ECONOMICAL ADVANTAGES OF USING FLY- ASH IN THE PRODUCTION OF HIGH STRENGTH CONCRETE

A case study for the Turkish Republic of Northern Cyprus

A MASTER THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF APPLIED SCIENCES
OF
THE NEAR EAST UNIVERSITY

BY

QAZI MOHAMMAD OMAR

In Partial fulfillment for the degree of

MASTER OF SCIENCE

IN
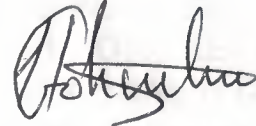
THE DEPARTMENT OF CIVIL ENGINEERING

FEBRUARY 1999

Approval of the Graduate School of Civil Engineering

Prof. Dr. Ergin İĞREK

Director

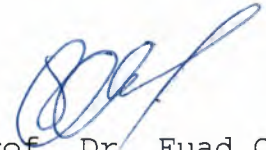I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Assoc. Prof. Dr. Hüseyin GÖKÇEKUŞ

Chairman of the Department

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Civil Engineering.
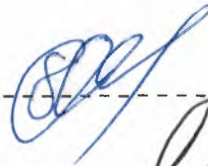
Asst. Prof. Dr. Fuad OKAY

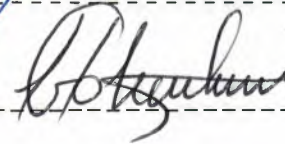Supervisor

Examining Committee in Charge:

Asst. Prof. Dr. Fuad OKAY ------------------------------

Assoc. Prof. Dr. Hüseyin GÖKÇEKUŞ ----------------------

Asst. Prof. Dr. Salah Eddin Sabri ----------------------
(Committee Chairman)

ABSTRACT

ECONOMICAL ADVANTAGES OF USING FLY-ASH IN THE PRODUCTION OF HIGH STRENGTH CONCRETE
A case study for the Turkish Republic of Northern Cyprus

QAZI MOHAMMAD OMAR

M. Sc. in Civil Engineering
Supervisor: Asst. Prof. Dr. Fuad OKAY
December, 1998, 78 pages

In recent years there has been a rapid growth of interest in *high-strength concrete.* As the strength of concrete increases most other engineering properties of concrete are also improved. Such concretes are produced using carefully selected cements, sands and gravels, admixtures including high-range water-reducers, plus very careful quality control during production.

Thus we can say that, as the strength of the concrete increases the concrete becomes more durable. But to increase the strength of concrete more cement paste is required, this in turn increases the cost of concrete production.

The use of fly ash, as an admixture in concrete is gaining popularity because being a waste-product of most industries, it has many benefits such as durability, high compressive strength, better resistance to sulfate attack and volume stability.

In this study, high strength concrete of strength level between 420 to 480Kg/cm^2 is produced in the laboratory. Keeping the amount and quality of aggregates as constant, fly ash is introduced into the concrete. It is seen that there is a gain in strength by introducing fly ash into the concrete.

The second step is to reduce the amount of cement (as cement being the most expensive ingredient of the mix), and to get the same strength level by adding fly ash (i.e. between 420 to 480 Kg / cm^2).

Thus it is seen that, using fly ash the cost of producing concrete decreases, as fly ash has many other advantages over normal concrete, the use of fly ash has both technical and economical advantages over normal concrete.

KEYWORDS: Admixtures, aggregates, concrete, durability, economical advantages, fly ash, high strength, sulfate attack.

ÖZ

YÜKSEK MUKAVEMETLİ BETON YAPIMINDA UÇUCU KÜL KULLANIMININ EKONOMİK AVANTAJLARI
Kuzey Kıbrıs Türk Cummuriyeti için yapılan çalışma

QAZI MOHAMMAD OMAR

Yüksek Lisans Tezi,İnşaat Mühendisliği Bölümü
Tez Yöneticisi.Yrd.Doç.Dr.Fuad OKAY
Şubat,1999, 78 Sayfa

Son yıllarda yüksek mukavemetli betona olan ilgi giderek artmıştır. Bu tip betonu elde edebilmek için daha dikkatle seçilmiş çimento,agrega,yüksek randımanlı katkı maddeleri kullanılmakta, üretim boyunca kalite kontrol çalışması dikkatle yapılarak yüksek mukavemetli beton elde edilmektedir.

Şunu söyliyebiliriz ki betonun gücü arttıkça, betonun ömrü daha uzun olmaktadır. Fakat betonun gücünü artırmak için daha fazla çimentoya ihtiyaç duyulmakta bu da beton üretiminin maliyetini artırmaktadır.

Elde edilecek betonun daha ekonomik olması için bazı deneylerin yapılması gerekmektedir. Aksi takdirde pahalı olan bir malzemenin rağbet görmesi mümkün olmayacaktır.

Son yıllarda, beton içerisinde uçucu külü bir katkı maddesi olarak kullanmak popüler olmuştur. Birçok endüstrinin atık ürünü olan uçucu kül, beton içerisinde kullanıldığı zaman çimento oranı daha az kullanılabilir. Buna mukabil beton

kaliteside artar. Boylece, ucuz olan uçucu maddenin kullanımından dolayı beton dahada ucuza elde edilmiş olur.

Bu çalışmada 420-480 kg /cm^2 arasında güç seviyesi olan beton, İnşaat Mühendisliği Bölümü malzeme labaratuvarında üretilmiştir. Deney sırasında agrega kalitesi ile miktarını sabit tutarak betona uçucu kül ilave edilmiş ve deney sonunda betondaki mukavemetin arttığı gözlenmiştir.

Daha sonra, çimento miktarı azaltılmış ve ayni mukavemeti elde etmek için uçucu kül ilave edilmiştir. Yapılan deneyler sonucunda daha ucuz ve ayni mukavemete sahip uçucu kül katkılı beton imal edilmiştir.

Anahtar kelimeler: Katkı maddeleri, agrega, beton, dayanıklılık, ekonomik avantaj, uçucu kül, yüksek mukavemetli beton, sulfat etkisi.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

CHAPTERS

LIST OF TABLES

LIST OF FIGURES

Figures.   *Page No.*

CHAPTER 1

INTRODUCTION

General

In recent years there has been a rapid growth of interest in HSC. Although HSC is often considered a relatively new material, its development has been gradual over many years. As the development continues, the definition of HSC is also changing. In 1950s, concrete with a compressive strength of 35 MPa was considered high strength. In the 1960s, concrete with 42 and 52 MPa compressive strength were used commercially. In the early 1970s, concrete of strength 62 MPa was being produced as high strength. More recently compressive strengths of over 110 MPa have been considered for applications in cast-in-place buildings and prestressed concrete members [5].

Although the exact definition of HSC is arbitrary, the term generally refers to concrete having compressive strength in the range of about 42 to 83 MPa or higher. Such concretes can be produced using carefully selected but widely available cements, sands, and stone, certain admixtures including high-range water-reducing superplasticizers, fly ash and silica fume, plus very careful quality control during its production [2].

The most common application of HSC has been in the columns of tall concrete buildings, where normal concrete would result in unacceptably large cross sections, with loss of valuable floor space. It has been shown that the use of HSC mixes in columns not only saves floor area, but also is more economical than normal strength concrete as it reduces the amount of concrete and steel reinforcement [5].

For bridges too, smaller cross sections bring significant advantages, and the resulting reduction in dead load permits longer spans. The higher elastic modulus and lower creep coefficient result in reduced initial and long-term deflections, and in the case of prestressed concrete bridges, initial and time-dependent losses of prestress force are less. Other recent applications of HSC include offshore oil structures, parking garages, bridge deck overlays, dam spillways, warehouses and heavy industrial slabs [5].

Thus we can say that, as the strength of the concrete increases the concrete becomes more durable. But to increase the strength of concrete more cement paste is required, this in turn increases the cost of concrete production.

OBJECT AND SCOPE

Cement is the most expensive ingredient of concrete, therefore in this thesis HSC is produced that is more economical, this is done by introducing fly ash, and instead reducing the amount of cement for the same strength concrete. Fly ash is much cheaper than cement, and thus reduces the cost of producing HSC. The cost of producing the same strength concrete with and without fly ash are compared, and it is seen that using fly ash reduces the cost of HSC by over 10 percent.

Fly ash has many other advantages when used in concrete, these advantages are described in detail in chapter 5. In the experimental part it can see that fly ash is used as a partial replacement of cement by 30 percent , thus reducing the cost of concrete production.

Introduction was given in Chapter 1. In chapter 2, the production and application of HSC is discussed in detail. Chapter 3 is concerned with the different types of pozzolanic materials, such as fly ash, blast furnace slag

and silica fumes. In Chapter 4, the effect of these pozzolanic materials on the properties of fresh and hardened concrete is discussed. Chapter 5 is concerned with the experimental program that was performed in the laboratory. Chapter 6 is devoted to Discussion and Conclusion.

CHAPTER 2

PRODUCTION AND APPLICATION OF
HIGH STRENGTH CONCRETE

The strength of concrete depends upon the properties of its ingredients, on the proportions of mix, the method of compaction, and other controls during placing, compaction and curing. Thus in the production of HSC all of the above steps should be improved in order to produce concrete satisfying performance requirements.

In the production of HSC, special attention is given to the concrete both in its fresh and also the hardened state.

In the fresh state the concrete should be workable and easy placeable. Due to the low water cement ratio in HSC they are often very harsh and may require additional water, therefore water reducing admixtures are used which reduces the water demand of the concrete and also makes the concrete workable and easy placeable.

In its hardened state concrete should be strong, durable, and impermeable, and it should have minimum volume changes. The voids or capillaries in the concrete affect these properties, which are caused by incomplete compaction or by excessive water in the mix. Within certain limits, the higher the cement content and the lower the water/cement ratio, the stronger and more durable will be the concrete. Dense, impervious concrete also prevents the reinforcement from corrosion. To keep the voids to a minimum the material must be so proportioned so that the mix is workable and can be fully compacted with the compaction means available [3].

The most important requirement for producing HSC is a low water-cement ratio. For normal concretes this usually falls in the range from about 0.40 to 0.60 by weight, but for high-strength mixes it may be between 0.3- 0.25 or even lower. To reach such low water cement ratios, which would have a zero slump mix, high-range water-reducing admixtures or superplasticizers are used. Other additives include fly ash and most notably silica fume and also carefully selected aggregates [2].

The strength of concrete depends upon three factors i.e. the strength of the cement paste, the strength of the aggregate, and the strength of the bond between the cement paste and the aggregate. Out of these three the strength between the cement paste and aggregate (the transition zone) is the most important one, therefore additional cement is required in order to cover all the aggregates surface. The size of the aggregate is also kept to minimum, so as to have minimum concentration of stresses around the particles, which are caused by the differences between the elastic moduli of the paste and the aggregate [5]. This reduction in the aggregate size increases the demand for cement to be used.

The Strength of concrete is considered to be the most important property and is taken as an index of its overall quality. Many other properties of concrete such as tensile strength and modulus of elasticity are generally related to its compressive strength, as shown in the table 1 below [4].

Table 1: Properties of concrete classes depending on their strength [4].

Concrete Class		Compressive Strength f_c'		Tensile Strength f_{ct}'		Modulus of Elasticity E_{c28}	
European	TS-500	Mpa	(Kgf/cm^2)	Mpa	(Kgf/cm^2)	Mpa	(Kgf / cm)
C14	BS14	14	(140)	1.4	(14)	26150	(261500)
C16	BS16	16	(160)	1.4	(14)	27000	(270000)
C20	BS20	20	(200)	1.6	(16)	28500	(285000)
C25	BS25	25	(250)	1.8	(18)	30230	(302300)
C30	BS30	30	(300)	1.9	(19)	31800	(318000)
C35	BS35	35	(350)	2.1	(21)	33200	(332000)
C40	BS40	40	(400)	2.2	(22)	34550	(345500)
C45	BS45	45	(450)	2.3	(23)	35800	(358000)
C50	BS50	50	(500)	2.5	(25)	36950	(369500)

For compressive strength of up to 83 MPa, the tensile strength f_{ct}', modulus of rupture f_{cr}' and modulus of elasticity E_c can be expressed as follows: [6].

$$f_{ct}' = 7.4(f_c')^{1/2} \quad \text{(MPa)} \dots\dots\dots\dots\dots 2.1$$

$$f_{cr}' = 11.7(f_c')^{1/2} \quad \text{(MPa)} \dots\dots\dots\dots\dots 2.2$$

$$E_c = [\, 275.8(f_c')^{1/2} + 6895 \,] \quad \text{(MPa)} \dots\dots 2.3$$

2.1 Factors Effecting the Strength of Concrete

As stated above there are many factors effecting the strength of concrete, but in general we can say that the strength of concrete depends upon the following factors:

1. Cement
2. Mineral admixture
3. Water
4. Water cement ratio (W/C ratio)
5. Water reducing admixtures
6. Aggregates
7. Compaction
8. Curing
9. Quality control

2.1.1 Cement

Although all materials that go into a concrete mixture are essential, cement is by far the most important constituent. The function of cement is first, to bind the sand and coarse aggregates together, and second, to fill the void spaces in between sand and coarse aggregate particles to form a compact mass. The cement generally used in the production of HSC may be of the same type used in the production of normal strength concrete, or they may be of special types, such as macro-defect free cement, high alumina cement.

There are a variety of cements available in the market and each type is used under certain conditions due to its special properties. For normal strength concrete the amount of cement is about 10 − 15 percent of the

total amount of concrete, but for HSC this may be between 25 – 30 percent. Higher cement content is generally used for HSC production (392 to 557 Kg/m^3). However, using cement content beyond an optimum level would not necessarily result in an increase in strength. In evaluating an optimum cement content, trial mixes are usually proportioned to equal consistencies, allowing the water content to vary according to the water demand in the mixture [5].

As the amount of cement in the production of HSC increases, high temperature rises are expected during hydration. If this rise in temperature becomes a problem then low heat of hydration (Type IV) cement may be used, provided that it meets the strength development requirement [2].

In terms of chemical composition, the two silicates, C_3S and C_2S, control most of the strength giving properties of concrete. Upon hydration, both C_2S and C_3S give the same product called calcium silicate hydrate ($C_3S_2H_3$) and calcium hydroxide ($Ca(OH)_2$) [2].

Tricalcium silicate (C_3S) has a faster rate of reaction and therefore evolves greater heat and develops strength much earlier than the other constitutes of cement. On the other hand, dicalcium silicate (C_2S) hydrates and hardens slowly and provides much of the ultimate strength. It is likely that both C_3S and C_2S phases contribute equally to the eventual strength of the cement as can be seen in the figure 1 [1].

C_3S and C_2S need approximately 24 and 21 percent water by weight, respectively, for complete chemical reaction to take place, but C_3S liberates nearly three times as much calcium hydroxide on hydration than C_2S (the effects of calcium hydroxide on the strength of concrete will be discussed later). Whereas, C_2S provides more resistance to chemical attack such as salt water. Thus a higher percentage of C_3S results in rapid hardening with an early gain in strength at a higher heat of

generation. On the other hand, a higher percentage of C_2S results in slow hardening, less heat of generation and greater resistance to chemical attack and more uniformly packed C-S-H bond. Thus we can say that a higher percentage of C_2S content of cement is beneficial in the production of late strength development of HSC [1].

The compound tricalcium aluminate (C_3A) is characteristically fast reacting with water and may lead to an immediate stiffening of paste, and this process is termed flash set. The role of gypsum added in the manufacture of cement is to prevent such a fast reaction. C_3A reacts with 40 percent water by mass, and this is more than that required for silicates. However, since the amount of C_3A in cement is comparatively small, the net water required for the hydration of cement is not much affected. It provides weak resistance against sulfate attack and its contribution to the development of strength of cement is perhaps less significant than that of silicates. In addition, the C_3A phase is responsible for the highest heat of evolution both during the initial period as well as in the long run [2].

C_4AF like C_3A, hydrates rapidly but its individual contribution to the overall strength of cement is insignificant. However, it is more stable than C_3A.
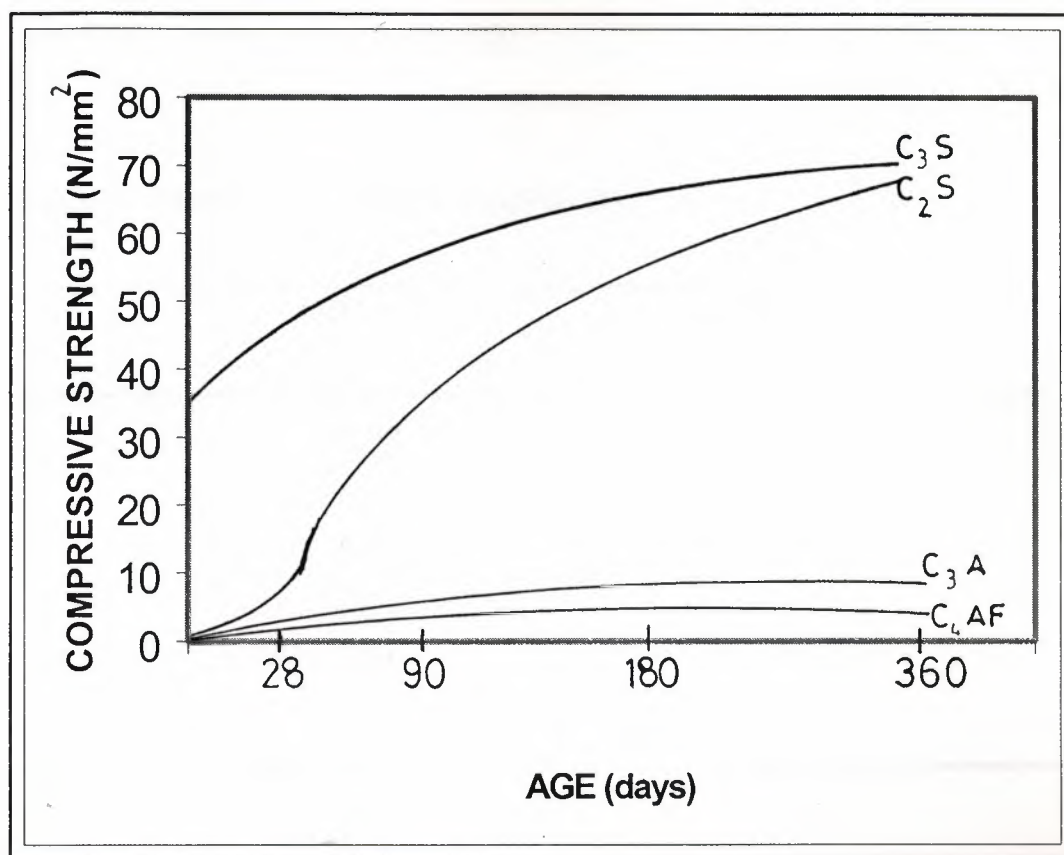
Figure 1: Contribution of cement compound to the strength of concrete [1].

The oxides present in cement also affect the strength characteristics of concrete. Table 2 gives the oxide composition of ordinary Portland cement.

A high lime content generally increases the setting time and results in higher strengths. A decrease in lime content reduces the strength of concrete. A high silica content prolongs the setting time and gives more strength. The presence of excess unburnt lime is harmful since it results in delayed hydration causing expansion (unsoundness) and deterioration of concrete. Iron oxide is not a very active constituent of cement, and generally acts as a catalyst and helps the burning process during the production of cement. Owing to the presence of iron oxide, the cement

derives the characteristic gray colour. Magnesia, if present in larger quantities, causes unsoundness [2].

Table 2: Oxide Composition of (OPC) [1]

Oxide	Percentage
CaO	60 - 65
SiO_2	17 - 25
Al_2O_3	3 - 8
MgO	0.5 - 4
SO_3	1 - 2
$Na_2O + K_2O$	0.5 - 1

In terms of fineness of cement, the surface area is more for a finer cement than for a coarser cement. The finer the cement, the higher is the rate of hydration, as more surface area is available for chemical reaction to take place. This results in the early development of ultimate strength. Ultrafine Portland cement (UFPC) having a specific surface of 700-900m^2/Kg have been used successfully in the production of high early strength concretes, and strengths of 40 to 80 MPa were obtained by one day [6]. The effect of fineness of cement on the compressive strength of concrete is shown in Figure 2.
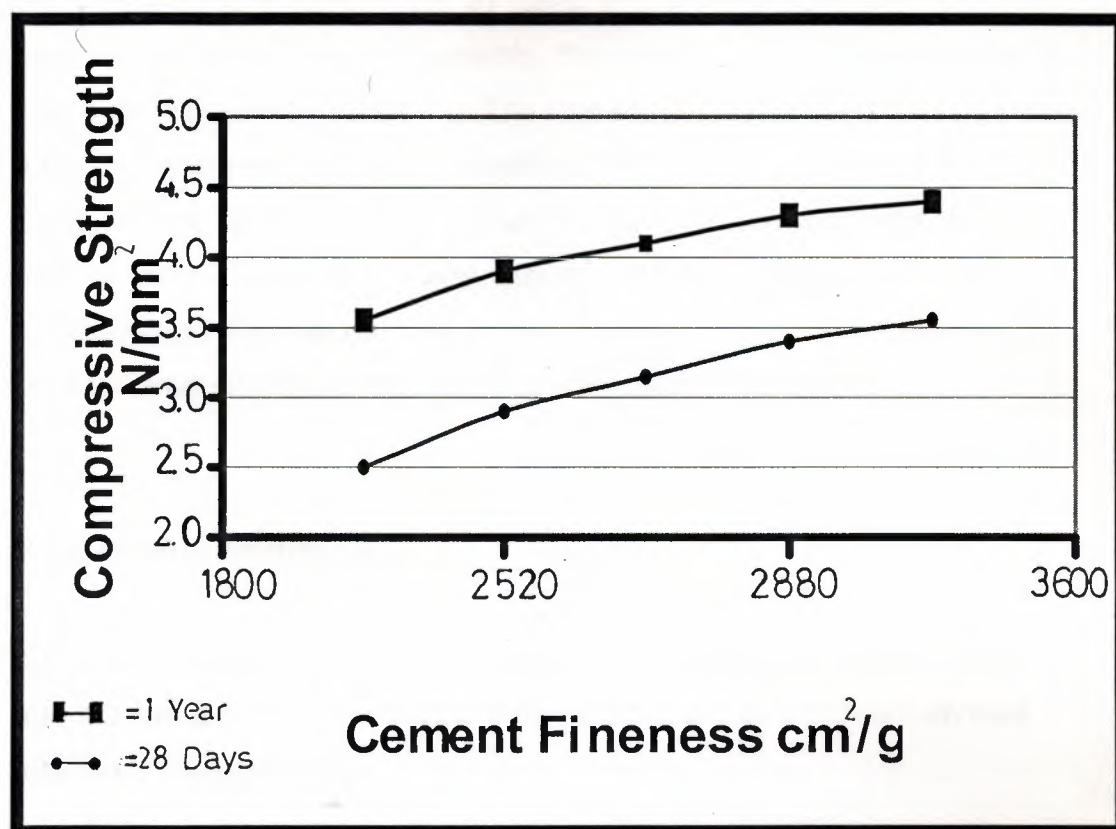
Figure. 2: Effect of fineness of cement on the compressive strength of concrete [3].

The hydration of cement is exothermic with approximately 120 cal/g heat being liberated called the heat of hydration. In the interior of a large concrete mass, the hydration can result in a large rise in temperature. At the same time, the exterior of the concrete mass losses some heat so that a steep temperature gradient may be established, and during the subsequent cooling of the interior, severe cracking may occur resulting in less durable concrete. On the other hand, the heat of hydration may be advantageous in preventing the freezing of water in the capillaries of freshly placed concrete in cold weather [2].

The heat of hydration increases with temperature at which hydration takes place. For OPC it varies from 37 cal/g at 5^0C to 80 cal/g at 40^0C. For common types of Portland cements, the total heat liberated between 1 and 3 days is about 50 percent. The rate of heat evolution as well as the total heat depends on the composition and quantity of cement used. By restricting the quantities of compounds C_3A and C_3S in cement, the high rate of heat liberation in early stages can be checked. The rate of hydration and the heat evolved increases with the fineness of cement but the total amount of heat liberated is unaffected by fineness [3].

2.2.2 Mineral Admixture

Of the many admixtures available for concrete, an important group falls into the category of finely divided mineral admixtures, which are divided into three categories:[5].

1. Those that are chemically inert.

2. Those that are pozzolanic in nature.

3. Those that are cementitious.

In the production of HSC the type of mineral admixture generally used are pozolanic in nature, such as silica fumes and fly ash. Pozzolanic materials do not possess any cementaneous properties in themselves but in the presence of $Ca(OH)_2$ reacts with water to produce C-S-H gel. Fly ash and silica fumes are discussed in detail in chapter 4.

2.2.3 Water

Water is the most important and the cheapest ingredient of concrete. A part of mixing water is utilized in the hydration of cement to form the

binding matrix in which the inert aggregates are held in the hardened state. The remaining water serves as a lubricant between the fine and coarse aggregates and makes concrete workable (i.e. readily placeable in forms). For HSC this excess amount of water is kept as low as possible.

Generally, cement requires about 0.25 – 0.30 of its weight of water for hydration. Hence the minimum water-cement ratio required is between 0.30 – 0.35. But the concrete containing water in this proportion will be very harsh and difficult to place. Additional water is required to lubricate the mix, which makes the concrete workable. This additional water must be kept to the minimum, since too much water reduces the strength of concrete [1].

If too much water is added to concrete, the excess water along with cement comes to the surface by capillary action and this cement-water mixture forms a thin layer of chalky material known as laitance. This laitance prevents bond formation between the successive layers of concrete and forms a plane of weakness. The excess water along with the cement paste may also leak through the joints of the formwork and make the concrete porous and weak. As a rule, the smaller the percentage of water, the stronger is the concrete [1].

For HSC, water-reducing admixtures and superplasticizers are used to reduce the water demand to as low as 0.25 (i.e. w/c ratio of 0.25) and also making the concrete workable.

The quality of water also effects the strength of concrete, the water used for the mixing and curing of concrete should be free from injurious amounts of deleterious materials. Drinkable water is generally considered satisfactory for mixing concrete i.e. water having a pH value between 6 and 8 [3].

Seawater contains dissolved salts which effects the strength of concrete, the reduction of strength may be in the order of 10 – 20 percent. Table 2 gives the effects of dissolved salts on the strength of concrete [1].

Table 3: Effects of dissolved salts in water on compressive strength[1].

Percentage of salt in water		percentage reduction in Compressive strength
0.5	SO_4	4
1.0	SO_4	10
5.0	NaCl	30
	CO_2	20

Sugar present in water also effects the strength of concrete, for small amount of sugar such as 0.05 percent by weight of water there is no effect on the strength of concrete. Small amount of sugar up to 0.15 percent retards the setting of concrete and increases the 28-day strength. When the quantity of sugar is increased to 0.20 percent there is an accelerated setting of concrete and further increase in the sugar content result in rapid setting and decreased 28 days strength [1].

Mineral oils mixed with animal or vegetable oil have no adverse effect on the strength of concrete. Up to 2 percent of mineral oil mixed with water have shown an increased strength, for a percentage of mineral oil more than 8 there is a decreased strength at later ages [1].

In general, we can say that the quantity and quality of water effects the strength of concrete, therefore, mixing water should be free from deleterious substances.

2.2.4 Water – Cement Ratio (W/C)

A cement of average composition, (i.e. Type I cement) requires about 25 percent of water by mass for chemical reaction. In addition, an amount of water is needed to fill the gel pores. The total amount of water thus needed for chemical reaction and to fill the gel pores is about 40-45 percent. The general belief is that a water-cement ratio of less than 0.40 or so should not be used in concrete because, for the process of hydration, the gel pores should be kept saturated. However this is not so because, even in the presence of excess water, the complete hydration of cement never takes place due to the decreasing porosity of the hydration products. As a matter of fact, a water-cement ratio of as less as 0.25 is being used to produce high-strength structural concrete [2].

2.2.5 Chemical Admixture

Since the strength of concrete depends mainly upon the water cement ratio, therefore in the production of HSC, the chemical admixture generally are water reducers. These admixtures, reduces the amount of water needed, making the concrete workable and easy placed in forms.

The types of admixtures that reduces the amount of water required are as follows: [5]

1   Type A: Water-reducing admixtures.
2   Type B: Retarding admixtures.
3   Type C: Accelerating admixtures.

4   Type D: Water-reducing and retarding admixtures.

5   Type E: Water-reducing and accelerating admixtures.

6   Type F: High-range water-reducing admixtures.

7   Type G: High-range water-reducing and retarding admixtures.

As stated before Water-reducing admixtures are used to reduce the quantity of mixing water required to produce concrete of a given consistency. Water-reducing admixtures are based on lignosulphonic acids, hydroxy carboxylic acids, and processed carbohydrates. For a given workability, they can reduce the water requirement of concrete by 5 to 15 percent.

High-range water-reducing admixtures (superplasticizers) were introduced in Japan in 1964, and later in 1970 in Europe and the United States. They are chemically different from the normal water reducers and are capable of reducing water requirement by about 30 percent for the same consistency. The superplasticizers are broadly classified into four main groups [6].

1. Sulphonated melamine-formaldehyde condensates.
2. Sulphonated naphtaline formaldehyde condensates.
3. Modified lignosulphonates.
4. Sulphonic acid esters, carbohydrate esters, and so on.

The advantage of water reducers and superplasticizers can be categorized in three ways [5].

1   Obtaining higher compressive strength; The addition of the admixture reduces the water-cement ratio without altering the workability producing a denser and stronger concrete.

2   Obtaining better Workability; The use of the admixture to concrete without reducing the water-cement ratio will improve the workability of concrete without any loss of strength.

3   Reducing the cement content; The addition of the admixture to a concrete mixture would yield a concrete with the same strength and workability characteristics of another concrete mixture with higher cement content.

The effect of water-reducing admixtures on fresh concrete can be described as follows; When water is added to the cement the cement particles tend to cluster together. This is attributed to the attractive forces that exist between positively and negatively charged surfaces. To break these clusters and improve the workability larger amount of water (higher water-cement ratio) is needed. This could result in lower strength for the hardened concrete. When water-reducing additives are added, they are absorbed by the cement particles, causing them to repel each other. Hence, a well-dispersed system is obtained and less water is required by the concrete.

2.2.6 Aggregates

The aggregates provide about 70 – 75 percent of the body of the concrete and therefore a good selection of aggregate is extremely important. The main properties of aggregate with respect to the strength of concrete are:

1. Shape
2. Size
3. Mechanical properties
4. Chemical interaction with cement paste

To produce good quality concrete having high strength the water cement ratio has to be kept as low as possible. To obtain this, the water required by the aggregate has to be low. This is generally governed by the shape size and mineral composition of the aggregates.

Fine aggregate: The particles passing No 4 sieve (i.e. 4.75-mm) is generally termed as fine aggregate. For the production of HSC the selection of fine aggregate is very important. The fineness Modulus of fine aggregate effects the strength of concrete. Sand with fineness modulus of 2.5 gives a very harsh concrete, whereas sand of (FM) of about 3.0 gives the best workability and compressive strength [5].

Since most sand obtained is from the seashore, they contain salts. These salts have to be removed so that the sand can used for concrete works. The effect of salts on the strength of concrete was given in table 1.

Smaller particles absorbs more water, therefore for producing HSC, aggregates passing No: 100 sieve should be avoided. These particles also have a higher surface area and therefore require more cement paste.

Shale and other particles of low density, such as clay lumps should be avoided to have higher strengths. Organic impurities usually present in fine aggregates should also be avoided as they interact with the chemical reactions of hydration [1].

Coarse aggregate: Aggregates retained on No:4 sieve is generally termed as coarse aggregate. For the production of high performance concrete, maximum size of 19 –25 mm has been used successfully. Aggregates larger than 25mm are more economical, but concrete produced with larger size aggregates are harsh and requires proper compacting techniques, which generally increases their cost if such compaction equipment's are unavailable.

As the size of the aggregate decreases more cement paste is required (i.e. more cement is required). This is due to the fact that more surface area is produced for the cement paste to cover [5].

The bond between coarse aggregate and cement paste depends upon the shape of coarse aggregate. Rounded aggregates (river or seashore gravels) having lesser voids, is much stronger than many other aggregates, but due to their smother surfaces they do not produce a stronger bond with cement paste. To use these aggregates for producing high performance concrete they have to be properly crushed. Table I and II in Appendix C gives some of the physical properties of rocks that are used as aggregates in concrete production.

The shape of the coarse aggregate also effects the strength and workability of concrete, rounded aggregates produces poor interlocking with the cement paste, angular and irregular aggregates have a larger percentage of voids ranging 35 – 40 percent, and therefore requires more cement paste to produce concrete. The ideal aggregate should be cubical, angular and 100 percent crushed, with minimum voids between them. Flaky and elongated aggregates should be avoided. Aggregates that are chemically reactive should also be avoided, these aggregate chemically reacts with the cement and produces weak concrete [5].

Absorption of aggregates: During mix design, it is very important to calculate the absorption capacity of aggregates. When water is added to the mix it is seen that they are immediately absorbed by the aggregates, therefore for mix design additional water should be added. This additional water is equal to the water that is absorbed by the pores of aggregates immediately during the mixing process.

The absorption water is also very beneficial for concrete strength because concrete requires a lot of water for curing, especially during their early stages of hydration. These absorbing aggregates serves as water reservoirs providing water which is beneficial during curing [5].

2.2.7 Compaction

During the manufacturing of concrete a considerable amount of air is entrapped and during its transportation there is a possibility of segregation. If the entrapped air is not removed and the segregation of coarse aggregate not corrected, the concrete may be porous, non-homogeneous and low strength. The process, of removal of entrapped *air* and of uniform placement of concrete to form a homogeneous dense mass is termed compaction. Compaction is accomplished by doing external work on the concrete. The density and, consequently, the strength and durability of concrete depend upon the quality of this compaction. Therefore, compaction is necessary for successful concrete manufacture. The concrete mix is designed on the basis that after being placed in forms it may be thoroughly compacted with available compacting equipments. The presence of even 5 percent voids in hardened concrete may result in a decrease in compressive strength by about 30 – 35 percent [1].

Therefore for producing quality concrete, the concrete must be properly compacted. Due to low water cement-ratios in HSC they are generally very stiff and cannot be compacted easily. Vibrating equipments are used to compact such dense concretes or water reducing admixtures are used to make them workable and easy placeable.

Over vibration or prolonged vibration may lead to bleeding and segregation of concrete, but for concrete with low water cement ratio this is not the case, prolonged or over vibration has found to increase the strength of concrete even at frequencies of 8000 rpm for 12 minutes or over [1].

2.2.8 Curing

The strength and other physical properties of concrete depend to a large extent on the extent of hydration of cement and the resultant microstructure of the hydrate cement. Upon coming in contact with water, the hydration of cement takes place both inward and outward in the sense that the hydration products get deposited on the outer boundary of cement grains, and the nucleus of unhydrated cement inside gets gradually diminished in volume. At any stage of hydration the cement paste consists of the product of hydration (called gel because of its large area), the remnant of unreacted cement, $Ca(OH)_2$ and water. The product of hydration forms a random three-dimensional network gradually filling the space originally occupied by the water [2].

Accordingly, the hardened cement paste has a porous structure, the pore sizes varying from very small (4×10^{-10} m) to very large and are called gel pores and capillary pores. As the hydration proceeds, the deposit of hydration products on the original cement grains makes the diffusion of water to the unhydrated nucleus more and more difficult, and so the rate of hydration decreases with time. Therefore, the development of the strength of concrete, which starts immediately after setting is completed, continues for an indefinite period, though at a rate gradually diminishing with time. 80 to 85 percent of the eventual strength is attained in the first 28 days and hence this 28-day strength is considered to be the criterion for the design and is called the characteristic strength [1].

As mentioned above, the hydration of cement can take place only when the capillary pores remain saturated. Moreover, additional water available from an outside source is needed to fill the *gel pores, which* will otherwise make the capillary empty. Thus, for complete and proper strength development, the loss of water in concrete from evaporation should be prevented, and the water consumed in hydration should be replenished. Thus the concrete continues gaining strength with time provided sufficient

moisture is available for the hydration of cement which can be assured only by a creation of favourable conditions of temperature and humidity. The desirable conditions are; a suitable temperature, as it governs the rate at which the chemical reactions involving setting and hardening take place; the provision of ample moisture or the prevention of loss of moisture; and the avoidance of premature stressing or disturbance. All the care taken in the selection of material, mixing, placing and compaction, etc, will be brought to nought if the curing is neglected. The curing increases compressive strength, improves durability, impermeability and abrasion resistance. Figure 3, describes the effect of curing temperature on the compressive strength of concrete [2].

The increase in strength with increased temperature is due to the speeding up of the chemical reactions of hydration. This increase affects only the early strengths without affecting the ultimate strengths. Hence, curing of concrete and its gain of strength can be speeded up by raising the temperature of curing, thereby reducing the curing period. This type of curing is called accelerated curing and is used mainly in the manufacturing of precast concrete products.

Curing technique, such as chemical curing may not be used for HSC. HSC requires a lot of water, therefore, chemical curing (in which chemicals like sodium silicate which acts as a membrane preventing the external water to penetrate the concrete) may not be suitable.
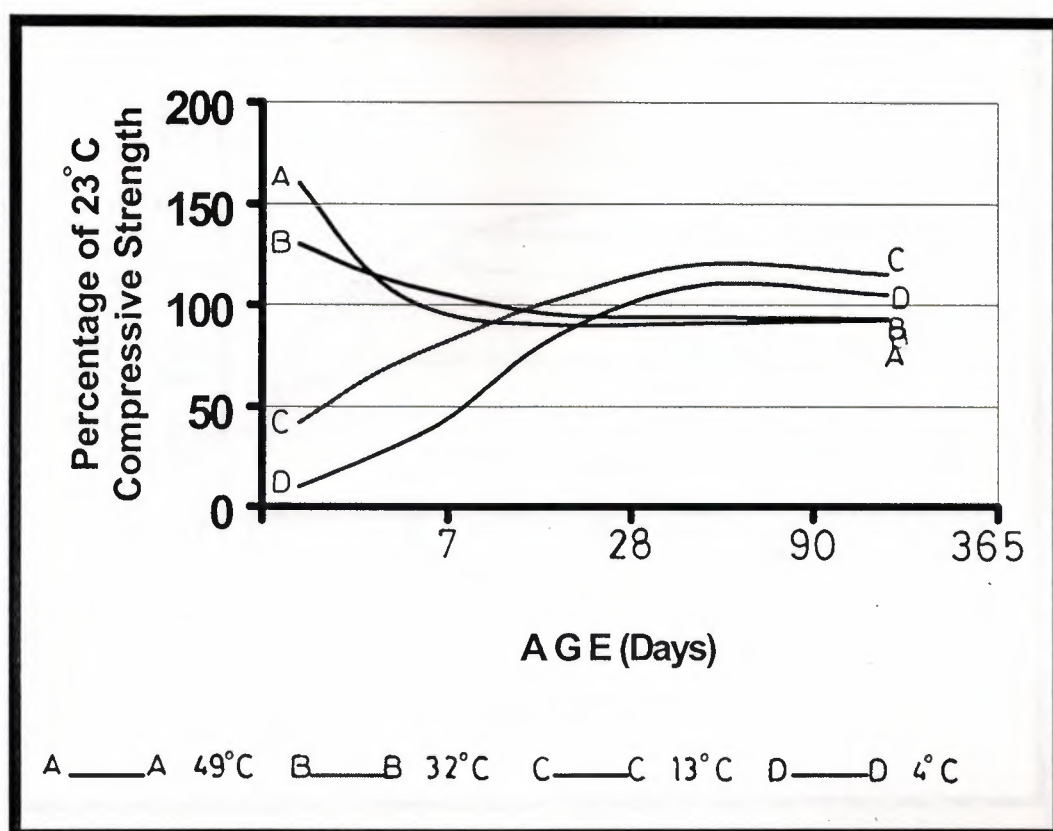
Figure 3: Effect of curing temperature on the compressive strength of concrete [2].

In addition, the length of curing is also important. The first three days are the most critical in the life of Portland cement concrete. In this period the hardening concrete is susceptible to permanent damage. On an average, the one-year strength of continuously moist cured concrete is 40 percent higher than that of 28 days moist cured concrete, while no moist-curing can lower the strength to about 40 percent. Moist curing for the first 7 to 14 days may result in a compressive strength of 70 to 85 percent of that of 28 day moist-curing as shown in Figure 4.

A=Cured in air
B= In air after 3 days
C= "   "   " 7 days
D= "   "   " 14 days
E= "   "   " 28 days
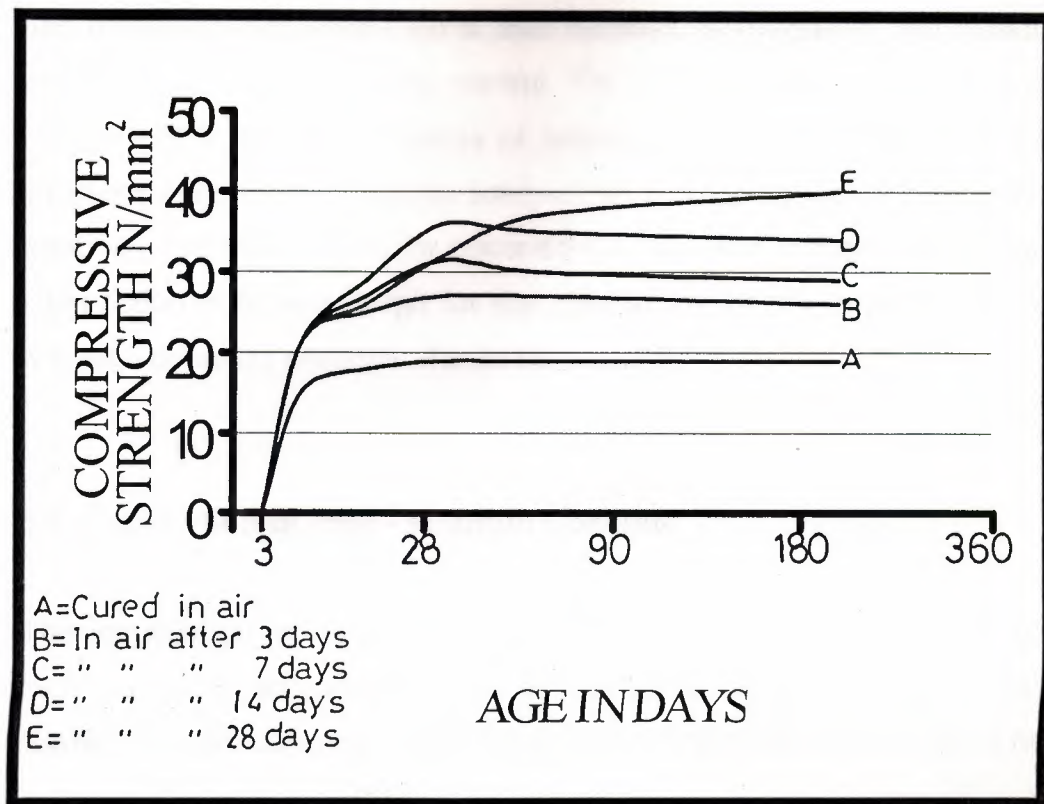
Figure 4: Strength of concrete depending upon the curing condition of moisture [2].

2.2.9 Quality control

The concrete generally produced at the site, is likely to vary from one batch to another. This variation depends upon many factors such as:

1. Variation in the quality of constituent materials.
2. Variation in mix proportions due to batching process.
3. Variation in the quality of batching.

Moreover the concrete undergo a number of operations such as transportation, placing, compaction and curing, which may reduce the

quality of concrete. As the quality of the concrete is reduced the strength and durability of the concrete is also reduced. Segregation and bleeding are also due to poor quality control. For HSC with low water - cement ratio, there is no much chance of segregation, but the quality of such concrete may be lost if proper compaction and curing techniques are not adopted. For high workability concrete (i.e. w/c ratio is high) proper hand compaction may be enough for the compaction of concrete. But for low w/c ratio concrete vibrators should be used [2].

2.3. Application of High - strength Concrete

The application of HSC in structures have many advantages, both technical and economical. Tall structures whose construction using normal strength concrete would not have been feasible in the past is now been completed using HSC.

Major application of HSC is in tall buildings (columns and shear-walls), long span bridges and some special structures. The use of HSC in Buildings and Bridges are summarized in table 3 and 4 respectively [6].

Table 4: Buildings with high strength concrete [6].

Building	Location	Year	Total Number of Stories	Max. Concrete Strength psi
Pacific Park Plaza	California	1983	30	6500
S.E financial center	Miami	1982	53	7000
Petrocanada Building	Calgary	1982	34	7250
Lake point tower	Chicago	1965	70	7500
Texas Commerce Tower	Huston	1981	75	7500
Helmsley Palace Hotel	New York	1978	53	8000
Collins Palace	Melbourne		44	8000
Royal Bank Plaza	Toronto	1975	43	8800
River Plaza	Chicago	1976	56	9000[a]
Merchantile Exchange	Chicago	1982	40	9000[b]

[a] *Two experimental columns of 11,000 psi strength were included.*

[b] *Two experimental columns of 14,000 psi strength were included.*

Metric equivalent: 1000 psi = 6.895 Mpa.

Table 5: Bridges with high strength concrete [6].

Bridge	Location	Year	Maximum Span (ft)	Max. Concrete Strength psi
Willows Bridge	Toronto	1967	158	6000
Houston Ship Canal	Texas	1981	750	6000
San Diego to Coronado	California	1969	140	6000*
Coweman River Bridge	Washington		146	7000
Huntington to Proctorville	West Virginia	1984	900	8000
Nitta Highway Bridge	Japan	1968	98	8500
Fukamitsu Highway bridge	Japan	1974	85	10,000
Ootanabe Railway bridge	Japan	1973	79	11,400
Akkagawa Railway Bridge	Japan	1976	150	11,400

* Light weight concrete

Metric Equivalent: 1000 psi = 6.895 Mpa.

1ft = 30.48 cm

CHAPTER 3

POZZOLANS AND POZZOLANIC MATERIALS

The most widely used mineral admixture in the modern concrete industry is the pozzolan. The use of pozzolans as a construction material parallels the history record works of man. About 2000 years ago Greeks, Romans and other Mediterranean peoples discovered the value of using pozzolans (fine volcanic ash) with burned lime to build historic structures, some are still in use today [7].

A pozzolan, is defined as "siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" [8].

This chemical reaction between pozzolan, calcium hydroxide and water is called the pozzolanic reaction.

Two types of pozzolanic materials are readily available. There are the natural pozzolans which are of volcanic origin (and these were used by the early Romans and Greeks) such as trass, pumicites and perlite. Since the volcanic ash was found near Pozzoli, Italy, the material was called Pozzolana or Pozzolan (in English) and this name has since been used to cover the entire class of mineral admixtures of which it is a member [7].

The second type are man-made pozzolans which include by-products such as fly ash (the burning of coal), blast furnace slag (steel industry), and silica fume (silicon and ferrosilicon manufacture).

3.1 Fly Ash

Fly ash is produced by the burning of coal. Coal as we know is a mixture of carbon, complex organic compounds and inorganic substances and when burned, energy is produced, the organic portion is converted to gases such as oxides of carbon and sulfur and water vapor. Whereas the inorganic portion is non-combustible, and is the principal component of the fly ash. The ash component of coal ranges from 10% to 20% by weight of the coal.

It should be pointed out here that not all of the ash derived from the burning of coal is fly ash. A good portion of it is what is often called "the bottom ash". Bottom ash consists of large agglomerates, and consists mainly of carbon.

Fly ash is described as being either Class C or Class F in ASTM C618 and the basic chemical requirements set forth for the two classes are listed in Table 6. Class C is assigned to those ashes which generally have a high calcium oxide (CaO) content and Class F is chosen for those ashes which generally have a high iron oxide (Fe_2O_3) content (i.e., C = CaO and F = Fe_2O_3 respectively) [7],[8].

Class C fly ash is generated during the firing of subbituminous or lignitic coal, whereas Class F fly ash is derived from the burning of bituminous coal.

Typical compositions of a type I Portland cement and of fly ashes representing Classes F and C are listed in Table 7. It can be seen that, when Class F or C fly ash is added to Portland cement concrete, the same kinds of metallic and non-metallic oxides as those of the cement are being added to the mix. In other words nothing new or strange is being introduced to the concrete [7].

Table 6. Chemical Requirements of Fly Ash [7].

FLY ASH CLASS CHEMICAL COMPONENT	C	F
SiO_2 + Al_2O_3+ Fe_2O (min %)	50	70
SO_3 max %	5	5
Moisture content (max %)	3	3
Available alkalies (as Na_2O) (max %)	1.5	1.5

Though the Class C fly ash appears to contain more calcium oxide (CaO), than the Class F fly ash, very little of it occurs as free, uncombined CaO.

The loss on ignition (L.O.I.) of a Class C fly ash is, as a rule, lower than that of Class F ashes. 99 percent, or more, of the L.O.I. of a given fly ash is due to unburned carbon in the ash and its presence can be detrimental when concrete to which the ash has been added is treated with an air entraining admixture [7].

The physical properties of fly ash, as they apply to the properties of concrete depends mainly on two factors, its fineness and density. The maximum amount retained on the No:325 (45 μm) sieve for both Classes has been set at 34 % . This amount, represents that portion of the fly ash that will exhibit very little pozzolanic reaction during the first 28 days of the life of the fly ash treated with Portland cement concrete [7].

Table 7: Chemical Composition of a Typical Type I Portland Cement and of Fly Ash [7].

CHEMICAL COMPONENT	TYPE I CEMENT %	CLASS F FLY ASH %	CLASS C FLY ASH %
SiO	19.8	43.4	32.5
Al_2O_3	6.1	18.5	21.9
Fe_2O_3	2.5	26.9	5.1
CaO	63.7	4.3	27.4
SO_3	2.2	1.2	2.8
MgO	3.5	0.9	4.8
Total Alkalies (as Na_2O)	0.9	0.6	1.1
Loss on ignition	1	3.2	1.2
Moisture	--	0.2	0.8

In addition, the total percentage of iron oxide and L.O.I. represents that portion of ash that merely "goes along for the ride" and contributes nothing to the pozzolanic activity of the ash.

The density, or specific gravity, of fly ash, which is somewhat related to its morphology, is also a determining factor in its pozzolanic activity. A reproduction of a highly magnified photograph of a fly ash is shown in Figure 5. The structural configuration of an ash is basically made up of hollow sphere which have a "skin" of amorphous silicon dioxide, or possibly complex compounds of silicon dioxide. This glassy skin is the principal reactive component in the fly ash. Small particles are generally

more glassy than large particles because of their more rapid rate of cooling [7].

Figure 5: Microphotography of a fly ash [7].

During the burning of coal (combustion process), carbon dioxide, steam, and oxides of sulfur and nitrogen act in such a way as to bloat the semi-fluid particles into the spherical shape. The density of the spheres depends upon their size, i.e., the smaller the size, the higher the density. Regardless of their size, the glassy hollow spheres tend to reduce the density of the ash, as measured by standard methods [7].

Most fly ashes, whether they be of the Class F or C variety contain some crystalline material, the major portion of which is the mineral mullite, $3Al_2O_3 . 2SiO_2$. It is that part of the crystalline component of fly ash, that can be considered non-reactive with respect to its pozzolanic response in

Portland cement concrete and that its addition is essentially equivalent to adding finely divided sand [7].

The amount of glassy, reactive material present in fly ash depends on at least two factors:

(1) The temperature in the power producer's coal burning furnace and

(2) The rate at which the ash is cooled.

The higher the former and the quicker the latter, the greater will be the amount of glass in the ash. It should also be pointed out here that the fineness of fly ash is directly related to the fineness to which the coal is ground or pulverized prior to burning.

While the pozzolanic activity of a given fly ash can be related to its density, several other factors enter into this relationship, such as its L.O.I., iron oxide and glassy silicon dioxide contents and fineness (or surface area). In recognition of the fact that fineness and density are inter-related, the suppliers of fly ash often express its overall fineness in units of cm^2/cm^3, which is the result of multiplying its fineness (cm^2/g) by its density (g/cm^3). Another relationship that tends to complicate the picture is that of fineness and L.O.I. In general, as the fineness of the fly ash decreases, its L.O.I. will also decrease. There is an optional physical requirement for Class F fly ashes, called the multiple factor, which is calculated as the product of L.O.I. and the amount retained on the No. 325 (45 μm) sieve [8].

3.2 Granulated Blast Furnace Slag

Another artificial, or manmade pozzolans is the granulated blast furnace slag which is a non-metallic product. It is a mixture of lime, silica and alumina obtained in the manufacture of pig iron.

The very rapid cooling of the slag results in most of its components being glassy (amorphous) which have a high pozzolanic activity. Blends of it with Portland cement generally possess properties superior to plain Portland cement after 3 to 7 days, at normal temperatures.

In the formation of the slag, the blast furnace is first charged with coke (carbon), iron ore and limestone ($CaCO_3$) and the mixture is heated to about 2600^0 F [8].

$$3C + 2Fe_2O_3 \longrightarrow 3CO_2 + 4Fe$$

The iron oxide component of the ore is reduced to molten iron. The limestone acts as a flux in the mixture and slowly floats to the top of the molten iron. The high temperature of the blast furnace converts it to calcium oxide, which then combines with the silicon dioxide and aluminum oxide to form a complex mixture of calcium silicates and aluminates. The production of 1 ton of raw, or pig, iron requires, on the average, 1.7 tons of iron ore, 0.9 tons of coke and 0.4 tons of high grade limestone. Roughly, 0.5 tons of slag is produced per ton of raw iron. Although the chemical composition of blast furnace slag will vary, as it does in the case of other pozzolanic materials, a typical chemical analysis is illustrated in Table 8 [7].

Table 8: Typical Chemical Composition of Blast Furnace Slag [7].

CHEMICAL COMPONENT	% BY WEIGHT
CaO	38.8
SiO_2	36.4
Al_2O_3	9.6
Fe_2O_3	0.7
MgO	10.4
SO_3	1.2
Alkalies (as Na_2O)	0.6

3.3 Silica Fume

Another artificial, or man-made, pozzolan that appears to have tremendous potential in the concrete industry is silica fume. It is referred to as a "fume" because it is so finely divided that its particle size approximates that of the solid particulates in smoke. Some purists prefer to call it microsilica and others as condensed silica fume. Silica fume is the by-product of the manufacture of elemental silicon and ferrosilicon alloys. During the process, which is carried out in an electric arc furnace (up to 3600^0 F), quartz (SiO_2) is reduced to elemental silicon and gaseous silicon monoxide. The latter is oxidized back to SiO_2 at the top of the open furnace to silicon dioxide when it comes in contact with the oxygen in the air.

$$SiO_2 + C \xrightarrow{\text{(HEAT)}} Si + CO_2 \qquad \text{(main reaction)}$$

$$3SiO_2 + 2C \xrightarrow{\text{(HEAT)}} Si + 2SiO + 2CO_2 \qquad \text{(secondary reaction)}$$

$$2SiO + O_2 \longrightarrow 2SiO_2 \qquad \text{(secondary reaction (silica fume))}$$
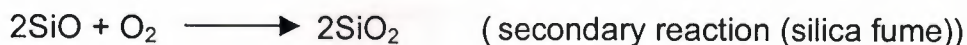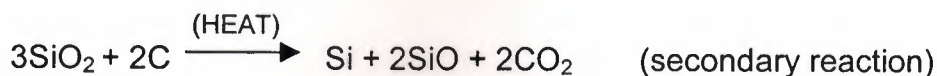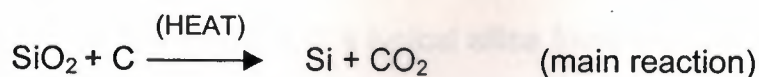
Because of its extreme fineness, the silica fume has to be separated from the furnace effluent gases by a sophisticated dust collecting apparatus. The silicon dioxide derived from this process is a solid of extremely small particle size, about one hundredth that of a typical type I Portland cement and consists of glassy spheres. The average diameter of the particles in silica fume has been established to be 0.1 μm (1 μm = 4 $\times 10^{-5}$ in.). Silica fume contains 86 to 98% silicon dioxide and because of its extreme fineness and high glassy SiO_2 content is a highly reactive pozzolanic material. Although the particle size of silica fume is near or above the upper limit for true colloids, its amorphous nature and specific surface area suggests that its behavior is more closely related to a colloid than a glass [7].

Published data indicate that there is little health hazard potential from the inhalation of amorphous silica fume due to its noncrystalline nature. However, it is strongly recommended that dust masks and proper ventilation facilities be available when handling the dry material [8].

Current concrete practice is to limit the amount of silica fume used in concrete to 10 to 15 pounds per 100 pounds of cement, mainly because of economic reasons. While silica fume was once considered a waste material, its potential use in concrete has resulted in an escalation of its cost which now exceeds that of portland cement.

The chemical composition of a typical silica fume is illustrated in Table 9 below [7].

Table 9: Chemical Composition of a Typical Silica Fume [7].

CHEMICAL COMPONENT	% BY WEIGHT
SiO_2	93
Al_2O_3	0.4
Fe_2O_3	0.8
CaO	0.6
MgO	0.6
SO_3	0.3
Alkalies (as Na_2O)	0.96

CHAPTER 4

EFFECTS OF POZZOLANS ON THE PROPERTIES OF CONCRETE

Though concrete seems quite strong mechanically, it is highly sensitive to chemical attack, and thus concrete structures may get damaged and even fail unless some measures are adopted to counteract these deterioration of concrete structure and thereby increase its durability.

The durability of concrete can be defined as its resistance to the deteriorating influences of both external and internal agencies. The external agencies include weathering, attack by salt-water etc. Whereas the internal agencies responsible for the lowering of durability are harmful alkali aggregate reactions, volume changes, presence of sulphates and chlorides from the ingredients of concrete, etc. In the case of reinforced concrete, the presence of moisture or air may lead to corrosion of steel, and cracking and spalling of concrete cover [8].

Pozzolanic mineral admixtures are used in concrete for a number of reasons. When the concrete is in the fresh state they improve its workability, although the finishers often complain about the stickiness of the concrete because the admixture increases the cohesiveness of the cementitious mass. Because they are generally finer than Portland cement, their presence tends to eliminate, or minimize bleeding and reduce segregation. In the hardened state, concrete containing any one of the types of pozzolan exhibits greater than normal strength (compressive, tensile and flexural), modulus of elasticity, resistance to sulfate attack, the deleterious alkali-aggregate reaction and (if air entrained) to freeze-thaw deterioration.

During hydration of cement calcium silicate hydride (C-S-H) and calcium hydroxide is produced. C-S-H is a gel, which binds the aggregates to form a compact mass. Research has shown that the presence of calcium hydroxide, in a hardened concrete is one of the main factors for the deterioration and destruction of concrete. Using fly ash and other pozzolans, reacts with these unwanted calcium hydroxide and produce additional C-S-H thereby improving the durability of concrete [9].

4.1 Effect of Pozzolans on the Compressive strength of concrete

As stated before the strength of concrete depends mainly upon three factors i.e. the strength of the cement paste, the strength of the aggregate, and the strength of the bond between the cement paste and the aggregate. Out of these three the strength between the cement paste and aggregate (the transition zone) is the most important one.

During hydration calcium hydroxide is produced as a by product, this calcium hydroxide weakens this bond and make the concrete weak. Using pozzolanic material such as fly ash or silica fumes reacts with these unwanted calcium hydroxide in the presence of water to produce additional C-S-H gel, thus preventing the concrete to fail under high compression and the C-S-H gel produced gives additional strength to concrete.

In one test on compressive strength, different pozzolanic materials were used. These pozzolans were added as a replacement for cement on a 20% level, but on a volume to weight basis. Each of the concrete fabricated in this program was designed to have a 3 ± ½ inch slump. The concrete was poured into 4 × 8-inch cylinders for compressive strength, at various ages. The batching and subsequent handling and testing of the test concretes were done in accordance to ASTM standards. The test

concretes are described in table 10. The strength contribution of different pozzolanic materials to the overall compressive strength of concrete is described in table 11, and is self-explanatory [7].

Table 10: Concrete made with different pozzolanic materials as a partial replacement of cement.

Specimen No.	1	2	3	4	5
Cement (lbs/yd^3)	552	449	442	446	445
Fine aggregate (lbs/yd^3)	1410	1405	1400	1385	1400
Coarse aggregate (lbs/yd^3)	1740	1715	1710	1695	1710
Water (lbs/yd^3)	294	300	310	303	300
Pozzolans (lbs/yd^3)	----	78	92	74	98
		Fly ash class C	Fly ash class F	Silica fumes	Blast furnace slag
Slump (inch)	3-1/4	2-3/4	3	3	3
Compressive strength (PSI)					
1day	1325	1275	1170	1350	1310
7days	3750	3610	3555	3990	3468
28days	5790	5825	5315	7120	6430

Table 11: Compressive strength contribution of different pozzolanic materials in PSI / lb / yd^3.

Age of test days	Cement Type I	Fly ash class F	Fly ash class C	Blast furnace slag	Silica Fumes
1day	2.4	1.2	2.5	2.3	3.8
7days	6.4	8.4	9.2	6.0	15.4
28days	9.7	12.1	18.8	21.4	38.1

Thus the effect of different pozzolanic materials to the strength giving properties can be rated (with decreasing effectiveness) as follows:

1. Silica fumes
2. Blast furnace slag
3. Fly ash

Moreover it should also be noticed that using pozzolonic mineral admixture in amount exceeding 20 percent by weight, the colour of pozzolan is very apt to dominate the colour of concrete. This thus not mean that the quality of concrete is decreased, but using these concrete for architectural purposes may cause aesthetic problems.

Fly ash type F has no cementaneous property in itself, and therefore gives the least strength development properties to the concrete. Fly ash type C possesses little cementaneous property in itself. Using these mineral admixtures in the production of HSC, special attention may be given to insure that the admixture comes from bulk supplies and the amount of cement and admixture requirement should also be checked by trial batching [9].

4.2 Effect of Pozzolans on Sulfate Resistance of Concrete

The use of pozzolans in concrete is not just limited to increase the compressive strength, but concrete with pozzolans have better resistance to sulfate attack. Sulfate attack can be defined as a "chemical or physical reaction between sulfates usually in soil or ground water with cement paste matrix to cause deterioration of concrete".

When concrete is exposed to ground water, sea water or soil containing soluble sulfate ions (usually as alkali metals or magnesium sulfate), the calcium hydroxide $(Ca(OH)_2)$, produced during hydration, reacts with these sulfate ions to form calcium sulfate. This calcium sulfate then reacts with the tricalcium alumino monosulfate (produced by C_3A in the presence of sulfate) to form a compound called ettringite. The compound ettingite has a volume 150% that of the reactants and results in expansion. The product ettringite form crystals in the pores and voids of concrete and slowly destroys by their expansive forces making the concrete porous and weak [9].

When such deterioration reaction takes place in reinforced concrete, the pours produced by sulfate attack allows water and air to enter the concrete resulting in the corrosion of steel bars.

When pozzolans are used in concrete production, they react with the calcium hydroxide produced by the silicates, to form C-S-H gel. Thus minimizing the formation of calcium sulfate that is the primary source of ettringite (sulfate attack). The C-S-H gel produced by the pozzolans fill up the voids and capillaries of the concrete making concrete nearly impermeable, preventing the corrosion of steel reinforcement [9].

The resistance of concrete to sulfate attack according to the nature of its cementitious constituents can be rated (with decreasing effectiveness) as follows [9];

1. Type V cement + Pozzolan. (greatest)
2. Type V cement.
3. Type II cement + Pozzolan.
4. Type II cement.
5. Type I cement + Pozzolan.
6. Type I cement. (least)

4.3 Effects of Pozzolans on Alkali Aggregate reaction

Another performance benefit of using pozzolanic mineral admixtures is their influence on the deleterious alkali-aggregate reaction that often takes place in plain Portland cement concrete.

Generally the alkali - aggregate reaction is grouped into three main types as given below [10];

1. Alkali-silica reaction: which involves the reaction between the alkali in the cement with active silicon dioxide (silica) present in certain aggregates (such as opal, chert and chalcedony). These silica reacts with alkalies in the concrete (either introduced by the Portland cement, admixtures or the environment) and forms a gel on the surface of the aggregate. In the presence of moisture these gel swell, developing stresses on the surface of concrete resulting in disruptive cracking.

2. Alkali-carbonate reaction: *is* caused by the presence of aggregates containing carbonates (such as argillaceous, dolomite, limestones that contain meta-stable calcium carbonate). These carbonates undergo a chemical reaction with alkali hydroxides creating products whose volume is larger than that of the reactants.

3. Alkali-silicate reaction: *is* the result of aggregates containing greywackes (sandstone containing feldspars or clays) and those that exfoliate, such as vermiculites, interacting with the alkali and producing expansive stresses within the mass of the concrete.

The use of pozzolanic mineral admixtures seems to be the best solution at this point in time. The influence of pozzolans on the normal alkali-aggregate is basically attributed, several theories have been proposed to explain how pozzolans neutralizes the alkali-aggregate reaction. One theory holds that the alkalies in the concrete combine with the highly reactive silica in the pozzolans, rather than the alkali active silicas, carbonates or silicates present in the aggregate. Because the pozzolanic particles are evenly distributed throughout the concrete, any swelling or expansion that occurs is so evenly distributed that the expansive forces can be tolerated by the concrete as a whole. A second theory holds that, the nature of the CSH produced by the pozzolanic reaction has a lower $CaO\text{-}SiO_2$ ratio than that produced by the hydrating cement silicates, and thus is able to incorporate large amounts of alkali ions in its structure, leading to a reduction in the amount available for the alkali-aggregate reaction. A third theory simply says that the presence of the finely divided pozzolans in the concrete restricts the mobility of the alkali and hydroxyl ions needed to cause the destructive expansive reactions [9],[10].

4.4 Effect of Pozzolans on Freezing and Thawing of Concrete

The resistance to freezing and thawing of concrete usually depends upon the permeability and the degree of saturation of concrete when exposed to frost. In cold countries salt is used for de-icing this generally increased the risk of damaging the concrete. Therefore air-entrained concrete is used which has a higher resistance to frost action.

The air-entrained concrete is produced either by using air-entrained cement or air-entrained admixtures. These concrete has minute air bubbles uniformly distributed throughout the concrete matrix. The air bubbles increases the workability of the concrete, but decreases the compressive strength.

For high - strength air - entrained concrete a low spacing factor, increases the resistance of concrete to rapid freezing and thawing exposure. The same factor apply to air entrained Pozzolanic concrete and therefore we can say that using pozzolanic materials in concrete increases the freezing thawing resistance of concrete

4.5 Effect of Pozzolans on Shrinkage of Concrete

The water - cement ratio in pozzolanic concrete is generally higher than normal concrete, in order to attain a desired slump. This is because of the nature of these mineral admixtures to store and prevent water, results in the formation of fewer empty voids (which is responsible for a good portion of concrete shrinkage) in the concrete upon drying. Therefore we may say that pozzolans, reduces the shrinkage of concrete, and published data indicates that the reduction may be as high as 25 percent [9].

When fly ash is used, a good portion of the ash consists of unreacting substance mullite, this substance may be used as a partial replacement of fine sand. These substance has a much lower absorption capacity, and using them as a partial replacement of sand reduces the water demand for concrete [5].

Using fly ash also reduces the setting time of concrete and thus little heat is evolved upon hydration. This results in the reduction of expansion

forces and upon drying these particles also reduces the shrinkage of concrete by evenly filling the pores of concrete.

4.6 Effect of Pozzolans on the Bleeding of Concrete

Bleeding can be defined as the separation of cement paste from the concrete matrix. Bleeding of concrete has to be minimized because it produces weak surfaces for successive concreting, but a little bleeding is also essential for concreting in hot weather, in order to reduce plastic shrinkage. This shrinkage is caused by the rapid loss of moisture from the surface of fresh concrete, due to high temperature and low relative humidity. If the rapid loss of moisture is not counteracted tensile stresses develop on the surface of the concrete and cracking results [9].

Using Pozzolanic mineral admixtures such as silica fumes minimizes bleeding, and therefore concrete produced with these admixtures should be properly cured immediately after final setting. This is one of the disadvantage of using these materials as an admixture [9].

CHAPTER 5

EXPERIMENTAL PROGRAM

The experimental program of this study consisted of;

Producing HSC of strength level between 62 to 83 Mpa. But since the coarse aggregate available in North Cyprus, failed at about 52 to 55 Mpa therefore concrete of strength level between 42 to 48 MPa was produced instead.

The object of this thesis was to produce HSC, and to make it as economical as possible. HSC has many advantage over normal strength concrete, but the cost of producing HSC usually exceeds over normal concrete. Other disadvantages of HSC is, that they are very stiff and cannot be compacted easily by the standard compaction means available.

Therefore, in this thesis, HSC which is economical and can even be produced at the construction site, was produced. The concrete had good workability and could easily be compacted by the available compaction equipments.

The main step taken in the experimental process was to reduce the amount of cement (as cement is the most expensive ingredient of the mix). This was done by introducing fly ash, as a replacement of cement, and to get the same strength level (i.e. between 42 to 48 Mpa or above).

5.1 MATERIALS USED

The materials used in the experimental program are as follows:

5.1.1. Cement

Normal Portland cement Type I was used throughout the experimental program. The cement was obtained from Necipoglu. And the bag once opened was used within a period of one month, this is because the cement bag once opened absorbs moisture from the surrounding atmosphere. The absorbed moisture reacts with the finely divided cement particles to form lumps of hydrated cement, decreasing the strength giving properties of cement.

The chemical composition of the cement used was as follows:

Table 12: Composition of Ordinary Portland cement.

Chemical composition	Percentage by weight
COMPOUND COMPOSITION	
C_3S	40
C_2S	30
C_3A	11
C_4AF	11
OXIDE COMPOSITION	
CaO	63
SiO_2	20.6
Al_2O_3	6.3
FeO	3.6

5.1.2. Water

Water is the most essential ingredient of the concrete mix. The quality and quantity of water effects the durability of concrete, therefore its selection is very important. Water used in the mix design was obtained from the clean water supply of Dikmen. Since the tap water of Cyprus is not suitable for drinking, it is also not suitable for concrete making.

Curing water was also clean water, and the curing tank was filled such that all the cubes obtained were fully immersed into the water.

5.1.3. Aggregates

The aggregates used for concrete making were obtained from the near by sand and gravel or crushed stone deposits. Since aggregates occupies about 75 percent of the body of the concrete, therefore their selection is of great importance in concrete mixes. They should therefore meet certain requirements if the concrete is to be workable, strong, durable, and economical. The aggregate must be of proper shape (crushed), clean, hard, strong and well graded. It should be clean and free from alkali substances and should possess chemical stability. Different tests were performed on aggregates before using them as a component of concrete, these tests are illustrated in Appendix B. These tests are in accordance to ASTM standards.

The fine aggregate used in the experiment had a fineness modulus of 3.5. The sieve analysis of fine and coarse aggregate are shown in the tables 11 and 12 respectively. The gradation curve is illustrated in figure 6 for both fine and coarse aggregate. The sieve analysis of these aggregates was done according to ASTM C136.

Table 13: Sieve analysis of Fine aggregate.

SIEVE SIZE	WEIGHT RETAINED ON EACH SIEVE (gr.)	CUMULATIVE WEIGHT (gr.)	CUMULATIVE % RETAINED	CUMULATIVE % PASSING
No:4 (4.76mm)	89	89	4.45	95.55
No:8 (2.38mm)	481	570	28.5	71.5
No:16 (1.19mm)	550	1120	56	44
No:30 (0.59mm)	362	1482	74.1	25.9
No:50 (0.297mm)	279	1761	88.05	11.95
No:100 (0.149mm)	181	1942	97.1	2.9
PAN	58	2000	100	0

Table 14: Sieve analysis of Coarse aggregate.

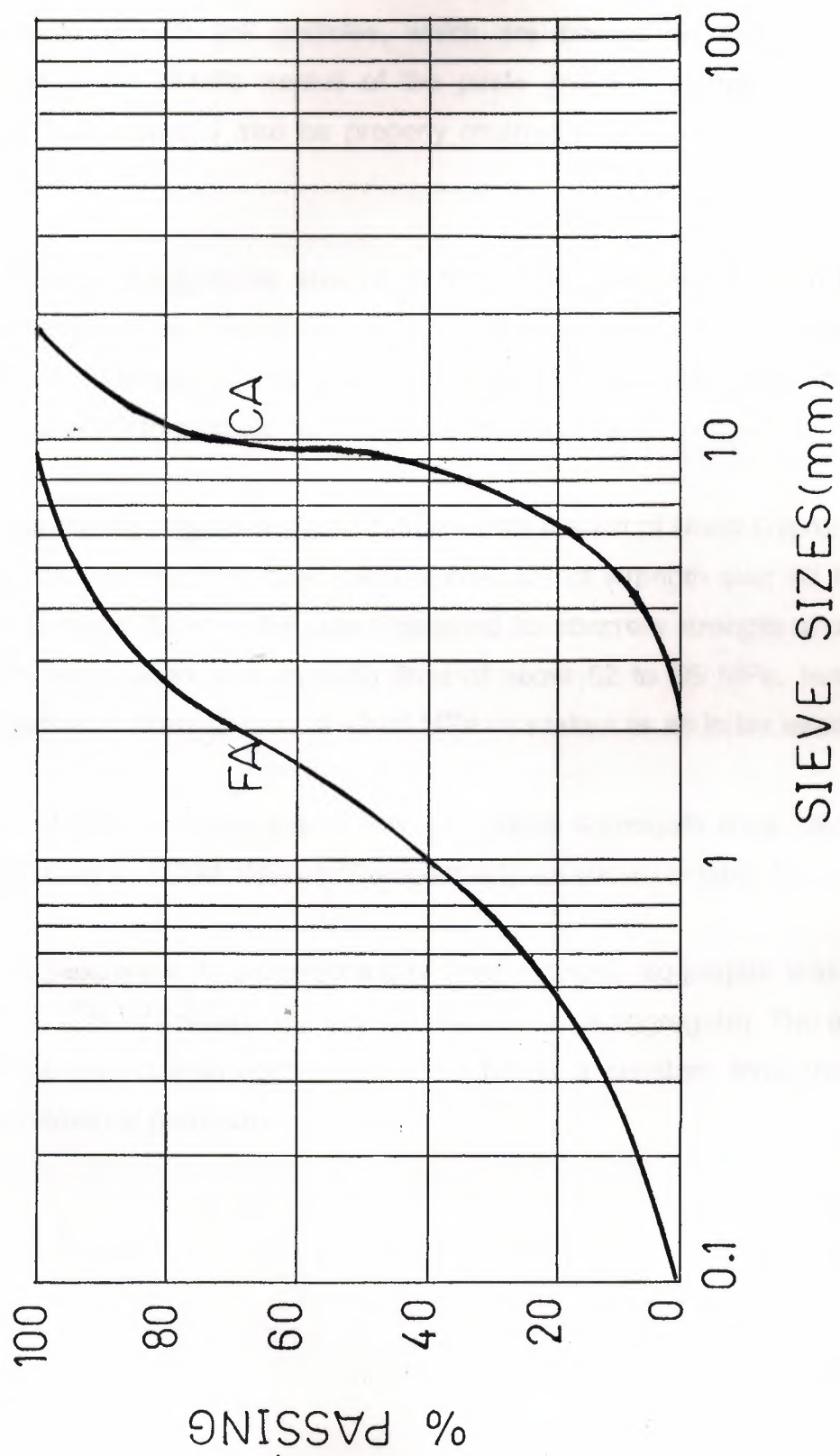| SIEVE SIZE	WEIGHT RETAINED ON EACH SIEVE (gr.)	CUMULATIVE WEIGHT (gr.)	CUMULATIVE % RETAINED	CUMULATIVE % PASSING
3" (76.2mm)	----	----	----	----
1.5" (38.1mm)	----	----	----	----
1" (25.4mm)	----	----	----	----
¾" (19.1mm)	0	0	0	100
½" (12.7mm)	752	752	15.04	84.96
3/8" (9.5mm)	1750	2502	50.04	49.96
No:4 (4.76mm)	2208	4710	94.2	5.8
No:8 (2.38mm)	290	5000	100	0

Figure 6.: Proportioning of Aggregates

The maximum size of coarse aggregate used in the experiment was 19mm. For the production of HSC the maximum size of the aggregate has to be as small as possible, so as to have minimum concentration of stresses around the particles, which are caused by the differences between the elastic moduli of the paste and the aggregate [5]. The aggregates should also be properly crushed and should be strong and durable.

A maximum aggregate size of 12.5mm was used, but it did not yield proper strength. Therefore the size of the aggregate was increased to 19mm. The aggregates were thoroughly washed and dried at room temperature to produce SSD condition aggregates.

Since the aggregate available in the normal market of North Cyprus is not 100 percent crushed, production of concrete of strength over 62 MPa is not possible. Most of the cubes obtained for concrete strength of over 62 MPa were failed at a strength level of about 52 to 55 MPa. Instead a concrete of strength level of 42-48 MPa was taken as an index strength.

The absorption capacities of fine and coarse aggregate were calculated according to ASTM 128 & 127 respectively, as shown in table 13 and 14.

In the experiment, proportioning of fine to coarse aggregate was 40:60 (i.e. 40 pts. of fine aggregate to 60 pts. of coarse aggregate). The amount of fine and coarse aggregate was kept as a constant throughout the experimental program.

Table 15: Absorption capacity of fine aggregate.

A	Weight of oven dry aggregate (gr.)	1042
B	Weight of aggregate in SSD condition (gr.)	1080
(B – A) / A ×100	Absorption capacity (%)	3.65

Table 16: Absorption capacity of coarse aggregate.

A	Weight of oven dry aggregate (gr.)	5050
B	Weight of aggregate in SSD condition (gr.)	5087
(B - A) / A ×100	Absorption capacity (%)	0.73

5.1.4. Mineral Admixture

The mineral admixture used was fly ash. It was purchased from Turkey and had a silicate content of about 42 percent by weight. The maximum amount of the ash used was 40 percent of the amount of cement used.

Silica fumes though beeing the most widely used mineral admixture in the production of high strength concrete, was not used, it is because silica fumes are expensive and hard to find and requires special techniques in handling and mixing. They are generally used to produce very high strength concretes.

5.1.5. Water Reducing Admixture

The water reducing admixture used in the mix design was based on Lignosuphonate, which increases the workability of concrete. It was a brownish liquid called Pereplast BV 50, with a density of 1.2 Kg/liter.

Water reducers are generally used for increasing the strength of concrete by reducing the water cement ratio. But in the mix design water reducers were only used to increase the workability, so that the concrete produced can easily be placed without using mechanical compacting equipments such as vibrators.

5.2. Mix Design

Mix design for HSC depends upon many factors, such as quantity of cement used, water cement ratio, material characteristics, and curing environment.

After proper proportioning and using all the economical means available, a concrete strength of 420 to 450 was produced. The concrete was produced in a concrete mixer in the laboratory. Water reducing admixture was used in order to have a good workability concrete. After many trial mixes, the mix proportions chosen are tabulated in table 15. The strength development curve verses age for the six specimens are illustrated in figure 7 to 12 respectively.

For designing concrete of strength level up to 45 Mpa Appendix A may be used. It has to be pointed out here that the mix design procedure in Appendix A is based on producing concrete using normal Portland cement (type I), and without using any admixtures.

5.3. Compaction and Curing

After taking the slumps of the freshly prepared concrete, it was poured into cubes having a dimension of 20 × 20 × 20. To obtain proper compaction rodding bar were used. The bar had a diameter of 16mm, and the concrete was poured in three layers, rodding each layer 25-30 times.

After 10-15 hours when the final setting takes place, the cubes were covered with a wet cloth for curing. Then after 1 day the concrete were taken out from the cubes and placed into the curing tank.

Table 17: Mix design for concrete having same strength and workability but different cement content.

| MIX NUMBER	1	2	3	4	5	6
CEMENT (Kg/m³)	450	400	375	360	345	330
COARSE AGGRE-GATE (Kg/m³)	1100	1100	1100	1100	1100	1100
FINE AGGREGATE (Kg/m³)	735	735	735	735	735	735
WATER (Kg/m³)	180	180	182.5	182.5	183	184
FLY ASH (Kg/m³)	-----	50	75	90	105	120
WATER REDUCING ADMIXTURE (Kg/m³)	1.35	1.4	1.4	1.4	1.4	1.4
W/C RATIO	0.4	0.45	0.49	0.51	0.53	0.56
W/(C + M) RATIO	0.4	0.4	0.4	0.4	0.41	0.41
SLUMP (mm)	72	65	70	70	70	73
COMPRESSIVE STRENGTH (Kg/cm²)						
7-DAY	295.5	282.5	275.9	265.4	258.5	239.5
28-DAY	440	468.1	462.5	450.2	442.9	412.5
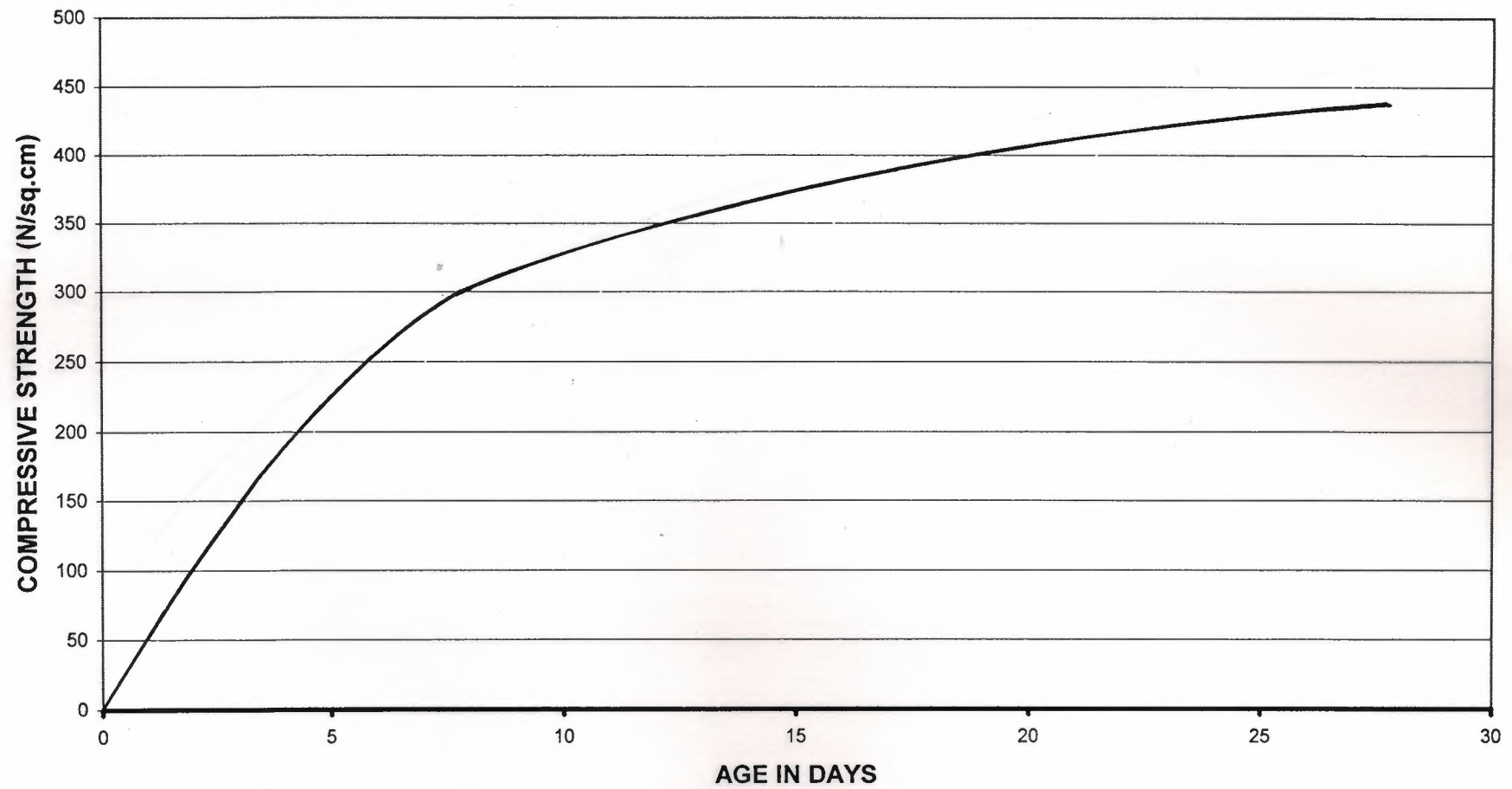
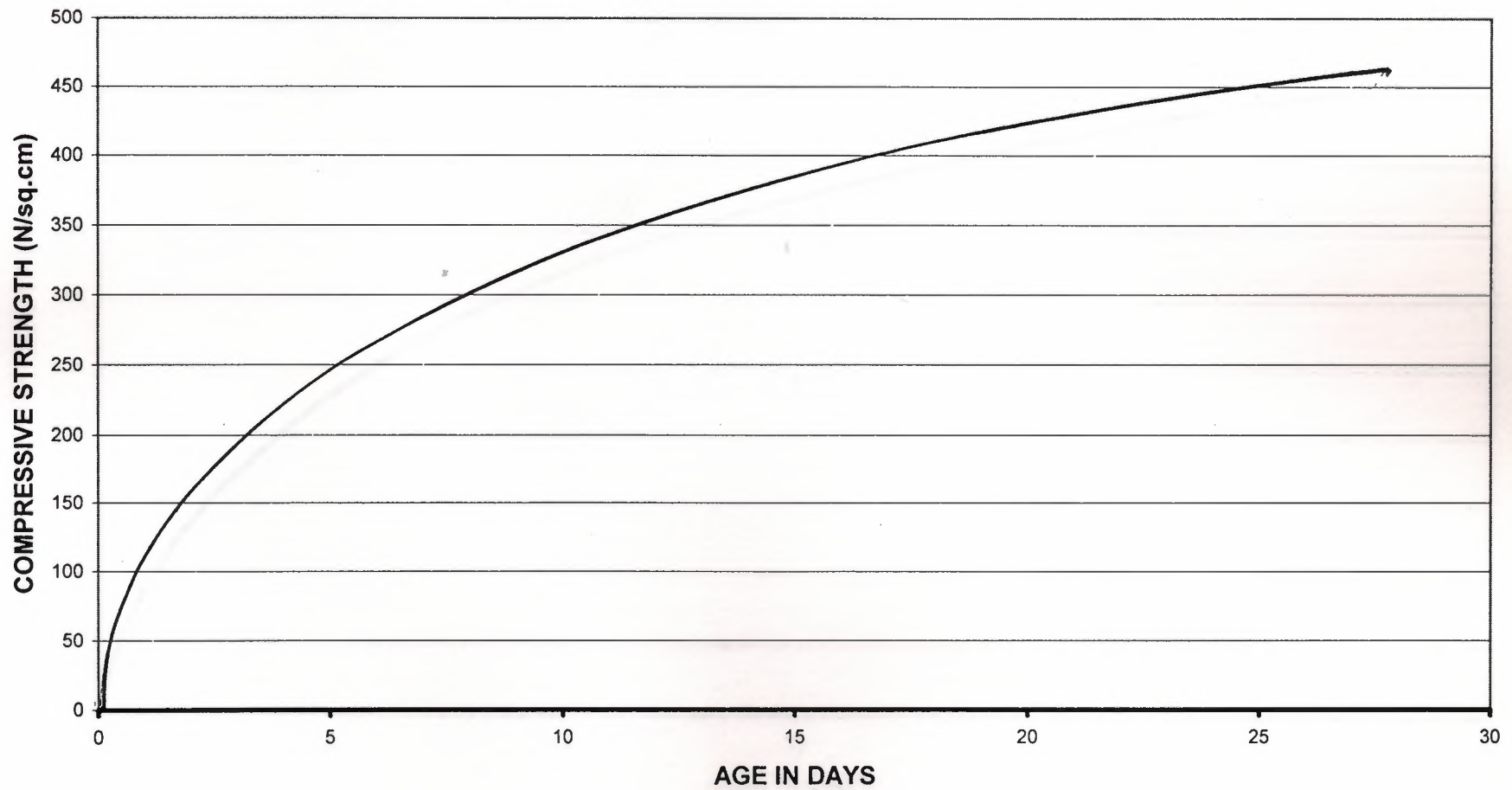**Figure 7: Strength development curve of specimen No. 1**

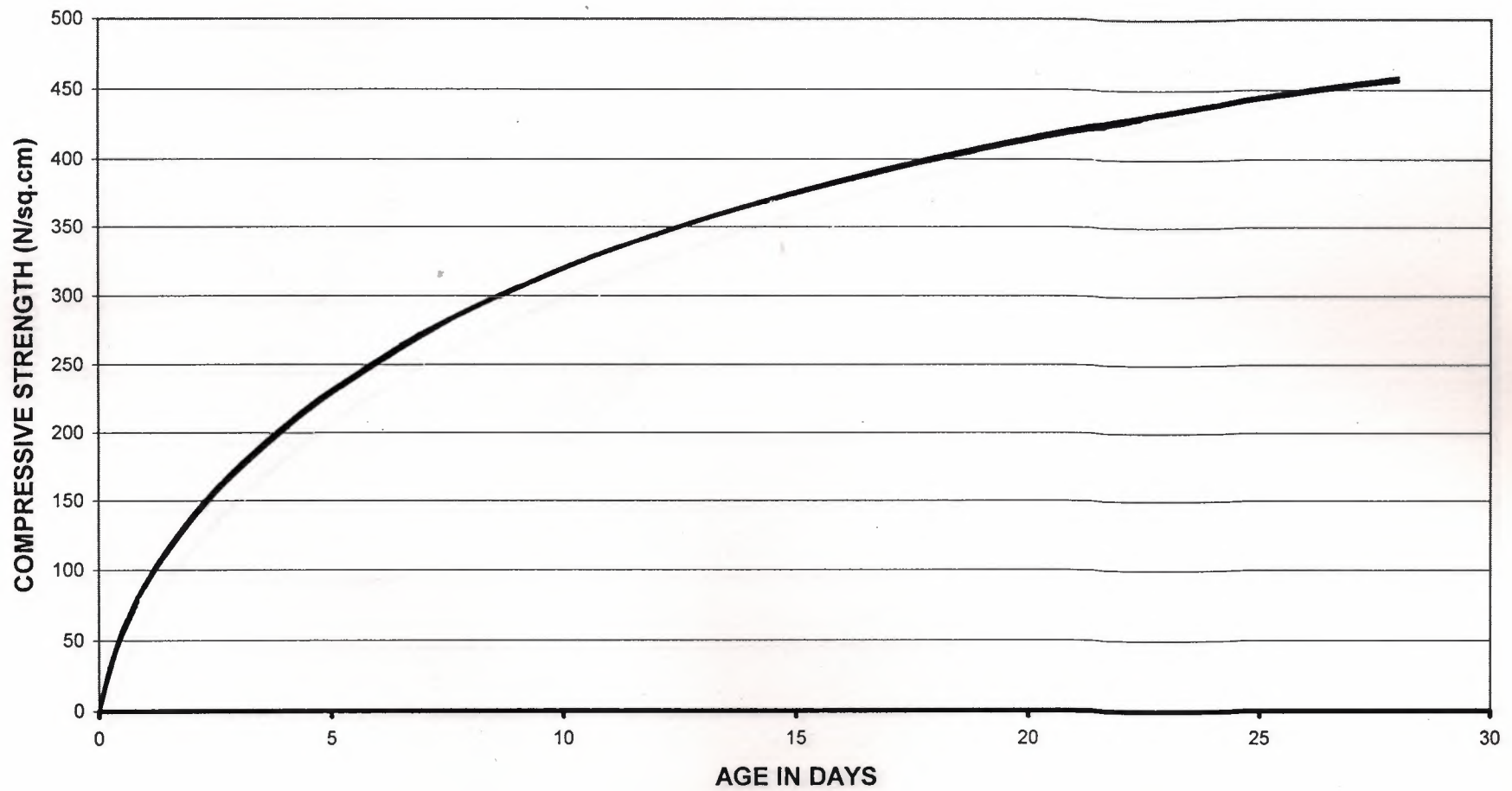Figure 8: Strength development curve of specimen No. 2

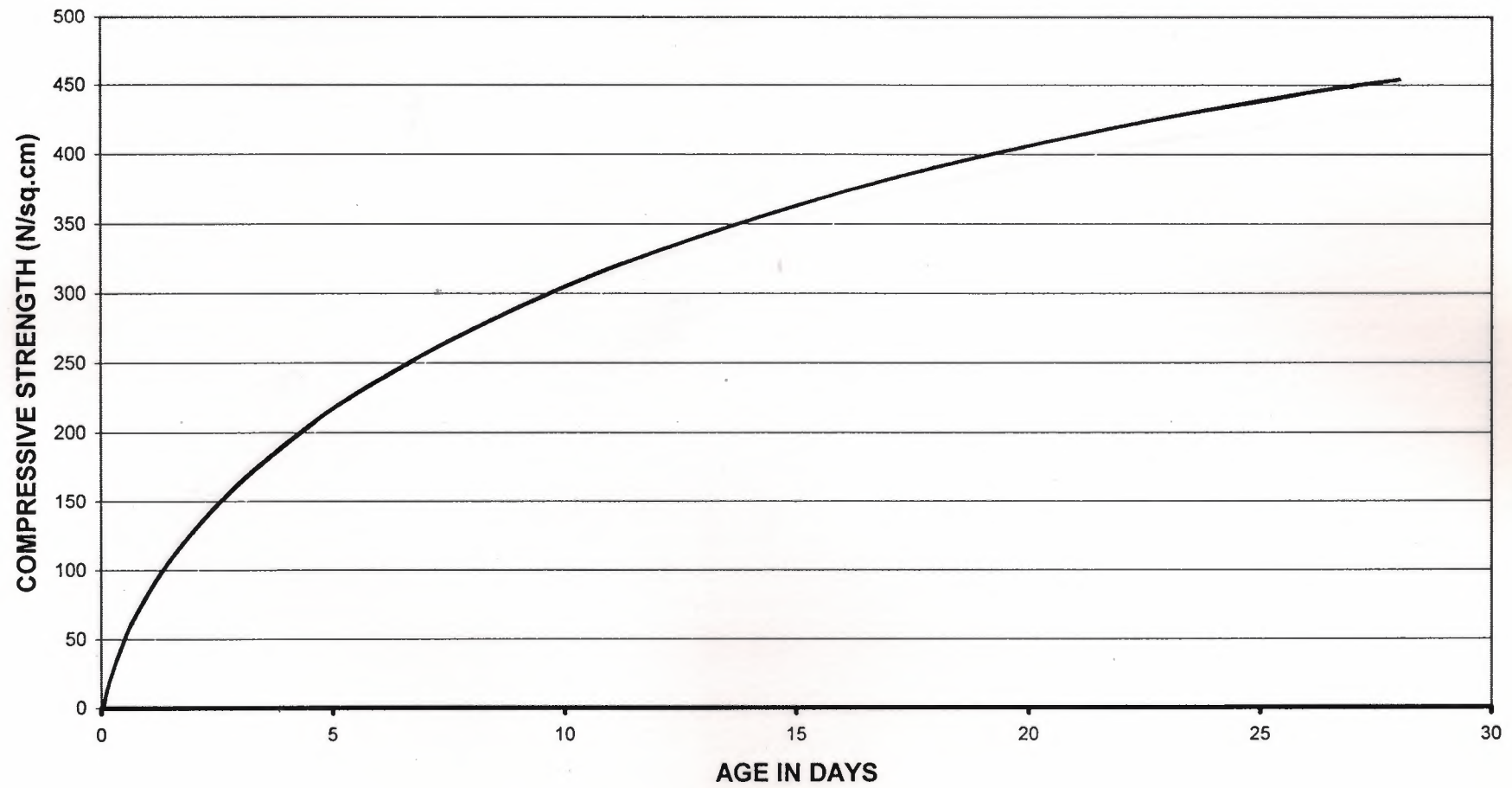Figure 9: Strength development curve of specimen No. 3

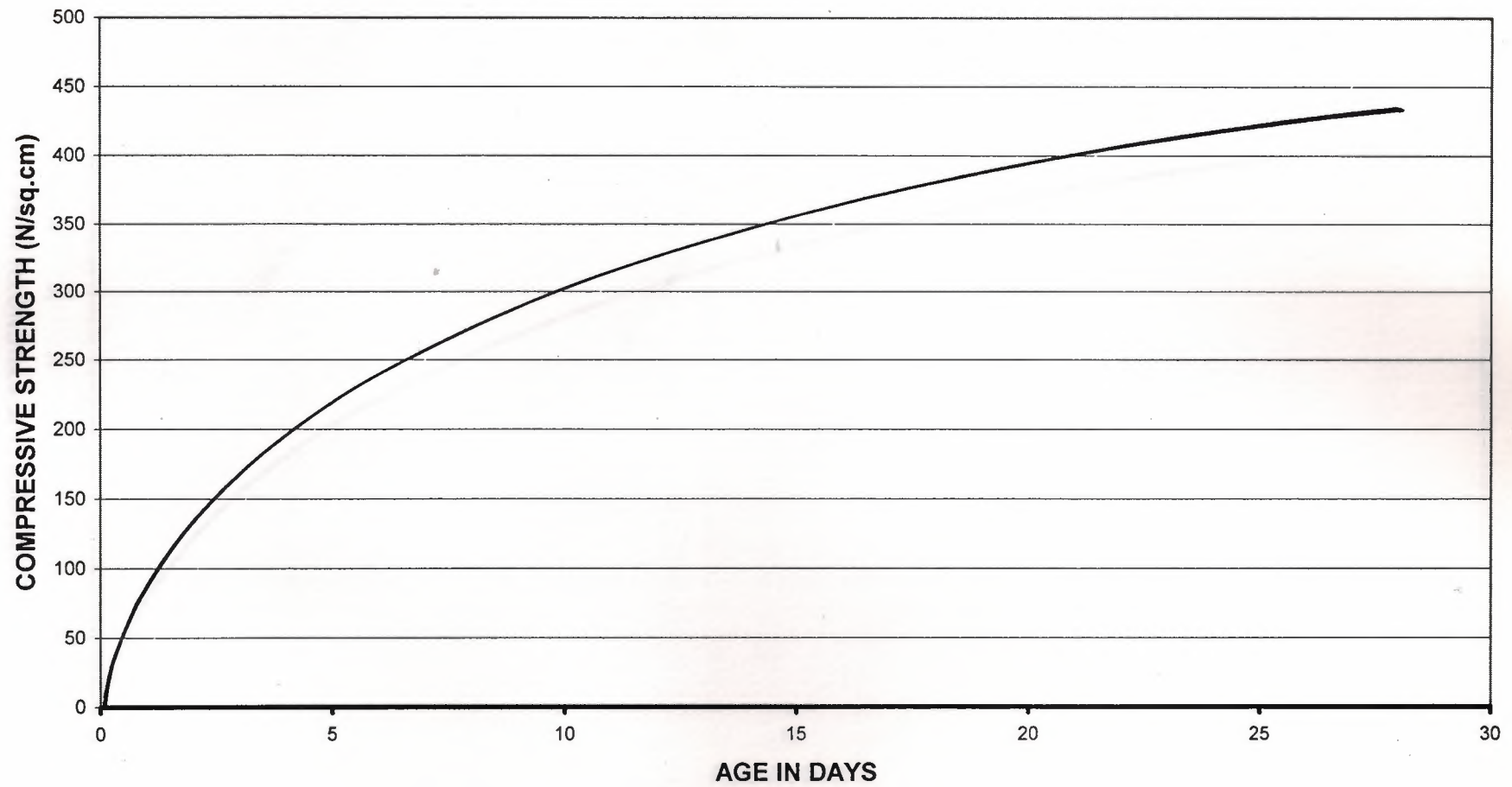**Figure 10: Strength development curve of specimen No. 4**

Figure 11: Strength development curve of specimen No. 5
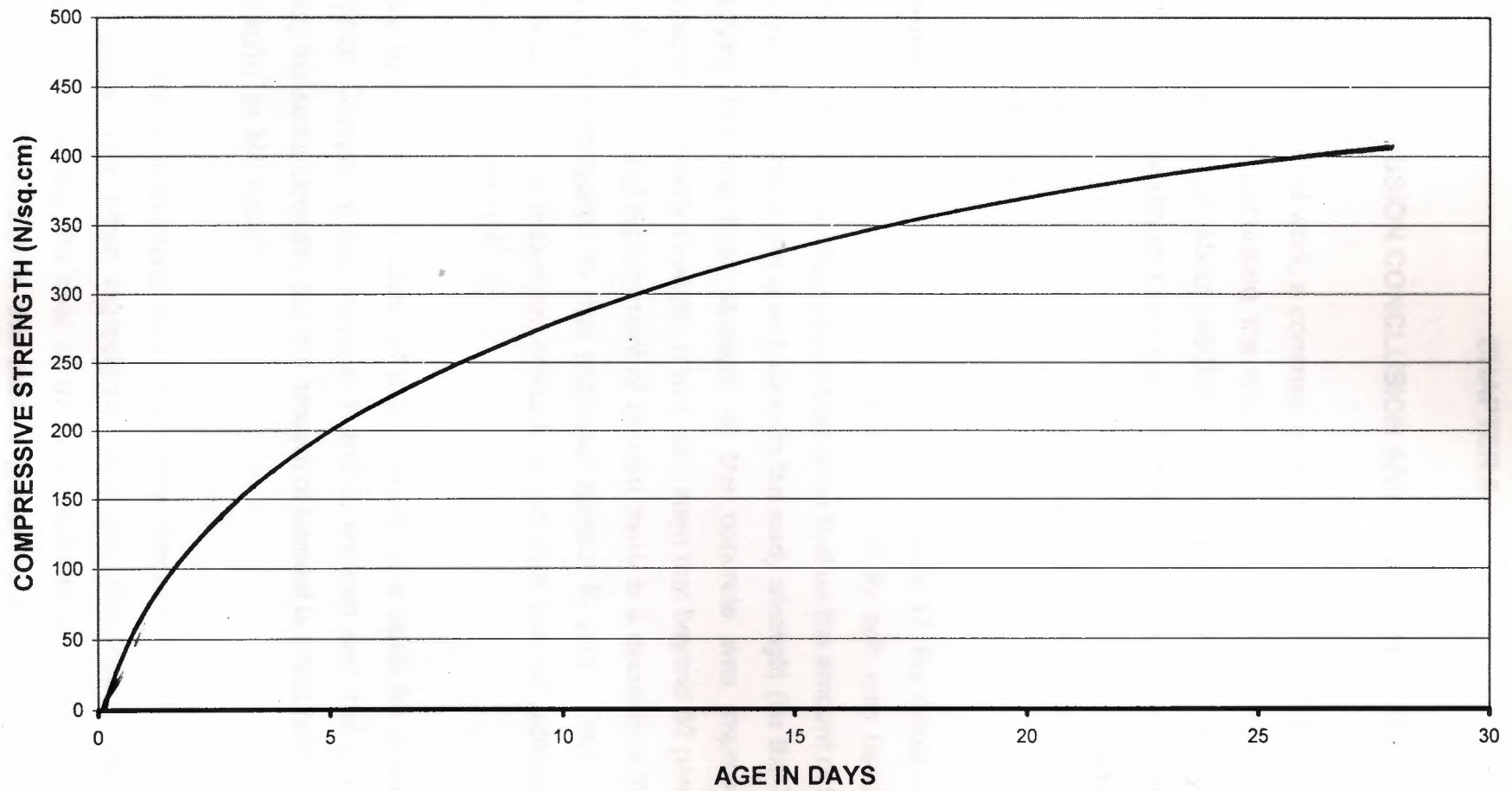
Figure 12: Strength development curve of specimen No. 6

CHAPTER 6

DISCUSSION CONCLUSION AND RECOMENDATION

In this experimental work, a concrete of strength between 42-48 MPa was produced. After calculating the mix design, it was found that using a cement content of about 450Kg/m³, was required to produce this concrete. The maximum size of coarse aggregate used was 19mm. The amount of fine and coarse aggregate was kept constant throughout the experimental program. Other materials used were Fly ash and water reducing admixture.

The results of the experiment are tabulated in table 17. For mixes number 2 to 6 an amount of 11.1 to 26.6 percent of fly ash was used as a replacement, by cement weight. It was seen that as the amount of fly ash was increased there was a reduction in the early strength (i.e the 7-days strength). But the later strength of the concrete was improved as compared to its early strength. It was also seen that beyond 30 percent of fly ash as a partial replacement of cement there is a decreased 28-days strength as compared to that produced without fly ash. Thus we can conclude that, the maximum amount of ash that can be replaced with cement is 23.3 percent.

Since fly ash is much cheaper than cement, it is used for economical purpose. Comparing mix number 1 and 5, we can see that they have nearly the same strength, but the amount of cement is being reduced from 450 kg/m³ to 345 kg/m³.

Both of these specimens have the same amount of fine and coarse aggregates. The other ingredients used are also nearly the same, therefore assuming the cost of these ingredients as constant we can calculate the reduction in the cost of producing concrete with fly ash.

Assuming the cost of cement is $0.085/kg and of fly ash is $0.045/kg, it follows that the cost of producing concrete with and without fly ash will be $34.05/m^3 and $38.25/m^3. Thus we can say that using fly ash as a replacement of cement for compressive strength of 44MPa, there is a reduction of $4.20/m^3 of concrete.

It is also noticeable that if the contractor is interested in the early strength fly ash may not be used as a partial replacement of (Type I) cement. Fly ash has many advantages when used in concrete and therefore it will be preferable to use these materials as a partial replacement of cement.

Conclusions:

The following conclusions can be given,

1. Concrete of 42-48 MPa strength was produced using locally available materials (In the TRNC region). These concretes were produced, with and without the use of Fly ash.

2. The economical replacement of fly ash was found to be 23.3% by weight of cement, for concrete of strength 42 MPa.

3. Using 23.3% of fly ash as a replacement of cement, produced concrete of the same strength, but with a saving of $4.20 / m^3 of concrete.

Recommendations:

1. The economical use of fly ash with different types of cement may also be checked.

2. The economical advantages of using other pozzolanic materials may also be studied.

References

[1]   M. L. Gambhir, *"Concrete Technology"*, Tata McGRAW-HILL Publication Company Limited, 1986.

[2]   ACI Committee, *"Guide to Durable Concrete"*, Journal of American Concrete Institute. December 1977

[3]   G. Barnbrook, et.al, *"Concrete Practice"*, Cement and Concrete Association, 1975.

[4]   UGUR Ersoy, *"Reinforced Concrete"*, Course book, Middle East Technical University, Ankara 1991.

[5]   ACI Committee 363, *"State of the Art Report on High Strength Concrete"*, ACI Material Journal, July-August 1984.

[6]   Kenneth N.D., George P.K., A Samer, *"Materials for Civil and Highway Engineering"*, PRENTICE HALL Inc. Publication 1994.

[7]   Lea, F.M., *"Concrete Admixtures"*, McGRAW- HILL Publication. 1985.

[8]   *"Cement and Concrete Technology"*, Americian Concrete Institude, 1988.

[9]   Graham D.E., *"Fly ash and its use in concrete"*, NRMCA Publication, 1972.

[10]   *"Manual of Aggregates and Concrete Testing "*, Annual book of ASTM Standards, 1988.

APPENDIX A

Concrete mix design tables: (ACI 211. 1-74).

Table A.I: Recommended slumps for various types of construction works

Recommended slumps for various types of construction		
Types of construction	**Maximum Slump (mm)**	**Minimum Slump (mm)**
Reinforced foundation walls and footings	75	25
Plain footings and caissons	75	25
Substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

Table A.II. Approximate mixing water requirements for different slumps and maximum sizes of aggregates.

NON-AIR ENTRAINED CONCRETE

Approximate mixing water (kg/m^3) for nominal Maximum aggregate size of								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5 mm	50 mm	75 mm	150 mm
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	
More than 175								
Approximate amount of entrapped air in non air-entrained concrete (%)								
	3	2.5	2	1.5	1	0.5	0.3	0.2

AIR ENTRAINED CONCRETE

Approximate mixing water (kg/m^3) for nominal maximum aggregate size of								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5 mm	50 mm	75 mm	150 mm
25 to 50	180	175	165	160	145	140	135	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	
More than 175								
Approximate amount of entrapped air in non air-entrained concrete (%)								
	3	2.5	2	1.5	1	0.5	0.3	0.2

Table A.III. Relationships between W/C ratio and Compressive strength.

Relationship between water cement ratio (w/c) and Compressive Strength of Concrete	
Compressive strength at 28 days (Mpa)	Water cement ratio by weight (Non air-entrained concrete)
45	0.37
40	0.42
35	0.47
30	0.54
25	0.61
20	0.69
15	0.79

Table A.IV. Volume of coarse aggregate per unit volume of Concrete.

Max. Size of Agg. (mm)	Volume of dry-rodded CA per unit volume of Concrete for different fineness moduli of FA			
	2.40	2.60	2.80	3.00
10	0.50	0.48	0.46	0.44
12	0.59	0.57	0.55	0.53
20	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
40	0.76	0.74	0.72	0.70
50	0.78	0.76	0.74	0.72
70	0.81	0.79	0.77	0.75

Table A.V. First Estimate of Weight of fresh Concrete

Max. Size of Agg. (mm)	First Estimate of Weight of fresh Concrete (Kg/m^3)	
	Non-air entrained	Air entrained
10	2285	2190
12	2315	2235
20	2355	2280
25	2375	2315
40	2420	2355
50	2445	2375
70	2465	2400

APPENDIX B

ASTM D75 (sampling aggregates)

The purpose of this test is to sample fine and coarse aggregate for the following purposes:

1. Preliminary investigation of the potential source of supply.
2. Control of the product at the source of supply.
3. Control of the operations at the site of use.
4. Acceptance or rejection of the materials.

In this procedure, sampling plans and acceptance and control tests vary with the type of construction in which the material is used. Samples for preliminary investigation tests are obtained by the party responsible for development of the potential source. The sampler must use every precaution to obtain samples that will show the true nature and condition of the materials they represent. Samples must be inspected and sampling taken from conveyor belts, flowing aggregate stream, or stockpiles. The number of samples taken depends on the variations and the properties measured.

Sampling is as important as testing: the test results depend on the sampling. If the sampler is inexperienced with the techniques involved, the entire test becomes questionable. Thus, in this specification. a person familiar with sampling should perform all sampling procedures.

ASTM C136 (sieve or screen analysis of fine and coarse aggregates.)

The purpose of this specification is to determine the particle size of fine and coarse aggregates to be used in various tests.

In this procedure, a weighed sample of dry aggregate is separated through a series of sieves or screens of progressively smaller openings for determination of particle-size distribution.

In this specification, the results are dependent upon individual technique. The test is placed in two categories: mechanical sieving and hand sieving. This excellent test determines the gradation of the aggregates. which is so important in mix design procedures.

ASTM C127 (specific gravity and absorption of coarse aggregate.)

The purpose of this specification is to ultimately determine the solid volume of coarse aggregate and the unit volume of the dry rodded aggregate such that a weight-volume characteristic can be determined so that a concrete design mix can be determined. The bulk specific gravity is used to determine the volume occupied by the aggregate.

In this procedure, approximately 5 kg of the aggregate is selected after quartering. After the aggregate is thoroughly washed to remove dust or other coatings from the surface of the particles, the sample is dried to constant weight at a temperature of 212 to 230^0F (100 to 110^0C) and cooled in air at room temperature for 1 to 3 hours. After cooling, the sample is immersed in water at room temperature for a period of 24 ± 4 hours. Next, the specimen is removed from the water and rolled in a large absorbent cloth towel until all visible films of water are removed. The large

particles are wiped by hand. Care is taken not to allow evaporation of water from aggregate pores during the operation of surface drying. The sample is weighed in the saturated-surface-dry condition. Then the sample is weighed in water. making sure that the entrapped air is removed. The sample is dried at 212 to 230^{0}F (100 to 110^{0}C) cooled at room temperature for 1 to 3 hours, and weighed. The bulk and apparent specific gravity and the percent absorption are determined as follows:

$$\boxed{\textbf{Bulk specific gravity = A / (B-C)}}$$

Where A = weight of oven-dry specimen in air, grams

B = weight of saturated-surface-dry specimen in air, grams

C = weight of saturated specimen in water, grams

$$\boxed{\textbf{Bulk specific gravity} = \textbf{B /(B-C)} \times \textbf{100}}$$
(saturated-surface-dry)

$$\boxed{\textbf{Apparent specific gravity} = \textbf{\textit{A / (A – C)}}}$$

$$\boxed{\textbf{Absorption} = \textbf{\textit{B – A / A}} \ \textit{×100}}$$

The specific gravity of aggregates is important, as it is used to determine the aggregate for use in a concrete mix.

ASTM C128 (specific gravity and absorption of fine aggregate.)

The purpose of this specification is to determine the bulk and apparent specific gravity of fine aggregate as well as the absorption.

In this procedure 500 g of fine aggregate is immersed in a pycnometer that is filled with water to 90 percent of capacity. The pycnometer is rolled, inverted, and agitated to eliminate air bubbles. The temperature is adjusted to 73.4 ± 3^0F (23 ± 1.7^0C). The total weight of the pycnometer sample, and water is determined. The fine aggregate is removed, dried to a constant weight at 212 to 230^0F (100 to 110^0C), cooled at room temperature for 0.5 to 1.5 hours, and weighed. The weight of the pycnometer is determined and the bulk specific gravity, bulk saturated-surface-dry specific gravity, apparent specific gravity, and the absorption are calculated as follows:

Bulk specific gravity = A / (B + 500 – C)

Where A = weight of oven-dry specimen in air. (grams)
B = weight of pycnometer filled with water. (grams)
C = weight of pycnometer with specimen and water to calibration mark. grams

Bulk specific gravity = 500 / (B + 500 – C)
(saturated-surface-dry)

Apparent specific gravity = A / (B + A – C)

Absorption = 500 – A / A $\times$ 100

This is an important test because the volume of aggregate is determined for the concrete mix. The results of this test are used in all concrete-mix design procedures, whether Portland cement or bituminous.

ASTM C29 (unit weight of aggregate.)

This method covers the determination of the unit weight of fine. coarse. or mixed aggregate.

In this procedure, the sample is dried to constant weight in an oven at 220 to 230^0F (105 to 110^0C) and thoroughly mixed. A cylindrical metal bucket is calibrated using water (knowing that water weighs 62.4 lb/ft^3). The measure is filled one-third full and the surface is leveled with the fingers. The layer of aggregate is rodded 25 times with a tamping rod. The strokes are applied evenly over the sample. This procedure is repeated at two-thirds full and at full. The measure is leveled, weighed, and multiplied by the volume of the bucket. This method applies to aggregates of 1.5 in. (3.81 cm) or less. For aggregate over 1.5 in. (3.81cm), use the jigging method.

The results of this test should check within 1 percent when duplicated. The results of this procedure are important, as they are used in the mix design procedure for both Portland cement and bituminous concrete.

APPENDIX C

1. Physical properties of rocks that may be used in the production of concrete.

Table I

Types of rocks	Mechanical strength	Durability	Chemical stability	Surface Characteri-stics	Presence Of Undesirable materials	Crushed shape
Igneous						
Granite,	Good	Good	Good	Good	Possible	Good
Syenite	Good	Good	Good	Good	Possible	Good
Diorite	Good	Good	Good	Good	Possible	Good
Felsite	Good	Good	Questionable	Fair	Possible	Fair
Basalt	Good	Good	Good	Good	Seldom	Fair
Diabase	Good	Good	Good	Good	Seldom	Fair
Gabbro	Good	Good	Good	Good	Seldom	Fair
Peridotite	Good	Fair	Questionable	Good	Possible	Good
Sedimentary						
Limestone	Fair	Fair	Good	Good	Possible	Good
Dolmite	Fair	Fair	Good	Good	Possible	Good
Sandstone	Fair	Fair	Good	Good	Seldom	Good
Chert	Good	Poor	Poor	Fair	Likely	Poor
Conglomerate	Fair	Good	Good	Good	Seldom	Fair
Breccia	Fair	Good	Good	Good	Seldom	Fair
Shale	Poor	Poor	Good	Good	Possible	Fair
Metamorphic						
Gneiss	Good	Good	Good	Good	Seldom	Good
Schist	Good	Good	Good	Good	Seldom	Good
Quartzite	Good	Good	Good	Good	Seldom	Fair
Marble	Fair	Good	Good	Good	Possible	Good
Serpentinite	Fair	Fair	Good	Fair	Possible	Fair
Amphibolite	Good	Good	Good	Good	Seldom	Fair
Slate	Good	Good	Good	Fair	Seldom	Poor

Table II.

Types of rocks	Bulk Specific Gravity	Absorption (%)	Hardness	Toughness
Igneous				
Granite,	2.65	0.3	18	9
Syenite	2.74	0.4	18	14
Diorite	2.92	0.3	18	15
Felsite	2.66	0.8	18	17
Basalt	2.86	0.5	17	19
Diabase	2.96	0.3	18	20
Gabbro	2.96	0.3	18	14
Peridotite	3.31	0.3	15	9
Sedimentary				
Limestone	2.66	0.9	14	8
Dolmite	2.7	1.1	14	9
Sandstone	2.54	1.8	15	11
Chert	2.5	1.6	19	12
Conglomerate	2.68	1.2	16	8
Breccia	2.59	1.8	17	11
Shale	1.85 – 2.5			
Metamorphic				
Gneiss	2.74	0.3	18	9
Schist	2.85	0.4	17	12
Quartzite	2.69	0.3	19	16
Marble	2.63	0.2	13	6
Serpentinite	2.62	0.9	15	14
Amphibolite	3.02	0.4	16	14
Slate	2.74	0.5	15	18