: Estimation of coarse aggregate content

Maximum aggregate size (in.)	Fineness modulus of Fine aggregate						
	2.4	2.5	2.6	2.7	2.8	2.9	3.0
0.75	0.66	0.65	0.64	0.63	0.62	0.62	0.60

From the above table, for maximum aggregate size = $\frac{3}{4}$ inch and Fineness modulus of Fine aggregate = 2.56, corresponding value is 0.65

Then, the coarse aggregate will occupy = 0.65 x 27 $\frac{ft^3}{yd^3}$ =17.55 $\frac{ft^3}{yd^3}$

The OD weight of coarse aggregate =17.55 $\frac{ft^3}{yd^3}$ x 97 $\frac{lb}{ft^3}$ = 1702.35 $\frac{lb}{yd^3}$

SSD weight of coarse aggregate =1702.35 $\frac{lb}{yd^3}$ x (1+ 0.45%) =1710.01 $\frac{lb}{yd^3}$

Step-5: Estimation of Fine aggregate content

Water = $\frac{315}{62.4}$ = 5.05 ft^3

Cement = $\frac{553}{3.15 \times 62.4}$ = 2.81 ft^3

Air = 27 x 2% = 0.54 ft^3

Coarse aggregate = $\frac{1710}{2.71 \times 62.4}$ = 10.11 ft^3

Total = (5.05+2.81+0.54+10.11) ft^3 =18.51 ft^3

Fine aggregate will occupy = 27 ft^3 - 18.51 ft^3 =8.49 ft^3

SSD weight of Fine aggregate = 8.49 ft^3 x 2.59 x 62.4 $\frac{lb}{ft^3}$ = 1372.12 $\frac{lb}{yd^3}$

<u>Final estimation: (To cast 33 concrete cylinders per day)</u>

Water =315 x 0.120 =37.80 lb =17.16 kg

Cement =553 x 0.120 =66.36 lb =30.13 kg

Coarse aggregate =1710.01 x 0.120 =205.20 lb =93.16 kg

Fine aggregate =1372.12 x 0.120 =164.65 lb =74.75 kg

APPENDIX-B

PROCEDURE OF MAKING AND TESTING OF CONCRETE SPECIMENS

B-1 Mixing of Concrete and Sample Preparation (ASTM C192)

Apparatus: Concrete Mixer (power driven), Tamping Rods (3/8" diameter for 4 inch diameter cylinders), Shovel, hand scoop, trowel, Mallet - rubber, weighing approximately 1.25 lb, cylindrical Molds (4" diameter by 8"), Vibratory Table

Materials: Cement, fine and coarse aggregate and water are proportioned as per mix design. Weights of fine aggregate; coarse aggregate and water is adjusted for aggregate moisture contents.

Procedure:

i. As per mix design, the required amount of coarse aggregate and some of the mixing water are damped into the mixer drum.
ii. The mixer machine is started.
iii. Fine aggregate, cement, and the balance of the water are added while the mixer is running.
iv. It has been mixed for 3 minutes followed by a 3 minute rest (the mixer is turned off).Final mix requires an additional 2 minutes.
v. The mixer is tilted while it is running and the concrete is poured into a clean and wet wheelbarrow.
vi. Any concrete stuck in the mixer is removed using a scoop or trowel.
vii. The concrete is remixed in the wheelbarrow using a shovel.
viii. The slump value is measured.
ix. The concrete is poured in the 4 in. diameter by 8 in. height cylindrical mould.
x. The mould is then kept on a vibration table. The machine is run for 2 to 3 minutes for proper compaction.

B-2 Slump Test of Concrete (ASTM C143)

Apparatus: Slump mold, base plate, Tamping Rod (3/8" diameter), Scale (tape measure), Shovel, hand scoop.

<u>Materials:</u> 0.3 ft^3 of mixed plastic concrete

<u>Procedure:</u>

i. The test has been started within 5 min. after obtaining the final portion of the mixed concrete sample.
ii. The mold is dampened (inside) and placed on the dampened base plate.
iii. The mold is hold firmly in place during the filling and rodding operation (by the operator standing on the two foot pieces).
iv. The mold is filled in three layers, each approximately one-third the volume of the mold.
v. Each layer is rodded with 25 strokes by the tamping rod. During filling and rodding the top layer, the concrete is heaped above the mold before rodding is started.
vi. The surface is stroked off by a screeding and a rolling motion of the tamping rod.
vii. The mold is removed immediately by raising it in a vertical direction. (steps 2 through 7 is completed in less than 2.5 minutes).
viii. The empty mold (inverted) is placed adjacent to the concrete sample and the vertical difference between the top of the mold and the displaced original center of the sample is measured. This is the slump value.
ix. The slump value is recorded in inches to the nearest ¼ in.

B-3 Capping Cylindrical Concrete Specimens (ASTM C617)

<u>Apparatus:</u> Capping Plate (mold), Alignment Device (guide bars), Melting Pot, Fume Hood (exhaust fan)

<u>Materials:</u> Moist cured concrete cylinders (with no moisture on the surface), Sulfur mortar (5000 psi strength at 2 hours)

<u>Procedure:</u>

i. Sulfur mortar for use is prepared by heating to about 265 F (130 C). Fresh sulfur mortar must is dried at the time of placement in the melting pot (dampness will cause foaming). Note: The flash point of sulfur mortar is approximately 440 F (225 C).
ii. The capping plate is oiled lightly.

iii. The molten sulfur mortar is stirred immediately prior to pouring each cap.

iv. The ends of the moist cured specimens are dried to preclude the formation of steam and foam pockets in the caps.

v. The molten sulfur mortar is poured into the capping plate (mold). The specimen is lowered, using the alignment device guide bars, ensuring that the axis of the specimen is perpendicular to the plate.

vi. The molded end caps on the specimen are ensured a minimum thickness of 1/8" (3 mm) but less than 5/16" (8 mm).

vii. After the sulfur mortar has set, the specimen is removed from the mold plate using a slight twisting motion.

viii. This process is repeated, capping both ends of the specimen.

B-4 Compressive Strength of Cylindrical Concrete Specimens (ASTM C39)

<u>Apparatus:</u> Compression Test Machine

The testing machine is equipped with two steel bearing blocks with hardened faces, one of which is a spherically seated block that bears on the upped surface of the specimen, and the other a solid block on which the specimen is rest. Bearing faces of the block has a minimum dimensions at least 3% greater than the diameter of the specimen to be tested.

The load of the compressive machine used in concrete testing is registered on a dial, the dial is provided with a graduated scale that is readable to at least the nearest 0.1% of the full scale load. The dial is readable within 1% of the indicated load at any given load within the loading rang level.

<u>Materials:</u> Capped cylindrical concrete specimens

<u>Procedure:</u>

i. The specimen is maintained in a moist condition up to the time of compression testing. Compression tests are made as soon as practicable after removal from moist storage. The specimens are tested in this cured moist condition.

ii. The bearing surfaces of the upper and lower platens of the compression testing machine are wipe cleaned. Both end caps of the test specimen are also wipe cleaned.

iii. The specimen is centered on the lower platen of the testing machine.

iv. The axis of the specimen is aligned carefully with the center of thrust of the spherically seated upper platen.

v. The upper platen is brought to bear on the specimen, adjusting the load to obtain uniform seating of the specimen.

vi. The load is applied at a loading rate of 20 to 50 psi/s (250 to 630 lb/s for 4” diameter cylinders). The time to failure for 3000 psi concrete is 1 to 2.5 minutes.

vii. The load is applied at the prescribed loading rate until the specimen fails. The maximum load (lb) is recorded to the nearest 10 lb.

viii. The unconfined compressive strength of the specimen has been calculated by dividing the maximum load by the cross-sectional area of the specimen to the nearest 10 psi.

APPENDIX- C

SCHEDULE FOR CONCRETE TESTING

Design Strength: 2500 psi, Cement Brand: A Date of Casting: 08-11-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	A2.5 03CU	11.11.2008	4.164	4.44	730	733
2	A2.5 03CU	11.11.2008	4.168	3.40	560	
3	A2.5 03CU	11.11.2008	4.137	5.47	910	
4	A2.5 07CU	15.11.2008	4.144	8.57	1423	1375
5	A2.5 07CU	15.11.2008	4.090	7.53	1283	
6	A2.5 07CU	15.11.2008	4.150	8.57	1419	
7	A2.5 14CU	22.11.2008	4.090	10.63	1812	1746
8	A2.5 14CU	22.11.2008	4.110	9.60	1620	
9	A2.5 14CU	22.11.2008	4.100	10.63	1803	
10	A2.5 28CU	06.12.2008	4.137	12.70	2116	2190
11	A2.5 28CU	06.12.2008	4.110	13.73	2318	
12	A2.5 28CU	06.12.2008	4.120	12.70	2133	
13	A2.5 3mCU	07.02.2009	4.117	15.01	2526	2573
14	A2.5 3mCU	07.02.2009	4.125	15.01	2516	
15	A2.5 3mCU	07.02.2009	4.133	16.04	2679	
16	A2.5 6mCU	08.05.2009	4.129	17.39	2909	3033
17	A2.5 6mCU	08.05.2009	4.145	19.47	3233	
18	A2.5 6mCU	08.05.2009	4.094	17.39	2959	
19	A2.5 1yCU	08.11.2009	4.148	20.51	3400	3307
20	A2.5 1yCU	08.11.2009	4.102	20.51	3477	
21	A2.5 1yCU	08.11.2009	4.156	17.43	3043	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	A2.5 28NC	06.12.2008	4.110	11.66	1969	2118
2	A2.5 28NC	06.12.2008	4.130	12.70	2123	
3	A2.5 28NC	06.12.2008	4.160	13.70	2263	
4	A2.5 3mNC	07.02.2009	4.102	13.98	2369	2526
5	A2.5 3mNC	07.02.2009	4.133	17.08	2852	
6	A2.5 3mNC	07.02.2009	4.113	13.98	2356	
7	A2.5 6mNC	08.05.2009	4.086	15.31	2615	2840
8	A2.5 6mNC	08.05.2009	4.188	19.47	3167	
9	A2.5 6mNC	08.05.2009	4.125	16.35	2740	
10	A2.5 1yNC	08.11.2009	4.148	19.49	3230	2988
11	A2.5 1YNC	08.11.2009	4.172	18.46	3025	
12	A2.5 1yNC	08.11.2009	4.156	16.40	2708	

Design Strength: 2500 psi, Cement Brand: B Date of casting: 09-11-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	B2.5 03CU	12.11.2008	4.180	4.23	690	667
2	B2.5 03CU	12.11.2008	4.120	3.40	570	
3	B2.5 03CU	12.11.2008	4.130	4.43	740	
4	B2.5 07CU	16.11.2008	4.087	8.57	1463	1358
5	B2.5 07CU	16.11.2008	4.135	8.05	1342	
6	B2.5 07CU	16.11.2008	4.110	7.53	1271	
7	B2.5 14CU	23.11.2008	4.140	10.63	1769	1712
8	B2.5 14CU	23.11.2008	4.140	10.63	1769	
9	B2.5 14CU	23.11.2008	4.140	9.60	1598	
10	B2.5 28CU	07.12.2008	4.090	10.87	1854	2124
11	B2.5 28CU	07.12.2008	4.140	15.01	2498	
12	B2.5 28CU	07.12.2008	4.100	11.91	2020	
13	B2.5 3mCU	09.02.2009	4.105	13.98	2365	2632
14	B2.5 3mCU	09.02.2009	4.137	17.08	2846	
15	B2.5 3mCU	09.02.2009	4.129	16.04	2684	
16	B2.5 6mCU	10.05.2009	4.109	18.43	3113	3096
17	B2.5 6mCU	10.05.2009	4.102	17.39	2947	
18	B2.5 6mCU	10.05.2009	4.148	19.47	3227	
19	B2.5 1yCU	09.11.2009	4.168	21.55	3538	3389
20	B2.5 1yCU	09.11.2009	4.156	21.55	3558	
21	B2.5 1yCU	09.11.2009	4.141	18.46	3071	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	B2.5 28NC	07.12.2008	4.160	13.98	2303	2089
2	B2.5 28NC	07.12.2008	4.130	11.91	1991	
3	B2.5 28NC	07.12.2008	4.150	11.91	1972	
4	B2.5 3mNC	09.02.2009	4.141	17.08	2841	2619
5	B2.5 3mNC	09.02.2009	4.125	13.98	2343	
6	B2.5 3mNC	09.02.2009	4.137	16.04	2674	
7	B2.5 6mNC	10.05.2009	4.125	15.31	2537	2843
8	B2.5 6mNC	10.05.2009	4.148	18.43	3077	
9	B2.5 6mNC	10.05.2009	4.133	17.39	2903	
10	B2.5 1YNC	09.11.2009	4.109	18.46	3118	2980
11	B2.5 1yNC	09.11.2009	4.125	18.46	3094	
12	B2.5 1yNC	09.11.2009	4.141	16.40	2727	

Design Strength: 2500 psi, Cement Brand: C Date of casting: 12-11-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	C2.5 03CU	15.11.1008	4.130	3.92	655	714
2	C2.5 03CU	15.11.1008	4.100	4.44	753	
3	C2.5 03CU	15.11.1008	4.150	4.44	735	
4	C2.5 07CU	19.11.2008	4.140	7.53	1253	1330
5	C2.5 07CU	19.11.2008	4.100	8.57	1454	
6	C2.5 07CU	19.11.2008	4.090	7.53	1283	
7	C2.5 14CU	26.11.2008	4.180	10.63	1735	1973
8	C2.5 14CU	26.11.2008	4.170	12.70	2082	
9	C2.5 14CU	26.11.2008	4.150	12.70	2103	
10	C2.5 28CU	10.12.2008	4.140	11.91	1982	2270
11	C2.5 28CU	10.12.2008	4.150	16.04	2656	
12	C2.5 28CU	10.12.2008	4.120	12.94	2174	
13	C2.5 3mCU	12.02.2009	4.117	17.08	2874	2798
14	C2.5 3mCU	12.02.2009	4.133	15.01	2506	
15	C2.5 3mCU	12.02.2009	4.141	18.11	3013	
16	C2.5 6mCU	12.05.2009	4.141	20.51	3412	3187
17	C2.5 6mCU	12.05.2009	4.137	19.47	3245	
18	C2.5 6mCU	12.05.2009	4.133	17.39	2903	
19	C2.5 1yCU	12.11.2009	4.109	20.52	3467	3447
20	C2.5 1yCU	12.11.2009	4.094	19.49	3317	
21	C2.5 1yCU	12.11.2009	4.156	21.55	3558	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	C2.5 28NC	10.12.2008	4.140	11.91	1981	2117
2	C2.5 28NC	10.12.2008	4.130	12.94	2164	
3	C2.5 28NC	10.12.2008	4.090	12.94	2206	
4	C2.5 3mNC	12.02.2009	4.090	15.01	2559	2724
5	C2.5 3mNC	12.02.2009	4.086	17.08	2918	
6	C2.5 3mNC	12.02.2009	4.121	16.04	2695	
7	C2.5 6mNC	12.05.2009	4.109	17.39	2937	2948
8	C2.5 6mNC	12.05.2009	4.191	17.39	2824	
9	C2.5 6mNC	12.05.2009	4.129	18.43	3083	
10	C2.5 1yNC	12.11.2009	4.117	18.46	3106	3107
11	C2.5 1yNC	12.11.2009	4.094	19.49	3317	
12	C2.5 1yNC	12.11.2009	4.141	17.43	2899	

<u>Design Strength: 2500 psi, Cement Brand: D Date of casting: 16-112008</u>

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	D2.5 03CU	19.11.2008	4.110	9.60	1620	1430
2	D2.5 03CU	19.11.2008	4.140	8.57	1425	
3	D2.5 03CU	19.11.2008	4.150	7.53	1247	
4	D2.5 07CU	23.11.2008	4.190	10.63	1727	1706
5	D2.5 07CU	23.11.2008	4.100	10.63	1804	
6	D2.5 07CU	23.11.2008	4.150	9.60	1589	
7	D2.5 14CU	30.11.2008	4.160	13.73	2263	2113
8	D2.5 14CU	30.11.2008	4.150	13.73	2274	
9	D2.5 14CU	30.11.2008	4.100	10.63	1804	
10	D2.5 28CU	14.12.2008	4.120	15.01	2522	2300
11	D2.5 28CU	14.12.2008	4.130	12.94	2163	
12	D2.5 28CU	14.12.2008	4.080	12.94	2217	
13	D2.5 3mCU	16.02.2009	4.133	15.01	2506	2762
14	D2.5 3mCU	16.02.2009	4.109	17.08	2885	
15	D2.5 3mCU	16.02.2009	4.102	17.08	2895	
16	D2.5 6mCU	16.05.2009	4.156	19.47	3215	3161
17	D2.5 6mCU	16.05.2009	4.160	20.51	3381	
18	D2.5 6mCU	16.05.2009	4.145	17.39	2887	
19	D2.5 1yCU	16.11.2009	4.109	19.49	3292	3425
20	D2.5 1yCU	16.11.2009	4.148	22.58	3743	
21	D2.5 1yCU	16.11.2009	4.141	19.49	3242	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	D2.5 28NC	14.12.2008	4.080	11.91	2040	2191
2	D2.5 28NC	14.12.2008	4.120	13.98	2348	
3	D2.5 28NC	14.12.2008	4.110	12.94	2185	
4	D2.5 3mNC	16.02.2009	4.125	17.08	2863	2755
5	D2.5 3mNC	16.02.2009	4.098	16.04	2725	
6	D2.5 3mNC	16.02.2009	4.133	16.04	2679	
7	D2.5 6mNC	16.05.2009	4.180	18.43	3008	2955
8	D2.5 6mNC	16.05.2009	4.141	17.39	2892	
9	D2.5 6mNC	16.05.2009	4.090	17.39	2965	
10	D2.5 1YNC	16.11.2009	4.156	20.52	3389	3080
11	D2.5 1yNC	16.11.2009	4.141	17.43	2899	
12	D2.5 1yNC	16.11.2009	4.102	17.43	2954	

Design Strength: 2500 psi, Cement Brand: E Date of casting: 19-11-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, Ton	Compressive Strength, psi	Avg. strength, psi
1	E2.5 03CU	22.11.2008	4.156	9.60	1585	1236
2	E2.5 03CU	22.11.2008	4.172	5.50	901	
3	E2.5 03CU	22.11.2008	4.180	7.50	1224	
4	E2.5 07CU	26.11.2008	4.160	11.66	1922	1918
5	E2.5 07CU	26.11.2008	4.190	10.63	1727	
6	E2.5 07CU	26.11.2008	4.150	12.70	2106	
7	E2.5 14CU	03.12.2008	4.160	16.04	2644	2316
8	E2.5 14CU	03.12.2008	4.140	12.93	2152	
9	E2.5 14CU	03.12.2008	4.140	12.93	2152	
10	E2.5 28CU	17.12.2008	4.080	16.04	2749	2568
11	E2.5 28CU	17.12.2008	4.090	13.98	2383	
12	E2.5 28CU	17.12.2008	4.080	15.01	2572	
13	E2.5 3mCU	19.02.2009	4.105	17.08	2891	2995
14	E2.5 3mCU	19.02.2009	4.125	19.15	3209	
15	E2.5 3mCU	19.02.2009	4.109	17.08	2885	
16	E2.5 6mCU	19.05.2009	4.090	19.47	3320	3308
17	E2.5 6mCU	19.05.2009	4.109	21.55	3641	
18	E2.5 6mCU	19.05.2009	4.098	17.39	2965	
19	E2.5 1yCU	19.11.2009	4.141	19.49	3242	3453
20	E2.5 1yCU	19.11.2009	4.148	21.55	3572	
21	E2.5 1yCU	19.11.2009	4.164	21.55	3545	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, Ton	Compressive Strength, psi	Avg. strength, psi
1	E2.5 28NC	17.12.2008	4.090	13.98	2383	2525
2	E2.5 28NC	17.12.2008	4.130	16.04	2683	
3	E2.5 28NC	17.12.2008	4.130	15.01	2510	
4	E2.5 3mNC	19.02.2009	4.148	18.11	3003	2898
5	E2.5 3mNC	19.02.2009	4.133	17.08	2852	
6	E2.5 3mNC	19.02.2009	4.141	17.08	2841	
7	E2.5 6mNC	19.05.2009	4.113	19.47	3283	3052
8	E2.5 6mNC	19.05.2009	4.121	17.39	2920	
9	E2.5 6mNC	19.05.2009	4.098	17.39	2953	
10	E2.5 1yNC	19.11.2009	4.094	18.46	3141	3167
11	E2.5 1yNC	19.11.2009	4.109	19.49	3292	
12	E2.5 1yNC	19.11.2009	4.141	18.46	3070	

Design Strength: 4000 psi, Cement Brand: A,   Date of casting: 29-11-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, Ton	Compressive Strength, psi	Avg. strength, psi
1	A403CU	02-12-2008	4.100	9.83	1668	1487
2	A403CU	02-12-2008	4.140	7.77	1293	
3	A403CU	02-12-2008	4.090	8.80	1500	
4	A407CU	6-12-2008	4.110	12.94	2185	2100
5	A407CU	6-12-2008	4.140	13.98	2326	
6	A407CU	6-12-2008	4.160	10.87	1792	
7	A414CU	13-12-2008	4.100	15.01	2547	2328
8	A414CU	13-12-2008	4.180	12.94	2112	
9	A414CU	13-12-2008	4.140	13.98	2326	
10	A428CU	27-12-2008	4.168	19.15	3144	3182
11	A428CU	27-12-2008	4.098	17.08	2901	
12	A428CU	27-12-2008	4.156	21.22	3503	
13	A43mCU	28-02-2009	4.152	23.29	3852	3952
14	A43mCU	28-02-2009	4.102	22.25	3772	
15	A43mCU	28-02-2009	4.133	25.36	4233	
16	A46mCU	29-05-2009	4.156	25.72	4247	4123
17	A46mCU	29-05-2009	4.117	23.64	3977	
18	A46mCU	29-05-2009	4.121	23.64	4145	
19	A41yCU	29-11-2009	4.141	26.71	4443	4280
20	A41yCU	29-11-2009	4.156	26.71	4410	
21	A41yCU	29-11-2009	4.109	23.62	3988	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, Ton	Compressive Strength, psi	Avg. strength, psi
1	A428NC	27-12-2008	4.156	20.18	3333	3127
2	A428NC	27-12-2008	4.141	19.15	3185	
3	A428NC	27-12-2008	4.125	17.08	2863	
4	A43mNC	28-02-2009	4.113	21.22	3577	3505
5	A43mNC	28-02-2009	4.125	19.15	3209	
6	A43mNC	28-02-2009	4.125	22.25	3730	
7	A46mNC	29-05-2009	4.109	20.51	3464	3626
8	A46mNC	29-05-2009	4.102	20.51	3476	
9	A46mNC	29-05-2009	4.137	23.64	3939	
10	A41yNC	29-11-2009	4.117	20.52	3453	3714
11	A41yNC	29-11-2009	4.172	22.58	3701	
12	A41yNC	29-11-2009	4.109	23.62	3988	

Design Strength: 4000 psi, Cement Brand: B Date of casting: 30-11-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, Ton	Compressive Strength, psi	Avg. strength, psi
1	B403CU	03-12-2008	4.090	6.73	1148	1315
2	B403CU	03-12-2008	4.110	8.80	1486	
3	B403CU	03-12-2008	4.110	7.76	1310	
4	B407CU	07-12-2008	4.140	13.98	2326	2029
5	B407CU	07-12-2008	4.150	10.87	1800	
6	B407CU	07-12-2008	4.160	11.91	1962	
7	B414CU	14-12-2008	4.090	15.01	2559	2364
8	B414CU	14-12-2008	4.140	13.98	2326	
9	B414CU	14-12-2008	4.090	12.94	2206	
10	B428CU	28-12-2008	4.098	17.08	2901	3066
11	B428CU	28-12-2008	4.090	18.11	3089	
12	B428CU	28-12-2008	4.125	19.15	3209	
13	B43mCU	02-02-2008	4.148	22.25	3688	3878
14	B43mCU	02-02-2008	4.133	23.29	3888	
15	B43mCU	02-02-2008	4.133	24.32	4060	
16	B46mCU	30-05-2009	4.156	28.84	4763	4445
17	B46mCU	30-05-2009	4.133	25.72	4295	
18	B46mCU	30-05-2009	4.141	25.72	4278	
19	B41yCU	30-11-2009	4.152	27.74	4589	4687
20	B41yCU	30-11-2009	4.141	28.77	4786	
21	B41yCU	30-11-2009	4.109	27.74	4686	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	B428NC	28-12-2008	4.129	18.11	3030	2966
2	B428NC	28-12-2008	4.145	19.15	3179	
3	B428NC	28-12-2008	4.125	16.04	2689	
4	B43mNC	02-02-2008	4.121	21.22	3563	3614
5	B43mNC	02-02-2008	4.133	23.29	3888	
6	B43mNC	02-02-2008	4.121	20.18	3389	
7	B46mNC	30-05-2009	4.133	24.68	4121	3889
8	B46mNC	30-05-2009	4.121	23.64	3969	
9	B46mNC	30-05-2009	4.145	21.55	3578	
10	B41yNC	30-11-2009	4.164	23.62	3884	3947
11	B41yNC	30-11-2009	4.125	24.65	4131	
12	B41yNC	30-11-2009	4.102	22.58	3828	

Design Strength: 4000 psi, Cement Brand: C Date of casting: 17-12-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	C403CU	20-12-2008	4.100	6.73	1142	1073
2	C403CU	20-12-2008	4.120	5.70	957	
3	C403CU	20-12-2008	4.140	6.73	1120	
4	C407CU	24-12-2008	4.150	11.91	1972	1927
5	C407CU	24-12-2008	4.150	10.87	1800	
6	C407CU	24-12-2008	4.110	11.91	2010	
7	C414CU	31-12-2008	4.156	15.01	2478	2433
8	C414CU	31-12-2008	4.148	13.98	2316	
9	C414CU	31-12-2008	4.133	15.01	2506	
10	C428CU	14-01-2009	4.121	17.08	2868	3276
11	C428CU	14-01-2009	4.133	20.18	3370	
12	C428CU	14-01-2009	4.105	21.22	3591	
13	C43mCU	17-03-2009	4.148	25.36	4203	3988
14	C43mCU	17-03-2009	4.133	23.29	3888	
15	C43mCU	17-03-2009	4.141	23.29	3873	
16	C46mCU	15-06-2009	4.113	23.64	3985	4322
17	C46mCU	15-06-2009	4.148	26.76	4435	
18	C46mCU	15-06-2009	4.176	27.80	4547	
19	C41yCU	17-12-2009	4.141	26.71	4442	4624
20	C41yCU	17-12-2009	4.164	29.80	4902	
21	C41yCU	17-12-2009	4.102	26.71	4528	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	C428NC	14-01-2009	4.133	20.18	3370	3186
2	C428NC	14-01-2009	4.125	19.15	3209	
3	C428NC	14-01-2009	4.164	18.11	2979	
4	C43mNC	17-03-2009	4.098	21.22	3603	3853
5	C43mNC	17-03-2009	4.129	23.29	3896	
6	C43mNC	17-03-2009	4.133	24.32	4061	
7	C46mNC	15-06-2009	4.145	25.72	4270	4062
8	C46mNC	15-06-2009	4.121	24.68	4144	
9	C46mNC	15-06-2009	4.133	22.60	3773	
10	C41yNC	17-12-2009	4.148	26.71	4426	4164
11	C41yNC	17-12-2009	4.133	24.65	4116	
12	C41yNC	17-12-2009	4.129	23.62	3951	

<u>Design Strength: 4000 psi, Cement Brand: D Date of casting: 20-12-2008</u>

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, Ton	Compressive Strength, psi	Avg. strength, psi
1	D403CU	23-12-2008	4.110	11.91	2010	1930
2	D403CU	23-12-2008	4.150	11.91	1972	
3	D403CU	23-12-2008	4.140	10.87	1809	
4	D407CU	27-12-2008	4.090	15.01	2559	2255
5	D407CU	27-12-2008	4.109	12.94	2186	
6	D407CU	27-12-2008	4.098	11.91	2022	
7	D414CU	03-01-2009	4.125	18.11	3036	2856
8	D414CU	03-01-2009	4.117	17.08	2874	
9	D414CU	03-01-2009	4.148	16.04	2660	
10	D428CU	17-01-2009	4.137	19.15	3191	3386
11	D428CU	17-01-2009	4.109	21.22	3584	
12	D428CU	17-01-2009	4.125	20.18	3383	
13	D43mCU	21-03-2009	4.109	24.32	4108	4117
14	D43mCU	21-03-2009	4.137	26.39	4398	
15	D43mCU	21-03-2009	4.156	23.29	3845	
16	D46mCU	18-06-2009	4.145	25.72	4270	4546
17	D46mCU	18-06-2009	4.156	29.89	4935	
18	D46mCU	18-06-2009	4.148	26.76	4435	
19	D41yCU	20-12-2009	4.156	30.83	5091	4854
20	D41yCU	20-12-2009	4.133	28.77	4804	
21	D41yCU	20-12-2009	4.117	27.74	4667	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	D428NC	17-01-2009	4.133	20.18	3370	3342
2	D428NC	17-01-2009	4.086	18.11	3094	
3	D428NC	17-01-2009	4.121	21.22	3563	
4	D43mNC	21-03-2009	4.133	21.22	3543	3868
5	D43mNC	21-03-2009	4.184	24.32	3962	
6	D43mNC	21-03-2009	4.113	24.32	4100	
7	D46mNC	18-06-2009	4.148	24.68	4090	4142
8	D46mNC	18-06-2009	4.164	25.72	4231	
9	D46mNC	18-06-2009	4.141	24.68	4105	
10	D41yNC	20-12-2009	4.160	25.68	4232	4220
11	D41yNC	20-12-2009	4.148	25.68	4255	
12	D41yNC	20-12-2009	4.102	24.65	4178	

<u>Design Strength: 4000 psi,   Cement Brand: E   Date of casting: 21-12-2008</u>

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	E403CU	24-12-2008	4.110	8.80	1485	1594
2	E403CU	24-12-2008	4.130	8.80	1471	
3	E403CU	24-12-2008	4.120	10.87	1826	
4	E407CU	28-12-2008	4.145	13.98	2320	2397
5	E407CU	28-12-2008	4.105	13.98	2365	
6	E407CU	28-12-2008	4.133	15.01	2506	
7	E414CU	04-01-2009	4.121	17.08	2868	2943
8	E414CU	04-01-2009	4.133	18.11	3025	
9	E414CU	04-01-2009	4.133	17.60	2938	
10	E428CU	18-01-2009	4.168	25.36	4163	3834
11	E428CU	18-01-2009	4.094	21.22	3610	
12	E428CU	18-01-2009	4.125	22.25	3730	
13	E43mCU	21-03-2009	4.148	25.36	4203	4207
14	E43mCU	21-03-2009	4.133	24.32	4061	
15	E43mCU	21-03-2009	4.156	26.39	4358	
16	E46mCU	20-06-2009	4.141	26.76	4451	4508
17	E46mCU	20-06-2009	4.148	28.84	4781	
18	E46mCU	20-06-2009	4.133	25.72	4294	
19	E41yCU	21-12-2009	4.148	27.74	4597	4683
20	E41yCU	21-12-2009	4.141	29.80	4958	
21	E41yCU	21-12-2009	4.117	26.71	4494	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	E428NC	18-01-2009	4.133	21.22	3543	3776
2	E428NC	18-01-2009	4.082	23.29	3986	
3	E428NC	18-01-2009	4.086	22.25	3801	
4	E43mNC	21-03-2009	4.160	24.32	4008	4047
5	E43mNC	21-03-2009	4.117	23.29	3918	
6	E43mNC	21-03-2009	4.141	25.36	4217	
7	E46mNC	20-06-2009	4.125	26.76	4486	4284
8	E46mNC	20-06-2009	4.105	24.68	4177	
9	E46mNC	20-06-2009	4.109	24.68	4191	
10	E41yNC	21-12-2009	4.109	24.65	4163	4392
11	E41yNC	21-12-2009	4.117	25.68	4320	
12	E41yNC	21-12-2009	4.105	27.74	4694	

Design Strength: 6000 psi,   Cement Brand: A   Date of casting: 22-12-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	A603CU	25-12-2008	4.130	19.15	3202	3169
2	A603CU	25-12-2008	4.120	18.11	3042	
3	A603CU	25-12-2008	4.090	19.15	3264	
4	A607CU	29-12-2008	4.125	21.22	3556	3602
5	A607CU	29-12-2008	4.137	20.18	3363	
6	A607CU	29-12-2008	4.133	23.29	3888	
7	A614CU	05-01-2009	4.137	26.39	4398	4244
8	A614CU	05-01-2009	4.117	25.36	4266	
9	A614CU	05-01-2009	4.129	24.32	4069	
10	A628CU	19-01-2009	4.125	31.56	5290	4992
11	A628CU	19-01-2009	4.133	28.46	4752	
12	A628CU	19-01-2009	4.129	29.49	4934	
13	A63mCU	22-03-2009	4.109	33.63	5681	5498
14	A63mCU	22-03-2009	4.133	32.60	5443	
15	A63mCU	22-03-2009	4.094	32.56	5371	
16	A66mCU	20-06-2009	4.148	34.05	5644	5815
17	A66mCU	20-06-2009	4.117	35.09	5905	
18	A66mCU	20-06-2009	4.180	36.13	5898	
19	A61yCU	22-12-2009	4.164	35.99	5920	6112
20	A61yCU	22-12-2009	4.180	38.05	6212	
21	A61yCU	22-12-2009	4.125	37.02	6205	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	A628NC	19-01-2009	4.176	29.49	4823	4942
2	A628NC	19-01-2009	4.137	30.53	5087	
3	A628NC	19-01-2009	4.137	29.49	4915	
4	A63mNC	22-03-2009	4.148	30.53	5060	5314
5	A63mNC	22-03-2009	4.125	31.56	5290	
6	A63mNC	22-03-2009	4.141	33.63	5594	
7	A66mNC	20-06-2009	4.148	31.97	5298	5438
8	A66mNC	20-06-2009	4.148	33.01	5472	
9	A66mNC	20-06-2009	4.121	33.01	5544	
10	A61yNC	22-12-2009	4.164	29.80	4902	5385
11	A61yNC	22-12-2009	4.102	32.90	5577	
12	A61yNC	22-12-2009	4.129	33.93	5676	

Design Strength: 6000 psi, Cement Brand: B Date of casting: 24-12-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	B603CU	27-12-2008	4.148	15.01	2488	2333
2	B603CU	27-12-2008	4.125	13.98	2343	
3	B603CU	27-12-2008	4.125	12.94	2169	
4	B607CU	31-12-2008	4.133	20.18	3370	3164
5	B607CU	31-12-2008	4.086	18.11	3094	
6	B607CU	31-12-2008	4.129	18.11	3030	
7	B614CU	07-01-2009	4.152	25.36	4195	3774
8	B614CU	07-01-2009	4.113	21.22	3577	
9	B614CU	07-01-2009	4.129	21.22	3550	
10	B628CU	21-01-2009	4.117	25.36	4266	4641
11	B628CU	21-01-2009	4.148	29.49	4889	
12	B628CU	21-01-2009	4.125	28.46	4770	
13	B63mCU	24-03-2009	4.125	31.56	5290	5413
14	B63mCU	24-03-2009	4.105	32.60	5517	
15	B63mCU	24-03-2009	4.137	32.60	5433	
16	B66mCU	22-06-2009	4.129	31.97	5348	5755
17	B66mCU	22-06-2009	4.141	35.09	5838	
18	B66mCU	22-06-2009	4.117	36.13	6080	
19	B61yCU	24-12-2009	4.164	38.05	6259	6062
20	B61yCU	24-12-2009	4.156	35.99	5942	
21	B61yCU	24-12-2009	4.141	35.99	5987	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	B628NC	21-01-2009	4.082	26.39	4517	4507
2	B628NC	21-01-2009	4.164	28.46	4681	
3	B628NC	21-01-2009	4.090	25.36	4323	
4	B63mNC	24-03-2009	4.137	29.49	4915	5100
5	B63mNC	24-03-2009	4.145	30.53	5068	
6	B63mNC	24-03-2009	4.180	32.60	5321	
7	B66mNC	22-06-2009	4.145	30.93	5135	5345
8	B66mNC	22-06-2009	4.164	33.01	5430	
9	B66mNC	22-06-2009	4.148	33.01	5472	
10	B61yNC	24-12-2009	4.141	33.93	5644	5452
11	B61yNC	24-12-2009	4.156	32.90	5432	
12	B61yNC	24-12-2009	4.148	31.87	5281	

Design Strength: 6000 psi, Cement Brand: C Date of casting: 31-12-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	C603CU	03-01-2009	4.160	16.04	2644	2546
2	C603CU	03-01-2009	4.148	15.01	2488	
3	C603CU	03-01-2009	4.133	15.01	2506	
4	C607CU	07-01-2009	4.141	20.18	3357	3386
5	C607CU	07-01-2009	4.133	21.22	3543	
6	C607CU	07-01-2009	4.094	19.15	3259	
7	C614CU	14-01-2009	4.141	25.36	4218	4412
8	C614CU	14-01-2009	4.129	27.42	4588	
9	C614CU	14-01-2009	4.121	26.39	4432	
10	C628CU	28-01-2009	4.086	26.39	4508	4847
11	C628CU	28-01-2009	4.168	30.53	5012	
12	C628CU	28-01-2009	4.164	30.53	5021	
13	C63mCU	31-03-2009	4.105	32.60	5517	5638
14	C63mCU	31-03-2009	4.148	33.63	5575	
15	C63mCU	31-03-2009	4.121	34.67	5822	
16	C66mCU	29-06-2009	4.164	35.09	5772	5950
17	C66mCU	29-06-2009	4.125	35.09	5882	
18	C66mCU	29-06-2009	4.137	37.18	6195	
19	C61yCU	31-12-2009	4.152	38.05	6294	6258
20	C61yCU	31-12-2009	4.125	38.05	6378	
21	C61yCU	31-12-2009	4.102	35.99	6102	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	C628NC	28-01-2009	4.102	30.53	5174	4816
2	C628NC	28-01-2009	4.129	27.42	4588	
3	C628NC	28-01-2009	4.086	27.42	4685	
4	C63mNC	31-03-2009	4.137	33.63	5604	5430
5	C63mNC	31-03-2009	4.148	32.60	5403	
6	C63mNC	31-03-2009	4.129	31.56	5280	
7	C66mNC	29-06-2009	4.141	33.01	5490	5572
8	C66mNC	29-06-2009	4.148	35.09	5817	
9	C66mNC	29-06-2009	4.105	31.97	5411	
10	C61yNC	31-12-2009	4.141	32.90	5471	5660
11	C61yNC	31-12-2009	4.133	34.96	5837	
12	C61yNC	31-12-2009	4.129	33.93	5676	

Design Strength: 6000 psi,   Cement Brand: D   Date of casting: 03-01-2009

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	D603CU	06-01-2009	4.121	16.04	2694	2732
2	D603CU	06-01-2009	4.133	16.56	2766	
3	D603CU	06-01-2009	4.090	16.04	2736	
4	D607CU	10-01-2009	4.125	23.29	3903	3902
5	D607CU	10-01-2009	4.117	21.22	3570	
6	D607CU	10-01-2009	4.133	25.36	4233	
7	D614CU	17-01-2009	4.145	27.42	4553	4504
8	D614CU	17-01-2009	4.137	26.39	4398	
9	D614CU	17-01-2009	4.141	27.42	4562	
10	D628CU	01-02-2009	4.172	32.60	5342	5185
11	D628CU	01-02-2009	4.090	29.49	5029	
12	D628CU	01-02-2009	4.098	30.53	5185	
13	D63mCU	04-04-2009	4.164	36.73	6042	5750
14	D63mCU	04-04-2009	4.133	33.63	5616	
15	D63mCU	04-04-2009	4.141	33.63	5594	
16	D66mCU	02-07-2009	4.098	34.05	5783	6007
17	D66mCU	02-07-2009	4.137	37.18	6195	
18	D66mCU	02-07-2009	4.129	36.13	6045	
19	D61yCU	03-01-2010	4.156	35.99	5942	6157
20	D61yCU	03-01-2010	4.168	39.08	6417	
21	D61yCU	03-01-2010	4.098	35.99	6113	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	D628NC	01-02-2009	4.160	30.53	5031	5129
2	D628NC	01-02-2009	4.145	31.56	5239	
3	D628NC	01-02-2009	4.125	30.53	5117	
4	D63mNC	04-04-2009	4.145	33.63	5583	5520
5	D63mNC	04-04-2009	4.105	31.56	5342	
6	D63mNC	04-04-2009	4.125	33.63	5637	
7	D66mNC	02-07-2009	4.141	33.01	5490	5643
8	D66mNC	02-07-2009	4.148	35.09	5817	
9	D66mNC	02-07-2009	4.156	34.05	5623	
10	D61yNC	03-01-2010	4.117	33.93	5709	5710
11	D61yNC	03-01-2010	4.125	34.96	5860	
12	D61yNC	03-01-2010	4.105	32.90	5566	

Design Strength: 6000 psi,   Cement Brand: E   Date of casting: 27-12-2008

Curing Type: Continuously cured

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample,, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	E603CU	30-12-2008	4.148	21.22	3516	3668
2	E603CU	30-12-2008	4.102	22.25	3772	
3	E603CU	30-12-2008	4.133	22.25	3716	
4	E607CU	03-01-2009	4.145	27.42	4553	4367
5	E607CU	03-01-2009	4.129	25.36	4242	
6	E607CU	03-01-2009	4.098	25.36	4307	
7	E614CU	10-01-2009	4.137	29.49	4915	4785
8	E614CU	10-01-2009	4.090	26.39	4499	
9	E614CU	10-01-2009	4.125	29.49	4943	
10	E628CU	24-01-2009	4.102	31.56	5350	5594
11	E628CU	24-01-2009	4.109	32.60	5506	
12	E628CU	24-01-2009	4.145	35.70	5926	
13	E63mCU	28-03-2009	4.148	35.70	5918	6058
14	E63mCU	28-03-2009	4.156	38.80	6407	
15	E63mCU	28-03-2009	4.172	35.70	5850	
16	E66mCU	25 -06-2009	4.164	36.13	5944	6203
17	E66mCU	25 -06-2009	4.137	37.18	6195	
18	E66mCU	25 -06-2009	4.160	39.26	6470	
19	E61yCU	27-12-2009	4.117	37.02	6229	6294
20	E61yCU	27-12-2009	4.156	40.11	6623	
21	E61yCU	27-12-2009	4.125	35.99	6032	

Curing Type: 14 days cured only

Serial no.	Sample ID.	Date of Test	Avg. dia. of sample, in.	Load, ton	Compressive Strength, psi	Avg. strength, psi
1	E628NC	24-01-2009	4.113	32.60	5496	5460
2	E628NC	24-01-2009	4.137	31.56	5260	
3	E628NC	24-01-2009	4.129	33.63	5626	
4	E63mNC	28-03-2009	4.152	32.60	5392	5665
5	E63mNC	28-03-2009	4.180	35.70	5827	
6	E63mNC	28-03-2009	4.137	34.67	5778	
7	E66mNC	25 -06-2009	4.148	36.13	5988	5825
8	E66mNC	25 -06-2009	4.145	35.09	5825	
9	E66mNC	25 -06-2009	4.141	34.05	5663	
10	E61yNC	27-12-2009	4.160	37.02	6101	5875
11	E61yNC	27-12-2009	4.156	34.96	5772	
12	E61yNC	27-12-2009	4.102	33.93	5752	