# CONCRETE MIX DESIGN FOR LIGHTWEIGHT AGGREGATES
# AND
# AN OVERVIEW ON HIGH STRENGTH CONCRETE

**BY**

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# DECLARATION

It is hereby declared that, except where specified references have been made to other investigators, the work embodied in this thesis is the result of investigation carried out by the author under the supervision of Dr. Sohrabuddin Ahmed, Professor, Department of Civil Engineering, BUET and Dr. Alamgir Habib, Professor, Department of Civil Engineering, BUET.

Neither this thesis, nor any part of it has been or is being concurrently submitted for any degree at any other institution.

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Author

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# ABSTRACT


Concrete can be regarded as the most widely used construction material available nowadays because it can be prepared from locally available material and also because of its flexibility in handling and placing. Despite all its advantages, when it comes to attaining the desired strength, concrete is the most unpredictable material encountered ever. Extensive research work and experiences gained over the years have shown that quality and durability of concrete depend mostly on the properties of its constituents, and at the same time, mix design, method of preparation, placement, curing condition etc. have their influence on it.

In designing concrete mix, the most widely used and most popular methods are the ACI method and BS method. In Bangladesh, present practices indicate the adoption of these methods using the locally available materials. Most importantly, these methods primarily employ stone as coarse aggregate, whereas, here in Bangladesh, a cheaper substitute, crushed brick aggregate, known as "khoa" is extensively used. It is seen that no proper guideline is provided for using this relatively lightweight aggregate as a substitute for stone in the design methods.

Previous studies at BUET indicated that designing concrete mixes by ACI method, using broken brick aggregates, give anomalous results. Backed by the parametric study and extensive research data, past researchers concluded that the ACI methods of mix design fails in proper proportioning of fine aggregate content, requiring modification of the method for brick aggregate. The objective of the present research is to check the consistency of the ACI method of mix design, using both stone chips and brick chips as coarse aggregate. In the present research, a relationship between the strength parameter of stone chips and brick chips were developed and the mix proportions were determined accordingly to attain desired strength.

However, the use of these concretes with relatively low strength is becoming more and more obscure day by day. Nowadays, concretes are designed to impose special properties within themselves as the construction demands. Concretes can be designed to resist cold or heat, to be highly workable (flowing) or to withstand immense level of compressive force. The last of these hybrid concrete types has a name of 'High Strength Concrete' and has redefined the concrete practice. This report also includes a brief overview on 'High Strength Concrete'.

**Chapter 1**

# INTRODUCTION

## 1.1 General

Concrete is a material that literally forms the basis of our modern history. It is by far the most widely used construction material today. We can hardly find any aspect of our daily lives that does not depend directly or indirectly on concrete. We may live, work, study, or play in concrete structures to which we drive over concrete roads and bridges. Our goods may be transported by trucks traveling on concrete superhighways, by trains that run on rails supported on concrete sleepers, by ships that moor at concrete piers in harbors protected by concrete breakwaters, or by airplanes landing and taking off on concrete runways. Water for drinking and raising crops is stored behind massive concrete dams and is distributed by systems of concrete waterways, conduits and pipes. The water thus stored may also be used to generate electric power. Alternatively, electricity can be generated by burning coal in power stations built from concrete, or by harnessing the power of the atom within massive reinforced concrete pressure vessels.

The various unique properties of concrete have marked its superiority over many other construction materials. The versatility and mouldability of concrete, its high compressive strength, and the discovery of reinforcing and pre-stressing techniques, which helped to make up for its low tensile strength, have contributed largely to its widespread use. The cheapness, durability, exclusive resistance to weather, fire, water and corrosion, make concrete a particularly suitable and unique material for road building, bridges, buildings and dams, for the foundations, frame work, floors and roofs of large buildings of all kinds and for structures in collieries and industrial plants. Hence it has proved itself conducive to form the basis of modern engineering as well as having a greater influence on dramatic impact of technology.

Concrete has the unique distinction of being the only construction material actually manufactured on the site, using locally available materials, with its ability to be cast to any desired shape and configuration. This is an important characteristic that can offset all of its shortcomings. However, this advantage is associated with some factors that have to be considered in order that the concrete fulfills its requirements both in the fresh and the hardened state.

Concrete-both 'good' and 'bad', surprisingly are made of the same ingredients. Bad concrete, often a substance of unsuitable consistence, hardening into a honeycombed, non-homogeneous and weak mass, is made simply by mixing cement, aggregate and water, the same as that of good concrete. It is only the 'know-how', often without additional cost of labor, that is responsible for this difference. Here comes the necessity of proper proportioning of the constituents of concrete, which is otherwise known as Concrete Mix Design. This is done, incorporating the knowledge of the properties of the constituent materials, in the process of choosing a suitable proportion that will allow for

- Sufficient workability of fresh concrete, for convenient transportation, placement and compaction.
- Sufficient strength and durability of hardened concrete that will enable it to withstand the load imposed on it throughout its design life, without much distortion.

Thus, the primary concern in attaining the desired strength, from the designers' viewpoint, is the proper proportioning of the constituent materials of the concrete. In this regard, concrete mix is designed for particular design strength and to obtain this, several methods are available.

## 1.2 Background of Research

In designing concrete mix, the most widely used and most popular methods are the ACI method and the BS method. In Bangladesh, present practices indicate the adoption of these methods using locally available materials. Both the ACI and BS methods of mix design employ, primarily, stone as coarse aggregate, whereas, here, in Bangladesh, unlike other countries of the world, a cheaper substitute, broken brick aggregate, commonly known as "khoa" is extensively used. It is seen that no proper guideline is provided for using this relatively lightweight aggregate as a substitute for stone in the either of the design methods.

For the past few years, during research on the effect of curing conditions on concrete strength at BUET, it has been found that the concrete designed by ACI method gives satisfactory strength behavior when stone is used as the coarse aggregate. However, when broken brick is used in place of stone, the ACI method fails terribly in proper proportioning of the mix. In such a case, for a particular design strength, the design asks for a relatively higher fine aggregate content compared to coarse aggregate, which in turn increases the total surface area to a great extent, keeping the total cement content same. So, lesser amount of cement is available for the proper bonding of fine aggregate with the coarse aggregate and this leads to failure of the concrete specimen prior to the attainment of the design strength.

Furthermore, specific gravity and unit weight of brick chips are much lower, and absorption capacity much higher, as compared to that of the common natural stone aggregates; but the unit weight is not as small which would enable it to be treated as a 'Light-Weigh' aggregate. Therefore, mix design method for lightweight concrete is not applicable to design concrete mixes of broken brick chips.

This observation exactly conforms to the parametric study of ACI method of mix design, done at BUET, which concluded that there is a need for further research with a view to incorporating some modification into the ACI method of mix design in predicting and assessing coarse aggregate content, when coarse aggregate of lower unit weight is used.

These experimental findings, particularly the result of the parametric study of ACI method, demanded the verification of the applicability of the ACI method of mix design in Bangladesh context, i.e., the applicability of ACI method to brick aggregate.

So, our study is mainly based on checking the consistency of the ACI design method in designing normal concrete mixes using brick aggregate and also, to verify and add additional experimental data to the previous anomaly encountered in ACI method.

## 1.3 Objective of Research

In the light of the reasons stated above, some objectives of this research have been identified and these are as follows:

- To study the ACI methods of mix designs, having considered all the parameters and material properties involved.
- To study the applicability of the ACI method of mix design to broken brick aggregates, in terms of the ability of this method to suggest a rational and suitable mix proportion of cement, fine aggregate and coarse aggregate.
- To study the attainment of the design strength of concrete specimen cast with the mix proportions derived using ACI method employing brick aggregate.
- To check the findings of the past studies regarding the failure of the ACI method in rational proportioning of fine aggregates where coarse aggregate of lower unit weight is used.

## 1.4 Scope and Methodology of Research

In attaining the aforementioned objectives, following activities were undertaken:

- A thorough survey of the related literatures is to be carried out. The properties of the constituent materials of concrete, methods of investigation of materials, methods of proportioning of concrete mixes and properties of hardened concrete will also be covered in this review.
- Investigations of the materials will be performed and relevant material characteristics are to be evaluated.
- Mix designs will be performed using broken brick chips as coarse aggregate and Sylhet sand as fine aggregate for one batch and crushed stone as coarse aggregate and Sylhet sand as fine aggregate for the other batch employing ACI method of mix design.
- Casting of concrete will be done according to the mix design results for each batch in ACI method.
- Testing of the Concrete specimen will be done according to ACI standards and the results will be presented in tabular as well as graphical forms.

All the activities employed in accomplishing the objectives are performed in accordance with the standards specified by relevant regulatory agencies.

## 1.5 Concluding Remarks

Previous investigations on the effect of the mix design parameters, on mix proportion and strength revealed that the ACI method of mix design fails in proper proportioning of mixes while using coarse aggregate of lower unit weight (e.g. broken brick chips), whereas, BS method is quite satisfactory in giving a reasonable mix proportion while using such coarse aggregate.

However, both of these design methods suggest a higher value of the water-cement ratio while designing mixes of low design strength, which is totally impractical and might cause the concrete to fail prior to attaining the desired strength. The situation worsens when advanced methods of compaction (e.g. Vibrator) is used. In such a case, segregation occurs leading to non-homogenous concrete. Concrete of this type is generally weak at the top, thus, while used in structures; tend to crack at the top under the application of comparatively smaller stresses, resulting in premature failure.

Chapter 2

# LITERATURE REVIEW

## 2.1 General

The word 'Cement' is derived from the Latin word 'caementum', which was used by the Romans to denote the rough stone or chips of marble from which a mortar was made. 'Concrete' is derived from 'concretus', which signifies 'growing together'- a concise description of the 'binding of loose particles into a single mass'.

Concrete is an artificial stone like material having an excellent resistance to compression. It resembles the principal asset of natural stone and is usually cast in place in a plastic condition. The composition of concrete is determined by the properties of the constituent materials, which are binding material (e.g. cement), fine aggregate (e.g. sand), coarse aggregate (e.g. gravel) and water to harden in forms of the shape and dimensions of the desired structure.

The structural members to be made by concrete are more often than not made in situ, and their quality is almost exclusively dependent on the workmanship of concrete making and placing. Thus the importance of control of quality of concrete work on the site is apparent. Furthermore, as the trade of a concretor has not yet the education and the tradition of some of the other building trades, an engineer’s supervision in the site is essential. These facts must be borne in the mind by the designer, as careful and intricate design can be easily vitiated if the properties of the actual concrete differ from those assumed in the design calculations.

Some of the advantages of concrete, as a construction material, are as follows:

- Ability to be cast to any desired shape and configuration.
- Economical, because local materials and labor can be used to a large extent.
- Durable and does not require protective coatings except in very corrosive

environment.

- High compression taking member.
- Excellent material for fire resistance.
- Energy efficient because of its thermal properties.
- On-site fabrication.
- Aesthetic properties.

All of these advantages combine to make concrete very versatile and adaptable. However, concrete does have weaknesses, which may limit its use in certain cases. Some of the disadvantages of concrete are as follows:

- Brittle material with very low tensile strength.
- Low ductility.
- Volume instability in terms of shrinkage and creep.
- Low strength-to-weight ratio.

## 2.2 Constituent Materials

A diagrammatic representation of the composition of concrete of the proportions used in construction is shown in the fig. 2.1.

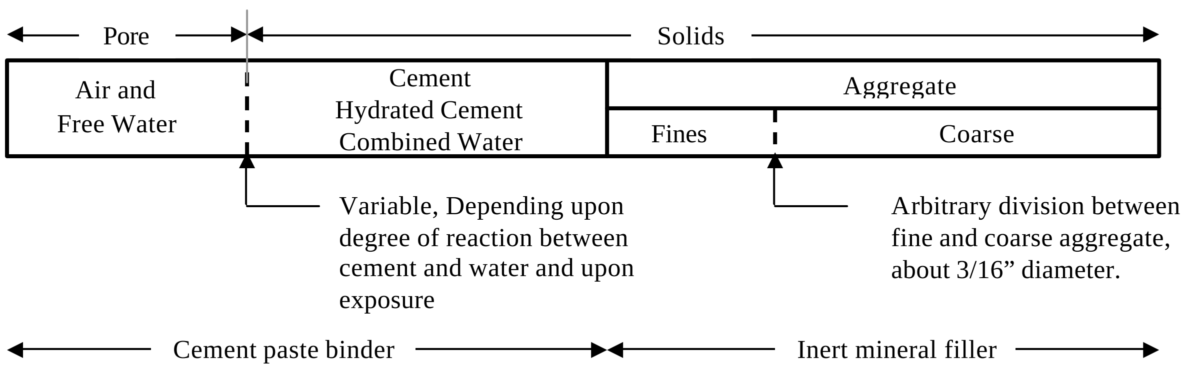



*Fig. 2.1 : Ingredients of Concrete*

### 2.2.1 Cement

#### 2.2.1.1 General

Cement, in the general sense of the word, can be described as a material with adhesive and cohesive properties, which make it capable of bonding mineral fragments into a compact whole. This definition embraces a large variety of cementing materials.

For constructional purposes, the meaning of the term cement is restricted to the bonding materials used with stones, sand, bricks, building blocks etc. Cement plays the central role in the concrete mix not by contributing volume but being primarily responsible for its strength. Among various cementing materials, the cements of interest in the making of concrete have the property of setting and hardening under water by virtue of chemical reactions with it and hence are known as hydraulic cements.

But the best known and most versatile type of artificial cement is the Ordinary Portland cement. It is known as the normal setting cement.

**Composition:**

Constituents of Portland cement are mainly two types-

- Mineral constituents
- Acid and alkaline constituents

The raw materials used for the manufacture of cement consist of mainly lime, silica, alumina and iron oxide. These oxides interact with each other during manufacturing process in the kiln to form more complex compounds. The relative proportions of these compounds are responsible for influencing various properties of cement in addition to rate of cooling and fineness of grinding.

Table 2.1 shows chemical constituents of Ordinary Portland Cement with their chemical formula and shorthand notation.

Table 2.1 : Chemical Constituents of Ordinary Portland Cement

| **Chemical Name** | **Chemical Formula** | **Shorthand Notation** |
|---|---|---|
| Tricalcium Silicate | $3CaO.SiO_2$ | $C_3S$ |
| Dicalcium Silicate | $2CaO.SiO_2$ | $C_2S$ |
| Tricalcium Aluminate | $3CaO.Al_2O_3$ | $C_3A$ |
| Tetra-calcium Aluminoferrite | $4CaO.Al_2O_3.Fe_2O_3$ | $C_4AF$ |
| Calcium Sulphate Dihydrate | $CaSO_4.2H_2O$ | $CSH_2$ |

There also exist minor compounds such as MgO, TiO2, Mn2O3, K2O, Na2O etc. usually amounting 2-8 percent of the weight of cement. Typical composition of Ordinary Portland Cement is shown in the fig. 2.2

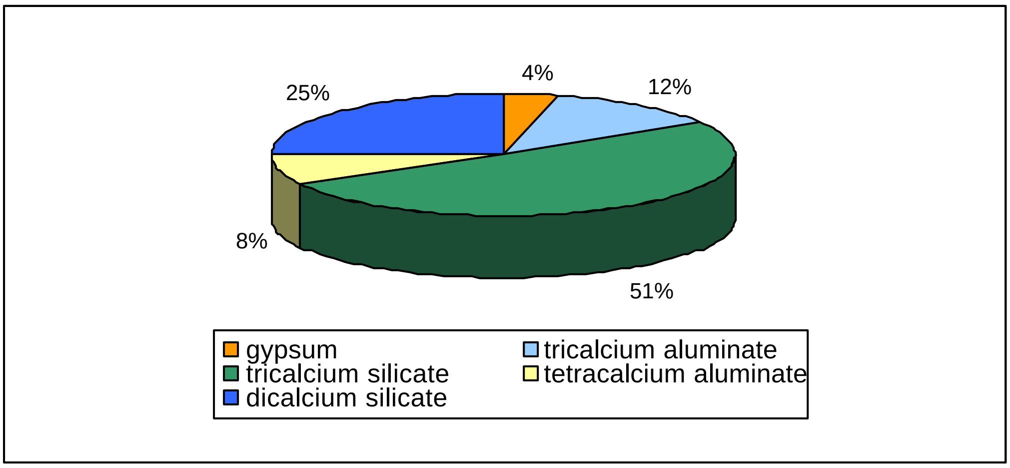



*Fig. 2.2 : Typical Composition of Ordinary Portland Cement*

Table 2.2 : Main Types of Portland Cement

| SL. | British Classification | ASTM Classification | Suitability |
|---|---|---|---|
| 1 | • Ordinary Portland Cement | Type I | By far the most commonly used in general concrete construction when there is no exposure of sulphate in the soil or ground water. |
| 2 | • Rapid Hardening Portland Cement<br>• Extra Rapid Hardening Portland Cement<br>• Ultra High Early Strength Portland Cement | Type III | For cold weather concreting or when a very high early strength is required. |
| 3 | • Low Heat Portland | Type IV | Used in gravity dams, also desirable to reduce cracking and shrinkage |
| 4 | • Modified Cement | Type II | Used where moderately low heat generation is desired, such as in mass concrete, huge piers, heavy abutments and retaining walls particularly when the water is hot |
| 5 | • Sulphate Resisting Portland Cement | Type V | For use when the structure is exposed to sulphate attack. |
| 6 | • Portland Blast furnace (Slag Cement) | Type IS<br>Type IS (MS) | Commonly used in countries where slag is widely available and can be considered to be a cement for general use |
| 7 | • Low Heat Portland Blast Furnace | - | - |
| 8 | • White Portland | - | Used for architectural purpose |
| 9 | • Portland – Pozzolan | Type IP<br>Type I(PM) | Used in rolled concrete, in concrete with low heat characteristics, and in concrete requiring good chemical resistance |

### 2.2.1.2 Properties of Cement

The most important properties of cement are -

- Hydration of cement
- Setting of cement
- Fineness of cement
- Soundness of cement
- Strength of cement

**Hydration of Cement**

The term "hydration" is applied to all reactions of cement with water. The reaction, by virtue of which Portland cement becomes a bonding agent, takes place in a water-cement paste. In other words, in the presence of water, the silicates and the aluminates form products of hydration, which in time form product of hard mass - the hardened cement paste. Process of hydration is mainly the formation of moist crystals of calcium and gels from the solution of cement and water, taking place in two stages, namely –

- True Hydration – a direct addition of some molecules of water takes place
- Hydrolysis – this is a complex phenomenon which takes place within the cement paste; the product of this has a low solubility in water

The hydration of different constituent compounds of cement is illustrated as follows:

$$2C_3S + 6H_2O \longrightarrow C_3S_2.H2O + 3Ca(OH)_2$$

$$2C_3S + 4H_2O \longrightarrow C_3S_2.H_2O + Ca\ (OH)_2$$

$$C_3A + 6H_2O \longrightarrow 3CA.3Ca_3SO_4.3H_2O \longrightarrow C_3A.H_2O$$

A schematic representation of the formation and hydration of Portland Cement is presented in Fig. 2.3.

**Component Elements** $O_2$ Si Ca Al Fe

↓

**Component Oxides** CaO $SiO_2$ $Al_2O_3$ $Fe_2O_3$

↓

**Cement Compounds** $C_3S$ $C_2S$ $C_3A$ $C_4AF$

↓

**Portland Cements** Various Types

↓

**Hydration Products** C–S–H Gel $Ca(OH)_2$

*Fig 2.3 : Schematic Representation of the Formation and Hydration of Portland Cement*

**Setting of Cement**

The term 'setting' is used to describe the stiffness of the concrete paste i.e. the change of cement paste from a fluid to a rigid state. The period of setting is divided arbitrarily into 'initial' and 'final' setting time. After attaining the final set, the process of increase in rigidity and strength is called hardening.

Setting time should not be too small because concrete becomes too rigid while transporting and placing or not be too large to delay the work. In general, most Portland cements attain initial set in 2-4 hr and final set in 5-8 hr.

The time of set of cement is affected by

- its chemical composition
- fineness of cement
- water content of paste
- storage temperature of the paste.

The finer the cement, the more rapid the set.

The reaction of pure $C_3A$ with water is very violent and tends to immediate stiffening of the paste, known as false set and to prevent this, gypsum ($CaSO_4.2H_2O$) is added to cement clinker.

**Fineness of Cement**

Fineness is directly related to the surface area. Since the hydration starts at the surface of the cement particles, it is the total surface area of the cement that represents the material available for hydration. Thus the rate of hydration depends on the fineness of the cement particles. For a rapid development of strength, high fineness is necessary because development of strength actually results from hydration. An increase in fineness of cement slightly improves the workability of a concrete mix. Fine cement bleeds less than a coarser one. On the other hand the disadvantages are:

- The cost of grinding is higher.
- Finer cement deteriorates on exposure to the atmosphere.
- Reacts with alkali-reaction aggregates.
- The paste becomes highly susceptible to shrinkage and cracking.
- Increase in amount of gypsum.

**Soundness of cement**

It is essential that a cement paste once it has set does not undergo a large change in volume. Such changes in volume may take place due to the delayed or slow hydration or other reaction of some compounds present in the hardened cement, namely free lime, magnesia, and calcium sulphate. Cements, which exhibit such expansion, are known as unsound and are totally undesirable.

**Strength of cement**

The mechanical strength of hardened cement is perhaps most obviously required for structural uses. This can be justified by the fact that availability of aggregates of high strength is usually not a problem in construction project. Now when the quality of aggregate is good enough, it is more or less certain that the concrete failure is due to the failure of mortar. As mortar is nothing but sand mixed cement paste, strength of cement practically determines the strength of concrete.

The strength of Concrete or Cement depends on

- the cohesion of cement
- the adhesion of cement to the aggregate particles

There are several forms of strength and they are :

1. Compressive strength
2. Tensile strength
3. Flexural strength

Among these, the compressive strength is the most important one, other types of strength are empirically related to compressive strength.

### 2.2.1.3 Testing of Cement

Strength of concrete is practically governed by the strength of cement, so desired quality of cement conforming to the relevant standard specification is the prime concern for a good mix design. Usually the following standard tests are conducted for ordinary Portland cement.

1. Test on physical properties of cement
   - Determination of normal consistency
   - Determination of setting time
     - ? Initial setting time
     - ? Final setting time
2. Strength test
   - Determination of compressive strength

- Determination of tensile strength

3. Other tests

- Chemical analysis
- Determination of specific gravity
- Fineness test
- Air content determination of mortar
- Sulphate expansion test
- Flexural strength etc.

## 2.2.2 Aggregates

### 2.2.2.1 General

Aggregate generally occupy about 70 to 80% of the volume of concrete, thus, it is not surprising that its quality is of considerable importance. Not only may the aggregate limit the strength of concrete, as weak aggregate cannot produce strong concrete, but the properties of aggregate greatly affect the durability and structural performance of concrete.

Aggregate are granular materials, derived for the most part from natural rock, crushed stone, or natural gravels, broken brick and sands. Aggregate was originally viewed as an inert material dispersed throughout the cement paste largely for economic reasons. It is possible however, to take an opposite view and to look on aggregate as a building material connected into a cohesive whole by means of the cement paste, in a manner similar to masonry construction. In fact, aggregate is not truly inert and its physical, thermal and sometimes also chemical properties influence the performance of concrete.

The mineral aggregate, has three principal functions while being used in concrete. These are:

- To provide a relatively cheap filler for the cementing material.
- To provide the mass of particles for resisting the action of applied loads, abrasion, percolation of moisture and the action of weather.
- To reduce the volume changes resulting from moisture changes in the cement-water paste.

Soft, porous aggregate can limit strength, wear resistance and also may break down during mixing and adversely affect workability by increasing the amount of fines. Aggregates should also be free of impurities like silt, clay, dirt or organic matter. If these materials coat the surface of the aggregate, they will interfere with the cement-aggregate bond. Silt and clay and other fine materials will also increase the water requirement of the concrete. Organic matter may interfere with cement hydration.

#### 2.2.2.2 Classification of Aggregate

Strength of concrete and mix design is essentially independent of the composition of aggregates. No particular rock or mineralogical type in itself, is required for aggregate In the absence of special requirements, most kinds of rocks and most of the artificial materials can produce acceptable aggregates that conform to BS and ASTM specification. Thus, classification by mineralogy or rock type has almost no practical engineering significance.

The simplest and most useful classifications of Aggregates are:

- Classification on the basis of specific gravity and origin

  **a.** Normal weight aggregate

    i. Natural aggregate (e.g. sand, gravel, crushed rock such as granite, quartz, basalt, sandstone etc.).

    ii. Artificial aggregate (e.g. Broken brick, Air cooled slag etc.)

  **b.** Lightweight Aggregate

  **c.** Heavyweight Aggregate

- Classification based on aggregate size

    a. Fine Aggregate

    b. Coarse Aggregate

Often fine aggregates are called sand and are not larger than 5 mm or 3/16 in. The coarse aggregates comprise the materials in size greater than this size.

However, in the USA the division is at #4 sieve, which is actually 3/16 inch or 4.16 mm in size, i.e. the same as mentioned above.

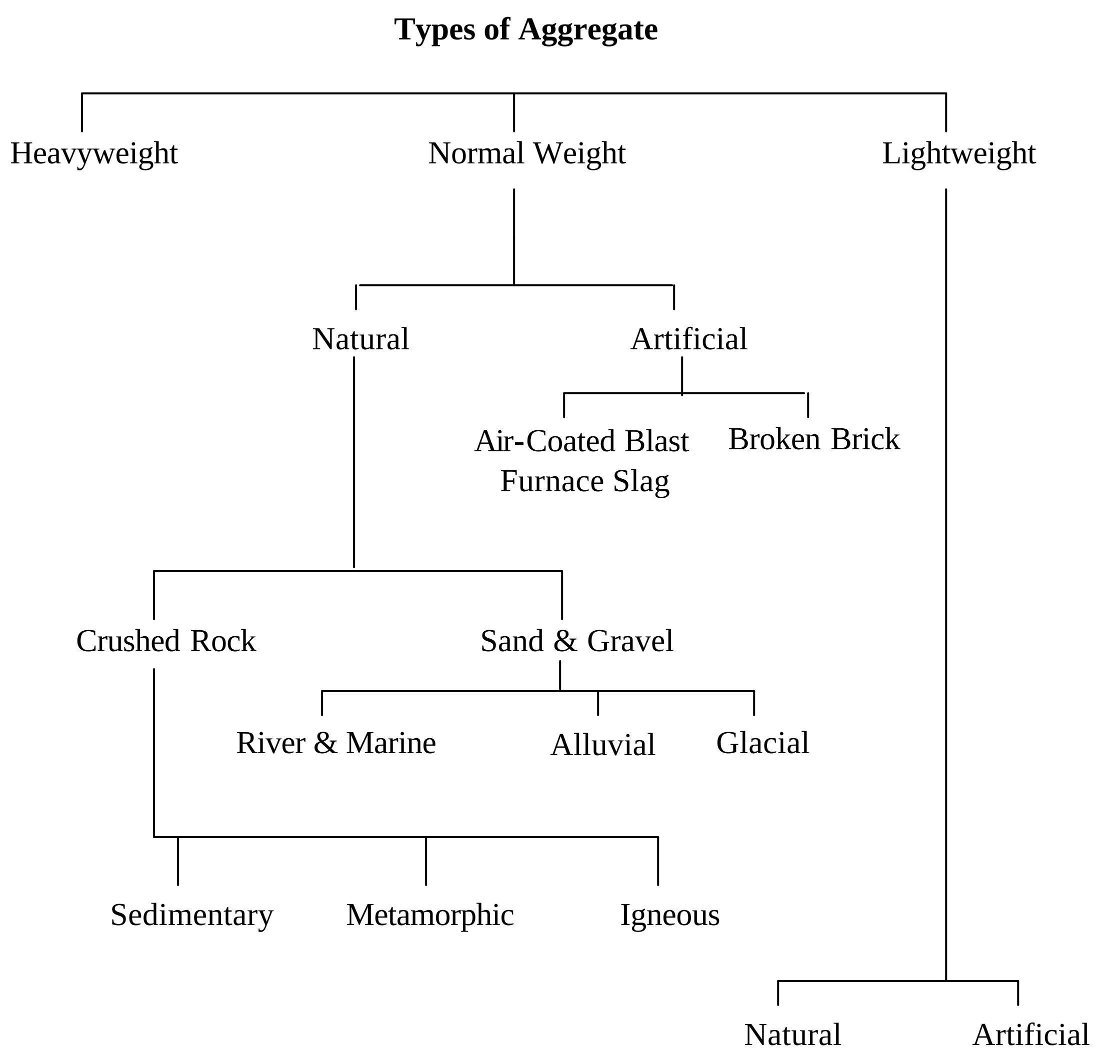



*Fig 2.4 : Classification of Aggregate*

### 2.2.2.3 Properties of Aggregate

Aggregates possess certain properties, which directly influence the strength of concrete. Some of these properties cannot be measured qualitatively and some indirect measures are sometimes adapted. The main properties of aggregates, which may influence the concrete properties, are:

- Shape
- Texture
- Size gradation
- Moisture content
- Specific gravity
- Bulk unit weight
- Strength of aggregate

**Aggregate shape**

Shape refers to the geometry of aggregates. Two important aspects of shape are:

- Roundness: It represents the relative sharpness or angularity of the edges and corners of a particle. Factors affecting roundness are-
    - ? For natural aggregates,
        - ? Strength of the parent rock
        - ? Abrasion resistance of the parent rock
        - ? Amount of wear to which the particles have been subjected.
    - ? For crushed aggregates,
        - ? Nature of parent material
        - ? Type of crusher
        - ? Reduction ratio

Table 2.3 : Particle Shape Classification

| Classification | Description | Examples |
|---|---|---|
| **Rounded** | Fully water worn or completely shaped by attrition | River or seashore gravel; desert, seashore and wind blown sand |
| **Irregular** | Naturally irregular, or partly shaped by attrition and having rounded edges | Other gravels; sand or dug flint |
| **Flaky** | Materials of which the thickness is small relative to the other two dimensions | Laminated rock |
| **Angular** | Possessing well defined edges formed at the intersection of roughly planer faces | Crushed rocks of all type; crushed slag |
| **Elongated** | Materials, usually angular, in which the length is considerably larger than the other two dimensions | ----- |
| **Flaky and Elongated** | Materials having the length considerably larger than the width, and the width considerably larger than the thickness | ----- |

Sphericity is mainly a concern of coarse aggregate and is defined as a function of the ratio of the surface area of the particle to its volume. In case of natural rock, sphericity is effected by –

? Bedding of parent rock

? Cleavage of the parent rock

Angularity is measured by angularity number, which bears a good relationship with the void ratio. The higher the number, the more angular the aggregate is. The range for angularity of practical aggregate is from 0 to 11 .

The ideal aggregate particle is one that is close to spherical in shape (well rounded and compact). Highly elongated, flat or irregular particles with re-entrant faces and sharp points affect workability in the following ways:

- They have a higher surface to volume ratio requiring more paste to fully coat the surface of each particle.
- Such particle interface more severely with the movement of adjacent particles during mixing and handling.
- Concrete containing flat or elongated aggregate are more prone to segregation during handling.

Shape can favorably influence strength by increasing the surface area available for bonding with the pastes for a given aggregate content. However, extremes in aggregate shape may lead to high internal stress concentrations and hence bond failure.

**Size gradation**

A suitable gradation of the combined aggregate in a concrete is desirable in order to secure workability and economy in the use of cement. The amount of paste depends on the amount of void space that must be filled and the total surface area of the aggregate that must be coated with paste. The largest maximum size of aggregate practicable to handle under a given set of condition should be used. However the maximum size of aggregate that can be used in any given condition may be limited by the following conditions.

- Thickness of section
- Spacing of reinforcement
- Clear cover

- Mixing handling and placing techniques

Use of largest possible maximum size will result in

- Reduction of cement content
- Reduction in water requirement
- Reduction of drying shrinkage

Generally, the maximum size of aggregate should not be greater than one-fourth of the maximum thickness of the number.

**Moisture Content**

Since aggregate contains some voids, water can be absorbed into the body of the particle. Also water can be retained on the surface of the particle as a film of moisture. It is convenient to define four moisture states of the aggregate –

1. Oven Dry (OD) : All moisture are removed from the aggregate. All pores are empty
2. Air Dry (AD) : All moisture are removed from the surface, but internal pores can be partially full.
3. Saturated Surface Dry (SSD) : All pores are filled with water, but no film of water on the surface
4. Wet : All pores are completely filled with water with film of water on the surface.

If there is a tendency for the aggregate to absorb water, water will be removed from the paste so that the water-cement ratio will be effectively lowered and the workability of the concrete decreased. Conversely, if excess water is present at the aggregate surface, extra water will be added to the paste and the water-cement ratio will be higher than desired.

The absorption capacity is a measure of the porosity of an aggregate; in determining the free moisture by the oven-drying method,

$$\text{Absorption capacity, AC} = (W_{SSD} - W_{OD}) / W_{OD} \times 100\%$$

where,

$W_{SSD}$ and $W_{OD}$ represent the weight of the aggregate in the SSD and OD state.

SSD condition is the better choice as a reference state. Its advantages are

- Aggregate will neither absorb nor give up water to the paste
- Field moisture content is much closer to SSD
- Bulk specific gravity can be easily determined
- Moisture content can be directly determined.

A major disadvantage of using SSD state is that it is not easy to obtain a true SSD condition even in the laboratory and it requires skill and practice to do this. However ACI code uses SSD as reference state. Actual mix proportion should be modified according to the field moisture condition of aggregate to produce a good concrete mix.

In addition to this, surface of moisture of additional water can be held in the interstices between fine particles as the result of formation of meniscus. The formation of this meniscus creates thicker films of water between the aggregate particles, pushing them apart and increasing the apparent volume of the aggregate. This phenomenon is known as bulking and can cause substantial errors in proportioning by volume. When sand is saturated with water, the meniscus are destroyed and the volume returns to normal. Coarse aggregate shows much less bulking since the particle size is large compared to the thickness of the water film and the effect of meniscus formation is slight.

**Specific Gravity**

Specific gravity serves the following purposes in mix design and concrete preparation.

- It establishes weight-volume relationship.
- It is required in calculating the compacting factor in connection with the workability measurement.
- Specific gravity of aggregate is required to be considered when we deal

with light and heavy weight concrete.

Specific Gravity (SG) = Density of Solid / Density of Water

Considering the pores of the aggregate, absolute and bulk specific gravity are:

$$\text{Absolute specific gravity (ASG)} = \frac{\text{Weight of aggregate (solid only)}}{\text{Volume of Aggregate ( solid only)}} \times \frac{1}{pw}$$

$$\text{Bulk Specific Gravity (BSG)} = \frac{\text{Weight of aggregate (solid + pore)}}{\text{Volume of Aggregate (solid + pore)}} \times \frac{1}{pw}$$

If the pores are filled with water, there is a finite contribution to weight, which is absent when the pores are empty. Hence, $ASG > BSG_{ssd} > BSG_{OD}$

However, since the porosity of most rocks used as concrete aggregates is only of the order of 1 to 2 percent, the values of all of the specific gravity are approximately the same. This is not true for light weight aggregates, whose BSGs are strongly dependent on moisture content.

The BSG value is the realistic one to use, since the effective volume that aggregate occupies in concrete includes its internal pores. The BSG value of most rocks is in the range of 2.5 to 2.8. A value well below this range is indicative of high porosity. However, BSG of an aggregate cannot be directly related to its performance in concrete and thus it is not a specified quantity. The only reason for specifying BSG is if a minimum density of concrete is required, since BSG directly relates to concrete density.

**Bulk Unit Weight**

Physically, it is not possible to pack aggregate particles so that there are no voids between them. In the light of this fact, unit weight, or more specifically, bulk density of aggregate is defined as the weight of the aggregate that would fill a concrete of unit volume.

Unit weight effectively measures the volume that the graded aggregate will occupy in the concrete and includes both the solid aggregate particles and the voids between them. Bulk density depends on

- Shape of the particle
- Size distribution of the particle
- Moisture content
- Degree of compaction achieved

For a given specific gravity, higher bulk density means fewer voids to be filled by sand and cement. For a given specific gravity, angular aggregates show a lower bulk density.

Void ratio is directly related to the bulk density as follows -

$$\textit{Void ratio} = 1 - \frac{\textit{Bulk density}}{\textit{Unit weight of water} \times \textit{bulk specific gravity}}$$

The bulk density of aggregate is of interest in connection with the use of light weight and heavy weight aggregate. The unit weights of both fine and coarse normal weight aggregates are generally (within the ASTM grading limits) in the range of 1450 to 1750 kg/m$^3$.

**Strength of aggregate**

Clearly, the compressive strength of concrete cannot significantly exceed that of the major part of the aggregate contained therein, although it is not easy to state what the strength of the individual particles is. The strength of concrete is not only to the characteristics between cement paste and aggregate. In general, the strength and elasticity of aggregate depend on its composition, texture and structure. Thus a low strength may be due to weakness of constituent grains of the grains may be strong but not well klint or cemented together. The modulus of elasticity of aggregate is rarely determined, but it has important influence on

- Modulus of Elasticity of concrete.

- The magnitude of creep and shrinkage that can be realized by the concrete.

Strong aggregates are an essential element to make strong concrete. The test for strength of aggregate is required to be made in the following situations:

- For production of high strength and ultra high strength concrete.
- When contemplating to use aggregates manufactured from weathered rocks.
- Aggregate manufactured by low industrial process.

Aggregate of moderate or low strength and modulus of elasticity can be valuable in preserving the durability of concrete. Volume changes of concrete, arising from thermal reasons, lead to a lower stress in the cement paste when the aggregate is compressible. Thus compressibility of aggregate would reduce distress in concrete while a strong and rigid aggregate might lead to cracking of the surrounding cement paste. The ten percent fines value or the crushing value of aggregate can be determined for the assessment of good aggregates.

**Other properties**

Other properties of aggregate of minor importance from strength of concrete point of view are listed below:

- Bond of aggregate
- Porosity and absorption of aggregate
- Toughness of aggregate
- Hardness of aggregate
- Cleanliness of aggregates from deleterious materials, namely, clay, salt concentrations, unsound particles like shale etc.
- Soundness of aggregate.
- Alkali- aggregate reaction
- Thermal properties of aggregate e.g. coefficient of thermal expansion, specific heat, conductivity, etc.

### 2.2.2.5 **Effect of Aggregate properties on the Concrete Strength**

Aggregate property is one of the most important factors affecting the strength of concrete. They are discussed as follows:

- **Deleterious Substances:**

Aggregate, contaminated by silt, clay, mica, coal, humus, wood, other organic matter, chemical salts, may cause the following problems:

- Decreases strength and durability
- Causes unsoundness
- Increases water requirement
- Inhibits the development of maximum bond between the hydrated cement and aggregate
- Hinders the normal hydration of cement
- Reacts chemically with cement constituents.

- **Shape:**

Elongated and flaky particles in the aggregate lead to harsh and weak concrete. If the aggregate is approximately cubical, less cement paste is required for a given workability and a cheaper mix can therefore be used. The improved workability and less modulus of rupture resulting from the use of good shaped aggregate is due chiefly to the fact that its surface area per unit volume is less than that of an aggregate of poor shape. In addition, a reduction in strength is caused by the increased water requirement for a given workability in case of badly shaped aggregate.

- **Texture**

Surface texture affects both the bond and the stress level at which micro cracking begins. Smooth gravel leads to cracking at lower stresses than rough angular crushed rack. The texture, therefore may affect the shape of the stress-strain curve, but has little effect on the ultimate compressive strength of the concrete and no effect on the tensile or flexural strength. At low water/cement ratio, crushed rock will load to higher concrete strengths because of the better mechanical bond

- **Size Gradation**

The use of a larger maximum size of aggregate affects the strength in several ways. Because the use of larger particles reduces the specific surface area of the aggregate, the bond strength is also less and this tends to reduce the strength. Also larger aggregate particles provide more restraint on the volume changes in the paste, and may thus induce additional stresses in the paste, which tend to weaken the concrete. These effects are offset, however, by the reduced water content necessary to achieve a suitable workability, so the net effect of using larger aggregate particles is slight.

- **Specific Gravity**

Specific gravity is a useful, quick indicator of suitability of an aggregate. Low specific gravity frequently indicates porous, weak and absorptive materials, and high specific gravity often indicates good quality.

- **Aggregate/Cement Ratio**

Aggregate/cement ratio affects the strength of medium and high-strength concrete. For a constant water/cement ratio leaner mix leads to a higher strength. This behaviour is probably associated with the absorption of water by the aggregate. A larger amount of aggregate absorbs a greater quantity of water, the effective water/cement ratio thus being reduced.

## 2.2.3 Water

### 2.2.3.1 General

Water is an important ingredient because,

- It actively participates in the reaction with cement.
- It ensures workability

The time-honored rule of thumb for water quality is, "If you can drink it you can make concrete with it", and a large fraction of concrete is made using municipal water supply. However, good quality concrete can be made with water that would pass normal standards for drinking water. There is no ASTM concrete water quality standard but BS 3148 addresses this matter.

### 2.2.3.2 Impurities in Water

Impurities in water affect the following concrete qualities.

- Setting time
- Drying shrinkage
- Resistance to efflorescence
- Durability

The tolerable limits of impurities in mixing water are listed in Table 2.10.

Impurities that make water unsuitable for use are discussed below.

**Suspended Solids**

Some examples of suspended solids and their effect on concrete mix are discussed below.

- Suspended clay/silt
  - increase water demand
  - increase drying shrinkage
  - cause efflorescence.
- Algae/suspended organic matter
  - retard setting
  - reduced strength
  - interfere with cement hydration
  - entrain excessive amount of water

**Dissolved Solids**

Hazards depends upon the nature of the dissolved materials. For example –

- soluble carbonatesand bicarbonates
- soluble inorganic salts of zinc, copper lead etc.
- acidic water
- organic acids
- alkaline water (NaOH / KOH)

**Dissolved Organic Material**

Dissolved organic materials which are mainly tannic and humid acids (make water colored) may retard the hydration of cements or entrain excessive amounts of air.

## 2.3 Curing of Concrete

The curing conditions with respect to moisture and temperature, through their effect on hydration of cement, exercise an important influence on the strength of concrete. The necessity of curing arises from the fact that hydration of cement can take place only in water-filled capillaries. This is why a loss of water by evaporation from the capillaries must be prevented. Furthermore, water lost internally by self-desiccation has to be replaced by water from outside, i.e. ingress of water into the concrete must be made possible.

The longer the period of moist storage, the greater is the strength. Exposure to air, with consequent drying, arrests hydration; the rate and extent of drying depend on the mass of concrete relative to the area of exposed surface as well as the humidity of the surrounding air.

The influence of temperature on moist curing on concrete strength depends on the time-temperature history. When concrete is cast and maintained at a given constant temperature, the higher the temperature (within limits), the more rapid the hydration and resulting gain in strength at early ages. At later stages the strengths are not greatly different but higher the curing temperature, the lower is the strength.

**Methods of Curing**

Curing methods of concrete can be divided into following 4 groups –

- Water Curing
- Sealed Curing
- Steam Curing
- Miscellaneous

## 2.4 Physical Properties of Concrete

Form engineers point of view, important properties of hardened concrete can be listed as follows –

- Strength
- Elasticity
- Water tightness
- Resistance to destructive agencies
- Volume changes
- Creep
- Extensibility
- Thermal properties
- Workability

Stronger concretes are stiffer, more nearly watertight, and more resistant to weathering and certain destructive agencies. On the other hand, however, stronger concretes usually exhibit higher drying shrinkage and lower extensibility, hence are more liable to cracking. A structure must be adequately designed and properly constructed of concrete which is strong enough to carry the design loads and which is economical not merely in terms of cost but also in terms of its ultimate service.

### 2.4.1 Strength of Concrete

Strength can be defined as the ability force. With regard to concrete for structural purpose, it is taken, unless stated otherwise, as unit force (stress) required to cause rupture. Rupture may be caused by applied tensile stress (failure in cohesion), by applied shearing (sliding) stress, or by compressive (crushing) stress.

#### 2.4.1.1 Compressive strength:

Except for highway pavements, most concrete structures are designed under an assumption, that the concrete resists compressive stresses but not tensile stresses; hence, for purposes of structural design the compressive strength is the criterion for quality, and working stresses are prescribed by codes in terms of percentages of compressive strength as determined by standard tests. A future consideration is that compression tests are relatively easy to make. The usual test employs a cylindrical specimen of height equal to twice the diameter, moist-cured at 21ºC for 28 days and then subjected to slow ("static") loading at a specified rate until rupture occurs; usually loading is completed within 2 or 3 minutes. Values of strength obtained in this way usually range from 2000-6000 psi.

#### 2.4.1.2 Tensile strength:

As previously stated, concrete is not expected to resist direct tensile forces because of its relatively low tensile strength and brittle nature. However, tension is of importance with regard to cracking, which is a tensile failure; most cracking (aside from that due to settlement of parts of the structure) is due to restraint of contraction induced by drying shrinkage or lowering of temperature. The general relationship between tensile and compressive strength of concrete is shown in figure 2.3. It is seen that the tensile strength ranges from 7 to 11, and average about 10 percent of the compressive strength; the higher the compressive strength, the lower the relative tensile strength.

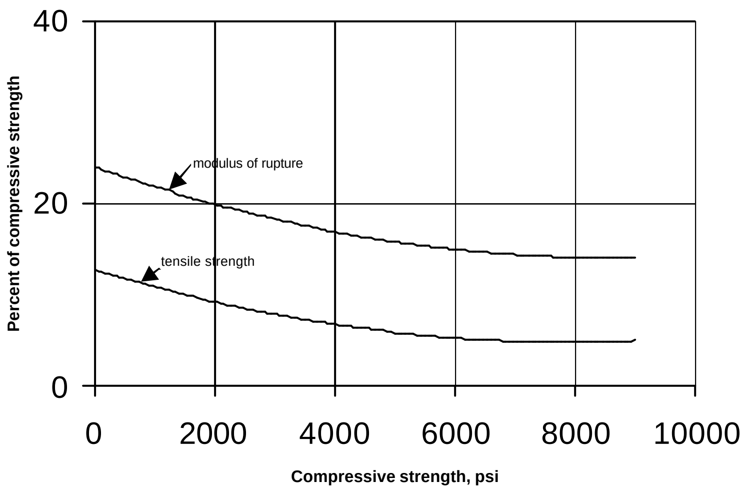



fig 2.3 : Relationship between tensile and compressive strength

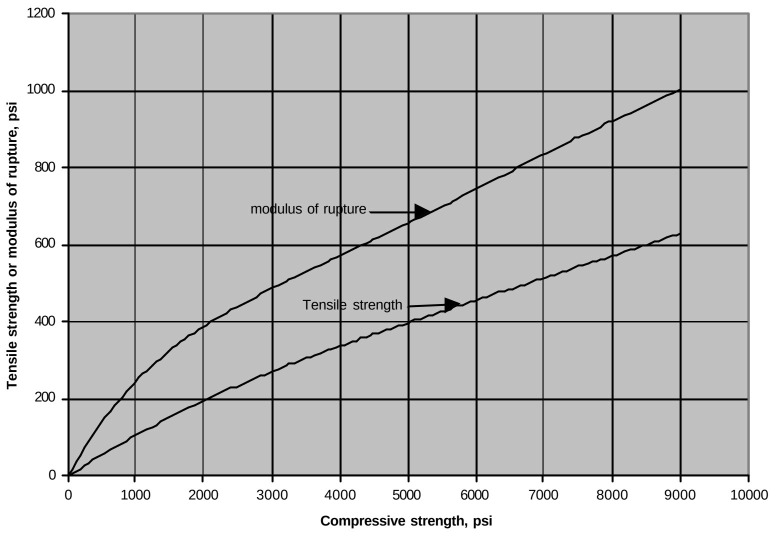



Fig: Relation between compressive strength, tensile strength, and modulus of rupture

### 2.4.1.3 Flexural strength:

When concrete is subject to bending, tensile and compressive stresses and in many case direct shearing stresses are developed. The most common plain concrete structure subjected to flexural is a highway pavement, and the strength of concrete for pavements is commonly evaluated by means of bending tests on beam specimens. Flexural strength is expressed in terms of "modulus of rupture", which is the maximum tensile (or compressive) stress at rupture computed from the well- known flexure formula:

$$s = Mc/I$$

Where,

s = stress in the fiber farthest from neutral axis,

M= bending moment at the section,

I = moment of inertia of the cross section,

c= distance from neutral axis to farthest fiber.

#### 2.4.1.4 Shear strength:

Shear is the action of two equal and opposite forces applied in planes a short distance apart. Shear stress cannot exist without accompanying tensile and compressive stresses. Pure shear can be applied only through torsion of a cylindrical specimen, in which case the stresses are equal in primary shear, secondary tension and secondary compression. Since concrete is weaker in tension than in shear, failure in torsion invariably occurs in diagonal tension.

#### 2.4.1.5 Impact strength

It has been suggested that the impact strength varies from 0.5 to 0.75 of the compressive cube strength. A measure of impact strength is the number of blows that concrete can withstand till there is “no rebound” of impacting device. Factors affecting impact strength are -

- Testing method
- Nature of cement aggregate bond
- Curing conditions

### 2.4.2 Workability and Consistency

The concrete must be easily capable of satisfying the following requirements

a. It must be easily mixed and transported.

b. It must be uniform throughout a given batch and between batches.

c. It should have flow properties such that it is capable of filling completely the forma for which it was designed.

d. It must have the ability to be compacted fully without an excessive amount of energy being applied.

e. It must not segregate or bleed during placing and consolidation.

f. It must be capable of being finished properly.

A concrete satisfying these conditions is said to be workable. Workability is often defined in terms of the amount of mechanical work, required to produce full compaction of the concrete without segregation.

Another term used to describe the state of fresh concrete is consistency. The word consistency refers to the fineness of a form of a substance or to the ease with which it will flow. In case of concrete, consistency is sometimes taken to mean the degree of wetness, within limits, wet concrete are more workable than dry concrete, but concretes of the same consistency may vary in workability.

### 2.4.3 Segregation and Bleeding

**Segregation**

Segregation can be defined as separation of the constituents of a heterogeneous mixture so that their distribution is no longer uniform. Absence of appreciable segregation is essential as full compaction of a segregated mix is impossible. There are two forms of segregation. In the first the coarser particles tend to separate out since they tend to travel further along a slope or to settle more than finer particles. The second form of segregation occurring particularly in wet mixes is manifested by the separating of grout from the mix. Addition of water would improve the cohesion of the mix but when the mix becomes too wet the second type of segregation would take place.

The factors that contribute to increased segregation have been listed as follows-

1. Larger maximum particle size and proportion of the large particles.

2. A high specific gravity of the coarse aggregate compared to that of the fine aggregate.

3. A decreased amount of fines.

4. Changer in the particles to odd-shaped, rough particles.

5. Mixes that is either too wet or too dry.

6. Method of handling and placing the concrete.

Attempts that can be made in order to reduce segregation are-

1. Correct and careful handling and placing of concrete.

2. Choice of suitable grading.

3. The use of a smaller proportion of coarse aggregate at the beginning.

4. Use of finely divided mineral admixtures or air-entrancing agents.

5. Prohibiting large amount of work to be done on the concrete e.g. vibration.

6. When concrete is transferred, the use of hoppers, buffles, and short vertical drops is recommended rather than long unconfined drops.

7. Using particularly cohesion mix.

**Bleeding**

The tendency for water to rise to the surface of freshly placed concrete is known as bleeding. This is caused by the inability of the solid constituents of the mix to held all of the mix to mixing water when they settle downwards. Some bleeding is normal for good concrete; it results in a small amount of uniform seepage over the entire surface.

Undesirable effects of bleeding are:

1. Upper layer of the concrete subjected to high w/c ratio leads to weakness, porosity and a lack of durability.

2. Lack of bonding with the upper layer to the material below.
3. Water pockets under large aggregate particles or reinforcing bars, leaving weak zones and reducing bonds.
4. If the bleed water evaporates quickly, plastic shrinkage cracks will form.
5. Scum of fine particles to the surface.
6. Salt may crystallize referred to as laitance.

Bleeding can be reduced in a number of ways-

1. By increasing cement fineness or by using pozzolans or other finely divided minerals admixtures.
2. By increasing the rate of hydration of cement using cement with higher alkali or $C_3A$ content or by using $CaCl_2$ as admixture.
3. Through air entrapment.
4. By reducing the water content.

### 2.4.4 Durability and Impermeability:

Concrete which can withstand the conditions for which it has been design, without deterioration, over a period of years is said to be durable. The absence of durability may be due to two causes—

External causes →
- Physical → 1.Freezing & thawing
  2. Wetting & drying
  3. Temperature changes
- Chemical → 1. Leaching & efflorescence
  2. Sulfate attack
  3. Attack by natural industrial liquids and gases
- Mechanical (Wear and abrasion)

Internal causes →
1. Alkali-aggregate reaction
2. Volume changes due to thermal properties of aggregate and cement paste
3. Permeability

*Fig. Causes of durability*

### 2.4.5 Permeability:

Permeability determines the relative ease with which concrete can become saturated with water.

Factors affecting permeability of concrete:

1. Constituent materials
    a. Amount and purity of water
    b. Fineness and compaction of cement
    c. Type, size, grading, impurities of aggregates
    d. Chemically active
2. Methods of preparation
3. Subsequent treatment
    a. Age
    b. Curing
    c. Test conditions

### 2.4.6 Shrinkage :

The term shrinkage is loosely used to describe the various aspects of volume changes in concrete due to the -

a. settlement of the fresh mass.

b. Chemical combinations of the cement with water.

c. Combination of high-alkali cements with certain relative aggregate.

d. Change in moisture content.

e. Change in temperature.

f. Applied loads.

To understand this aspect more closely, shrinkage can be classified in the following way-

1. Plastic shrinkage
2. Drying shrinkage
3. Autogenous shrinkage
4. Carbonation shrinkage

**Plastic shrinkage:** Loss of water from fresh concrete, if not prevented, can cause cracking. To control this, the most effective method is to ensure that the concrete surface is kept wet until the surface has been finished and routine curing began.

**Autogenous shrinkage:** If no additional water beyond that added during mixing is provided; it is possible that the concrete will begin to dry out even if no moisture is lost to the surroundings.

**Drying shrinkage:** Withdrawal of water from concrete stored in unsaturated air causes drying shrinkage. It is the most important type of shrinkage.

**Carbonation shrinkage:** Hardened cement paste will react chemically with carbon dioxide present in the atmosphere over a long period of time.

### 2.4.7 Effect of Loading Conditions:

Normally concrete structures are considered as being subject to steady, or “static”, loads, and compressive strength is evaluated by means of a test in which load is applied to failure within a few minutes. However, actually most structural members are subjected to long-continued steady loads ---- at least dead loads----- many are subjected to fluctuations of load or to impact. Under steady loading sustained for a number of years, concrete will withstand only about 70 percent of the stress at failure in the conventional test. Under a large number of cycles of repeated loading in either compression or flexure, dry concrete will fail at a stress approximately 50 to 55 percent of the strength under short-time loading.

### 2.4.8 Creep

The relation between stress and strain for concrete is a function of time. The gradual increase in strain with time under load is due to creep. When the concrete is unloaded, a relatively small portion (10-20%) of the total creep strain is reversible (after loading for 200 days). Factors influencing creep of concrete are shown in table below-

**Table: Effect of Creep on different Concrete Properties**

| **Different properties** | **Creep** | **Remark** |
|---|---|---|
| 1. Applied stress | ? | Linearly related upto a stress of 50% ultimate strength. |
| 2. W/C ratio | ? | Specific creep is used in the relation. |
| 3. Compressive strength | ? | " |
| 4. Curing condition | ? | Time and temperature is considered. |
| 5. Temperature condition | ? | Linear relation upto 80ºC. |
| 6. Moisture condition | ? | Creep= f(evaporable water, we and fall to zero when we=0.) |
| 7. Cement composition | ? ? | ? ;for C3A |
| 8. Admixture | ? | ?;for C3S |
| 9. Others- Aggregates<br>- Modulus of elasticity. | | Admixture that increases the drying shrinkage. |

## 2.5 Brick As Light Weight Coarse Aggregate

Broken Brick Chips, locally known as khoa, is commonly used as coarse aggregate in Bangladesh. Generally a brick is an artificial kind of stone made of clay whose chief characteristics are a plasticity when wet and stone like hardness after being heated to high temperature. In Bangladesh according to P.W.D. specification different classes of bricks are available. Crushed brick aggregates are widely used in parallel to stone aggregates in Bangladesh and other countries of the world where the sources of natural aggregate are not abundant. Earlier investigations on brick aggregate concrete by Akhtaruzzaman and Hasnat (1983) revealed that modulus of elasticity of brick aggregate concrete is 30% lower and tensile strength was about 11% higher for the same grade of stone aggregate concrete. Brick aggregate concrete was also characteristically found to be of lower unit weight to the extent of around 120 pcf. S. Ahmad and S. Amin (1998) reported the significance of very high absorption capacity (more than 10%) of brick aggregates in the compressive strength attainment behavior of discontinuously cured concrete.

## 2.6 Rationalizing Brick Aggregate with Stone Aggregate

ACI method is the most widely used method all over the world today. This method recommends Crushed Stone Chips as Coarse Aggregate, Ottawa Sand as Fine Aggregate and Ordinary Portland Cement of Type I as the binding material. All the Communities that practice ACI method of Mix Design in concrete construction should use these constituents to achieve the desired strength. Change in any of these constituents will result in a change in the ultimate strength of the concrete. Thus, a relevant modification is required to determine the actual proportion of the constituents which will finally lead to achieve the desired strength of the concrete.

In Bangladesh, as well as many other countries of the world, where natural stone, rock or gravel is scarce, broken brick chips are used as a substitute of rock in concrete. Brick is considered as a lightweight aggregate and can be defined as artificial stone made of clay. Brick is plastic when wet, but when burnt to high temperature, it resembles very much to stone. But still, it lacks in many ways compared to natural stone. Brick has low unit weight, high degree of porosity, high absorbance and it is highly liable to wear and decay compared to stone. Most importantly, it has inferior strength parameters compared to that of stone. Thus, concrete casted with Brick Chips as Coarse Aggregate can never provide the desired strength that concrete casted with Crushed Stone Chips would have produced, unless the method is modified to cope with the Lightweight Coarse Aggregate, i.e. - Brick Chips.

The procedure of ACI Method of Mix Design is described on Chapter 3, Article 3.5.4. In the sixth step of the procedure, i.e. – Estimation of Coarse Aggregate Content, table 3.6 gives the volume of Coarse Aggregate content per unit volume of concrete. When it is multiplied by the unit weight of the Coarse Aggregate, it gives the weight of Coarse Aggregate. As unit weight of Brick is much less than the unit weight of stone, weight of Brick found in this step is much less than the actual weight of stone that would have produced the desired strength in the concrete.

Again, on the next step, i.e. – Estimation of Fine Aggregate Content, Fine Aggregate is estimated by subtracting the weight of cement, water and coarse aggregate from the total weight of fresh concrete. As the weight of Brick Chips found in the previous step is much less than required, the amount of Fine Aggregate in the concrete goes up. This excess Fine Aggregate affects the strength of concrete adversely and reduces its strength. Moreover, it increases the tendency of mortar failure in concrete.

Thus, the amount of Brick Chips used in concrete should be increased to make it equal to the equivalent Stone Chips, which will further help to reduce the portion of Fine Aggregate in concrete. This is done by multiplying the amount of Brick Aggregate by a factor. This factor is the ratio of the Unit Weight of the Stone Aggregate to Unit Weight of Brick Aggregate. The amount of Brick Chip is multiplied by this factor. Then the Fine Aggregate content is found by subtracting Cement content, Water and increased Brick Aggregate content from the total weight of fresh concrete. This newly found Fine Aggregate content is much lower than the fine aggregate content found previously and is suitable to use with Brick Aggregate. Finally, the original amount of Brick Aggregate and newly found amount of Fine Aggregate is combined with Cement and Water to produce concrete of desired strength.

ACI Method of Mix Design also suggests to use Ottawa Sand as Fine Aggregate whereas in Bangladesh, Sylhet Sand is used widely as Fine Aggregate. The properties of these two sands are so near that they can be considered as identical and thus, no correction of modification corresponding to this is necessary.

## Chapter 3

# DESIGN OF CONCRETE MIXES

## 3.1 General

Concrete used in various types of construction works across the world has to withstand different types and magnitudes of loading. It may be subject to flexural, tensile, shear or most commonly compressive stresses. The magnitude of the stress may vary from a very small to a very large value depending upon the type of member where the concrete is going to be cast. Therefore the dimensions of the members to be cast will depend not only upon the load to be resisted but also upon the strength of concrete. It can be easily visualized that a stronger concrete would require a smaller dimension than a weak concrete to resist the some load. As design is obviously done ahead of construction, the designer has to assume a reasonable value of concrete strength and then select the dimensions of various members of the structures accordingly.

In the field any proportion of coarse aggregates, fine aggregates, cement and water is not going to produce the specified strength of concrete. Therefore it is not advisable to use an arbitrary combination unless there is much experience regarding the associated materials. Again it is not feasible to prepare a number of trial batches with arbitrary composition and test them for the specification because this may require a good number of trial batches to be prepared to achieve the goal. This is where the mix design methods come to rescue the engineers. Various mix design methods have been developed and being used by various organizations. These methods use slightly different parameters as their input but the purpose remains the same - to produce a concrete mix of suitable proportions that would be sufficiently workable to transport, place and finish without segregation and, upon hardening, would give satisfactory strength as per specification.

## 3.2 Basic Considerations of Mix Design

After considerable amount of investigation on the theoretical aspects of mix design, the design process still remains largely an empirical procedure. The points that are to be considered while designing a consider mixes are -

**Economy:**

The cost of concreting is made up of the cost of the materials, plant and labor. However, except for some special concretes, the cost of labor and equipment are largely independent of the type and quality of concrete produced. Again, mix design methods are directly concerned with the material cost of concrete. The variation in the cost of materials arises from the fact that cement is several times dearer than aggregate, so that it is natural in mix design to aim at as lean a mix as possible. The use of comparatively lean mixes confers also confers also considerable technical advantages, not only in the case of mass concrete where the evolution of excessive heat of hydration may cause cracking, but also in structural concrete where a rich mix ay lead to high shrinkage and cracking. In the view of economy some of the efforts practiced are:

i. Permitting lowest possible slump

ii. Using largest practical maximum size of aggregate ratio.

iii. Using optimum coarse/fine aggregate

iv. Using admixture etc.

**Workability:**

As a general rule, the concrete should be supplied at the minimum workability that will permit adequate placement. Where necessary, workability should be improved by increasing the mortar content rather than by simply adding more water or more fine material. In some cases a less economical mix may be the best solution.

**Strength and Durability:**

Although many durability properties of concrete are important, most design procedures are based primarily on achieving a specified compressive strength at some given workability and age. It is assumed that if this is done, the other properties will also be satisfactory. Special consideration will be required where water/cement ratio has to be modified, admixtures have to be used, compromise has to be made between the strength and workability.

## 3.3 Process of Mix Design

Proportioning of concrete mixes or mix design determines the relative amounts of materials to be used in batches of concrete for a particular purpose. Proportioning of the ingredients is highly important because it provides the means of meeting the fundamental requirements of quality as economically as possible. The basic factors in the process of mix design are expressed diagrammatically in figure 3.1.

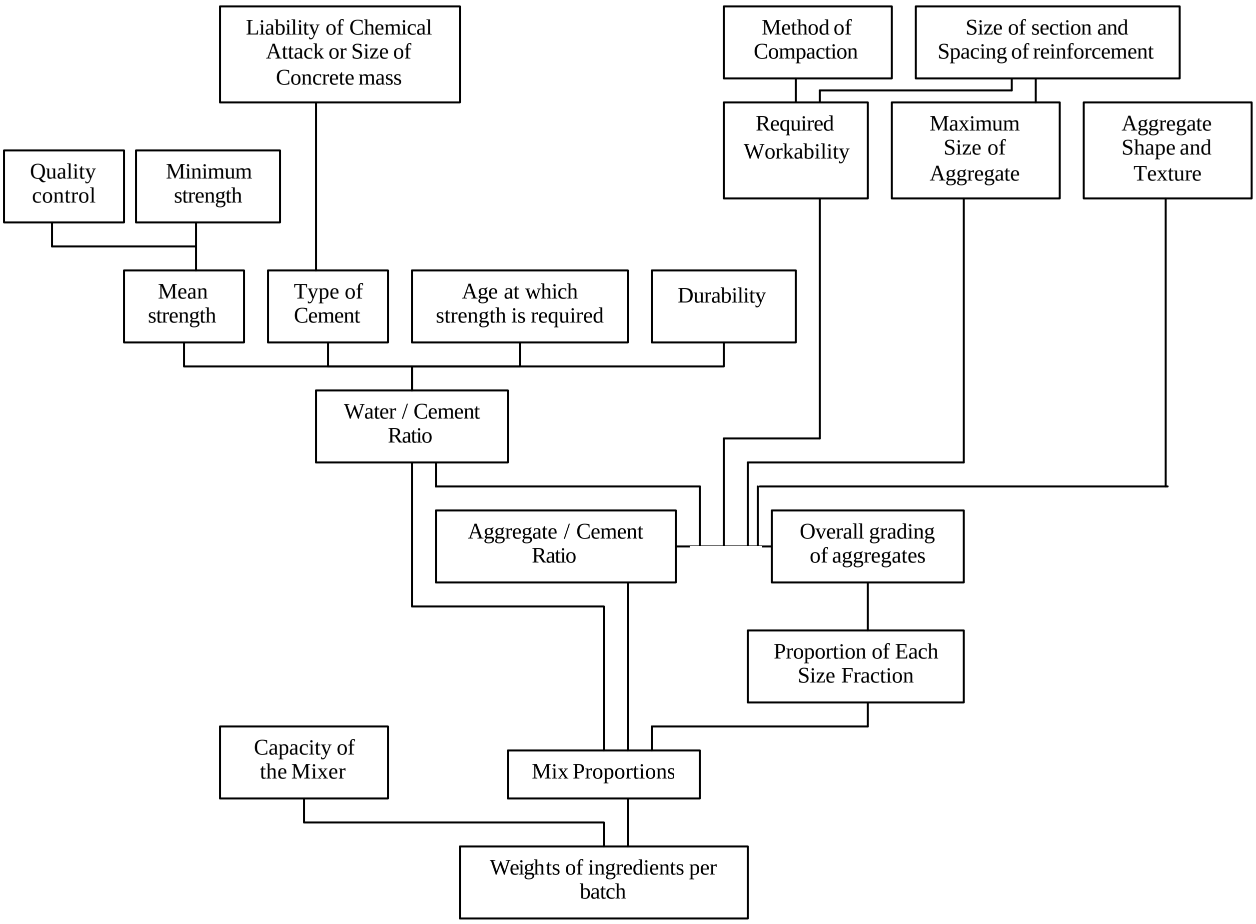



*Fig. 3.1 : Basic Factors in the Process of Mix Design*

However various methods used presently interpret these factors differently although the outcome may be satisfactory for all methods.

## 3.4 Different Mix Design Methods

Throughout the journey of time, men has developed many Design Methods for Concrete construction. Some of such methods are –

- BS Method of Mix Design
- ACI Method of Mix Design
- Minimum Void Method of Mix Design
- Sieve Analysis Method of Mix Design
- Trial Mixture Method of Mix Design
- Grading Curve Method of Mix Design
- Arbitrary Method of Mix Design

Among these methods, BS method and ACI methods are the mostly used methods.

**BS Method of Mix Design**

The BS method of Mix Design is based on a combination of British method (1987), Current British Method (1981) and Modified Road Note No. 4 method. It is developed by Teychenne, DC, Franklin, RE and Entray, Re of BRE, TRRL and CCA or UK. – Under DoE, BRE, TRE. The method uses SI units and is published by HMSO.

The principle of this method is to obtain a mix proportion in an attempt to produce concrete having the required workability and strength.

**ACI Method of Mix Design**

This is the most common method in use and is established by ACI recommended practice 211.1. It has advantages of simplicity in that it applies equally well and with more or less identical procedure irrespective of the shape and weight of aggregate and air entrainment feature of concrete.

## 3.5 ACI Method of Mix Design

### 3.5.1 General

In usual practice ACI method of mix design is actually the combination of experience and laboratory investigation aided absolute method of mix design. However, it must be remembered that this method will (like other design methods) provide only a first approximation of proportions, which must be checked by trial batches to adjust as necessary to produce the desired concrete characteristics. Once sufficient experience with local materials is occurred the ACI method should be modified to take their properties into account.

### 3.5.2 Scope

This standard practice describes methods for selecting proportions for hydraulic cement concrete made with and without other cementitious materials and chemical admixtures.

This concrete consists of normal and high-density aggregates. Hydraulic cements referred to in this standard practice are Portland cement and blended cement. The standard does not include proportioning with condensed silica fume.

The method provides a first approximation of proportions intended to be checked by trial batches in the laboratory or field and adjusted, as necessary, to produce the desired characteristics of the concrete.

### 3.5.3 Background material investigation

In ACI method of mix design the data to be collected are-

1. Fineness modulus of selected fine aggregate.
2. Unit weight of dry (SSD) nodded coarse aggregate.
3. Specific gravity of fine and coarse aggregate.
4. Absorption characteristics of both coarse and fine aggregate.
5. Specific gravity of cement.

### 3.5.4 Procedure

**a. Choice of Slump:**

If slump is not specified, a value appropriate for the work can be selected from the Table below. The slump ranges shown apply when vibration is used to consolidate the concrete. Mixes of the stiffest consistency that can be placed efficiently should be used.

**b. Choice of Maximum Aggregate Size**

Large nominal maximum sizes of well graded aggregates have less voids than smaller sizes. Hence, concretes with the larger-sized aggregates require less mortar per unit volume of concrete. Generally, the nominal maximum size of aggregate should be the largest that is economically available and consistent with dimensions of the structure.

The limitations on maximum aggregate size are:

I. For reinforced (or prestressed) concrete the maximum size should nor exceed one-fifth of the minimum dimension between forms or three-forth of the minimum clear spacing between reinforcements or between the reinforcement and the form work.

II. For slabs on grade, the maximum size may not exceed one-third the slab depth.

**Table 3.1: Recommended Slumps for various types of costruction**

| **Types of Construction** | **Slump(in)** | | **Slump (mm)** | |
|---|---|---|---|---|
| | **Max.[a]** | **Min.** | **Max.[a]** | **Min.** |
| Reinforced foundation walls and footings | 3 | 1 | 80 | 20 |
| Plain footings, caissons, and substructure walls | 3 | 1 | 80 | 20 |
| Beams and reinforced walls | 4 | 1 | 100 | 20 |
| Building columns | 4 | 1 | 100 | 20 |
| Pavements and slabs | 3 | 1 | 80 | 20 |
| Mass concrete | 3 | 1 | 80 | 20 |

[a] may be increased in. (25 mm) for methods of consolidation other than vibration.

**c. Estimation of mixing water and air content:**

The quantity of water per unit volume of concrete required to produce a given slump is dependent on:

1. The nominal maximum size.

2. Particle shape.

3. Grading of the aggregates.

4. The concrete temperature.

5. The amount of entrained air and

6. The use of chemical admixtures.

Slump is not greatly affected by the quantity of cement or cementitious materials within normal use levels (under favorable circumstances the use of some finely divided mineral admixtures may lower water requirements slightly). The Table given below provides estimates of required mixing water for concrete made with various maximum sizes of aggregate, with and without air entrainment.

**Table 3.2: Approximate mixing water and air content requirements for different slumps and nominal maximum sizes of aggregates** [a,b/]

| Water, lb/yd$^3$ (g/m$^3$) of concrete for indicated nominal maximum sizes of aggregates | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Slump, in. | 1/8 in. | 1/2 in | 3/4 in. | 1½in | 1 in | 2[c/] in | 3[c/] in | 6[c/] in |
| Non-air-entrained concrete | | | | | | | | |
| 1 to 2 | 350 | 335 | 315 | 300 | 275 | 260 | 220 | 190 |
| 3 to 4 | 385 | 365 | 340 | 325 | 300 | 285 | 245 | 210 |
| 6 to 7 | 410 | 385 | 360 | 340 | 315 | 300 | 270 | - |
| More than 7 | - | - | - | - | - | - | - | - |
| Approximate amount of entrapped air in non-air-entrained concrete, percent | 3 | 2.5 | 2 | 1.5 | 1 | 0.5 | 0.3 | 0.2 |
| Air-entrained concrete | | | | | | | | |
| 1 to 2 | 305 | 295 | 280 | 270 | 250 | 240 | 205 | 180 |
| 3 to 4 | 340 | 325 | 305 | 295 | 275 | 265 | 225 | 200 |
| 6 to 7 | 365 | 345 | 325 | 310 | 290 | 280 | 260 | - |
| More than 7 | - | - | - | - | - | - | - | - |
| Recommended averages total air content, % for level of exposure: | | | | | | | | |
| Mild | 4.5 | 4.0 | 3.5 | 3.0 | 2.5 | 2.0 | 1.5[a/] | 1.0[a/] |
| Moderate | 6.0 | 5.5 | 5.0 | 4.5 | 4.5 | 4.0 | 3.5[a/] | 3.0[a/] |
| Extreme | 7.5 | 7.0 | 6.0 | 6.0 | 5.5 | 5.0 | 4.5[a/] | 4.0[a/] |

[a] Adapted from ACI 211.1.

[b] These qualities of mixing water are for use in computing cement factors for trial batches. They are maxima for reasonably well-shaped, angular, coarse aggregates graded within limits of accepted specifications.

[c] The slump values of concrete containing aggregate larger than 11/2 in. are based on slump tests made after removal of particles larger than 11/2 in.

Depending on aggregate texture and shape, mixing water requirements may be somewhat above or below the tabulated values, but they are sufficiently accurate for the first estimate. The differences in water demand are not necessarily reflected in strength since other compensating factors may be involved. A rounded and an angular coarse aggregate, both well and similarly graded and of good quality, can be expected to produce concrete of about the same compressive strength for the same cement factor in spite of differences in w/c or w/(c+p) resulting from the different mixing oater requirements. Particle shape is not necessarily an indicator that an aggregate will be either above or below in its strength-producing capacity.

**d. Water/cement ratio:**

The required w/c or w/(c + p) is determined not only by strength requirements but also by factors such as durability. Since different aggregates, cements, and cementitious materials generally produce different strengths at the same w/c or w/(c + p), it is highly desirable to have or to develop the relationship between strength and w/c or w/(c + p) for the materials actually to be used. In absence of strength versus water/cement ratio data for the specific materials a conservative estimate can be made for the expected 28 day compressive strength from Table 3.3. However, these values should confirm to the ACI water/cement requirement (Table 3.4) for sever exposure conditions recommended from durability point of view.

**Table 3.3**: **Relationships between water/cement ratio and compressive strength of concrete** [a/]

| Compressive strength at 28 days, psi [b/] | Water/Cement ratio, by weight | |
|---|---|---|
| | Non-air-entrained concrete | Air-entrained concrete |
| 6000 | 0.41 | - |
| 5000 | 0.48 | 0.40 |
| 4000 | 0.57 | 0.48 |
| 3000 | 0.68 | 0.59 |
| 2000 | 0.82 | 0.74 |

[a/] Adapted from ACI 211.1. Reproduced with permission.

[b/] Values are estimated average strengths for concrete containing not more than the percentage of air shown in Table 9.2. strength is based on 6'12 in. cylinders moist-cured in accordance with ASTM C31.

**Table 3.4**: **Maximum permissible water/cement ratios for concrete in sever exposures** [a,b/]

| Type of structure | Structure wet continuously or frequently and exposed to freezing and thawing [c/] | Structure exposed to seawater or sulfates |
|---|---|---|
| Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 1 in. cover over steel. | 0.45 | 0.40 [d/] |
| All other sections. | 0.50 | 0.45 [d/] |

[a/] From ACI 211.1. Reproduced with permission.

[b/] Based on report of ACI Committee 201, Durability of Concrete in Service.

[c/] Concrete should also be air-entrained.

[d/] If sulfate-resisting cement (Type 11 or Type V of ASTM C150) is used, permissible water/cement ratio may be increased by 0.05.

**e. Calculation of cement:**

The amount of cement per unit volume of concrete is determined by dividing the estimated water requirement by the water/cement ratio. Water/cement ratio depends solely upon the compressive strength desired and table 3.3 and 3.4 are used for this purpose. However this should be in excess of the recommended minimum cement content (Table 3.5) for specified compressive strength less than 3600 psi to ensure satisfactory ending, good quality of vertical surfaces, sufficient workability protection against low strength due to increased water demands at the job sites etc.

**<u>Table 3.5</u>: Maximum permissible water and minimum cement contents to be used when suitable test data are not available.**

| Specified compressive strength (Mpa) | Minimum cement content (kg/m$^3$)[b/] | | | | | |
|---|---|---|---|---|---|---|
| | Non-air-entrained concrete | | | Air-entrained concrete | | |
| | Nominal size aggregate (mm) | | | | | |
| | 10 | 20 | 40 | 10 | 20 | 40 |
| 15 | 285 | 250 | 225 | 290 | 255 | 235 |
| 20 | 325 | 290 | 260 | 335 | 300 | 270 |
| 25 | 365 | 320 | 290 | 390 | 340 | 315 |
| Maximum water (kg/m$^3$) | 200 | 180 | 160 | 170 | 150 | 140 |

**f. Estimation of coarse aggregate content:**

It has been found empirically that aggregates of essentially the same nominal maximum size and grading will produce concrete of satisfactory workability when a given volume of coarse aggregate, on an oven-dry-rodded basis, is used per unit volume of concrete. Appropriate values for this aggregate volume are given in Table 3.6. it can be seen that, for equal workability, the volume of coarse aggregate in a unit volume of concrete is dependent only on its nominal maximum size and the fineness modulus of the fine aggregate. Differences in the amount of mortar required for workability with different aggregates, due to differences in particle shape and grading, are compensated for automatically by differences in oven-dry-rodded void content.

**Table 3.6: Volume of coarse aggregate per unit of volume of concrete**

| Maximum size of aggregate | | Volume of dry-rodded coarse aggregate b/ per unit volume of concrete for different fineness moduli of sand | | | |
|---|---|---|---|---|---|
| **inch** | **mm** | **2.40** | **2.60** | **2.80** | **3.00** |
| 1/8 | 10 | 0.50 | 0.48 | 0.46 | 0.44 |
| ½ | 12.5 | 0.59 | 0.57 | 0.55 | 0.53 |
| ¾ | 20 | 0.66 | 0.64 | 0.62 | 0.60 |
| 1 | 25 | 0.71 | 0.69 | 0.67 | 0.65 |
| 1½ | 40 | 0.76 | 0.74 | 0.72 | 0.70 |
| 2 | 50 | 0.78 | 0.76 | 0.74 | 0.72 |
| 3 | 75 | 0.82 | 0.80 | 0.78 | 0.76 |
| 6 | 150 | 0.87 | 0.85 | 0.83 | 0.81 |

b/ volume are based on aggregates in dry-rodded condition as described in ASTM C29. For less workable concrete, such as required for concrete pavement construction, they may be increased about 10%. For more workable concrete, such as may sometimes be required when placement is to be by pumping, they may be reduced up to 10%.

### g. Estimation of fine aggregate content:

#### a) Mass (Weight) Method:

Weight of fresh concrete per unit volume is estimated from pervious experience with the materials in question; failing this, the weight may be obtained from table 3.7 as a first estimate.

An exact calculation of the weight of the concrete (fresh) can be obtained using the following equation ---

$$V = 16.85\, G_a (100 - A) + C (1 - G_a/G_c) - W (G_a - 1)$$

Where,

$V$ = Weight of fresh concrete, $lb/yd^3$.

$G_a$ = Weighted average bulk specific gravity (SSD) of combined fine and coarse aggregate, assuming reasonable weight proportions.

$G_c$ = Specific gravity of cement.

A = Air content, percentage.

W = Mixing water requirement, lb/yd$^3$.

C = Cement requirement, lb/yd$^3$.

**Table 3.7: First estimation of weight of fresh concrete**

| Maximum size of aggregate | | First estimate of concrete weight [b/] | | | |
|---|---|---|---|---|---|
| | | Non-air-entrained concrete | | Air-entrained concrete | |
| inch | mm | lb/yd$^3$ | kg/m$^3$ | lb/yd$^3$ | kg/m$^3$ |
| 1/8 | 10 | 3840 | 2285 | 3690 | 2190 |
| ½ | 12.5 | 3890 | 2315 | 3760 | 2235 |
| ¾ | 20 | 3960 | 2355 | 3840 | 2280 |
| 1 | 25 | 4010 | 2375 | 3900 | 2315 |
| 1½ | 40 | 4070 | 2420 | 3960 | 2355 |
| 2 | 50 | 4120 | 2445 | 4000 | 2375 |
| 3 | 70 | 4160 | 2465 | 4040 | 2400 |

[b/] values calculated by Eqs. (9.4) and (9.5) for concrete containing 550 lb/yd$^3$ (330 kg/m$^3$) of cement, slump of 3 to 4 in. (75 to 100 mm), and aggregate bulk specific gravity of 2.7.

If the first estimate of the weight of the fresh concrete is not very good, an iterative procedure may be required in order to obtain $G_a$. The weight of fine aggregate is then the difference between the total weight of the fresh concrete and the weight of the other ingredients

.

**b) Volume Method:**

This is the preferred method, as it is a some-what exact procedure, which requires a knowledge of the volumes displaced by the various ingredients. That is the volume of the cement, water, air and coarse aggregate are subtracted from the total volume the difference is the volume of fine aggregate. The weight of the aggregate can then be obtained by multiplying this volume by the density of the fine aggregate.

In equation form this can be presented as follows

$$W + C/G_c + A_{ca}/G_{ca} + A_f/G_f = 62.5 \times 27 \times (1 - A/100)$$

Where,

| | | |
|---|---|---|
| $W$ | = | Mixing water requirement, lb/yd$^3$. |
| $C$ | = | Cement requirement, lb/yd$^3$. |
| $G_c$ | = | Specific gravity of cement. |
| $A_{ca}$ | = | Coarse aggregate content, lb/yd$^3$ (SSD). |
| $G_{ca}$ | = | Bulk specific gravity (SSD) of coarse aggregate. |
| $A_f$ | = | Fine aggregate content (to be estimated), lb/yd$^3$. |
| $G_f$ | = | Bulk specific gravity (SSD) of fine aggregate. |
| $A$ | = | Air entrained, percentage. |

The aggregate calculations given above are best carried out using SSD weight, but they can be done by using oven-dry weights as well.

### h. Adjustment for moisture in the aggregates:

The actual water content of the paste will be affected by the moisture content of the aggregates. If these are air-dry, they will absorb some water, thereby effectively lowering the water/cement ratio and reducing the workability. On the other hand, if the aggregates contain free moisture on their surface, they will contribute some of their surface moisture to the paste, increasing both the water/cement ratio and the workability and strength. Therefore these effects must be estimated and the mix adjusted to take then into account.

### i. Trial batch:

Using the estimated proportion of all the ingredients a trial batch is prepared, using as much water as is needed to reach the desired slump (but not exceeding the permissible water/cement ratio). The concrete thus produced should be tested for slump, unit weight, yield, air content, segregation tendencies, finishing characteristics and 28 day compressive (or flexural) strength. Adjustment can now be made in the batch proportions for those requirements, which are not satisfied by the original estimate—

a) If slump is incorrect, a new water content can be estimated from the observation that an increase or decrease approximately 1 inch. If the correct slump is obtained at a lower water content, it is permissible to reduce the cement content to reach the design water/cement ratio, consistent with any specified limitations on cement content. However, unless this will achieve a substantial saving in cement (which might indicate that mix should be entirely redesigned) it is probably advisable not to reduce the cement content. If the water content must be increased to obtain the desired slump, then the water/cement ratio will also be increased. In this case additional cement must be added until the design water/cement ratio is again achieved (or the entire mix redesigned). In both the cases, new batch weights should also be calculated, since the concrete volume has now been changed.

b) If the desired amount of air entrapment was not achieved, the amount of air-entrapment admixture should be re-estimated. The mixing water required should then be increased or decreased by 5 $lb/yd^3$ for each increase or decrease of 1 percent air entrapment, because of the influence of air entrapment on workability.

c) If the weight method of proportioning (not preferred) is used and if the estimated weight of fresh concrete is incorrect, this can be re-estimated from the unit weight of the trial batch, making allowance for the necessary changes in air content.

d) Any adjustment will change the yield, and therefore new batch weight must be calculated following the forgoing procedure from fifth step on.

### 3.5.5 ACI manual of concrete practice- 1994

**The Design Steps:**

**Step1: Choice of slump.**

For type of construction & compaction, determine slump. (Table 3.1)

**Step2: Choice of maximum aggregate size**.

From structural limitations and economy determine maximum size.

**Step3: Estimating mixing water and air content.**

For slump; maximum size, aggregate shape determine mixing water and air content from Table 3.2 for non-air & with exposure condition for air-entrained concrete.

**Step4: Selection of w/c ratio.**

For strength and air condition, determine w/c from Table 3.3 or 3.4

**Step5: Calculation of cement content**

For water content and w/c ratio, determine cement content.

**Step6: Estimation of coarse aggregate content.**

For maximum aggregate size and Fineness Modulus of fine aggregate, determine the volume of coarse aggregate (Table 3.6)

**Step7: Estimation of fine aggregate content.**

- For maximum size and air condition, determine weight of fresh concrete. (Table 6.3.7.1).

  F.A. wt. = wt. of fresh concrete – wt of (C.A, cement & water).

- Volume of F.A. =Vol. of concrete – vol. of (C.A. + Cement + Air).

**Step8: Adjustment for aggregate moisture.**

For aggregate moisture condition, adjust C.A., F.A. and mixing water.

**Step9: Adjustment of trial batch.**

For batch weights mix concrete, measure slump, adjust and cast specification for testing.

Chapter 4

# LABORATORY ACTIVITIES AND TEST RESULTS

## 4.1 General

In order to attain the objectives of this research, following activities were undertaken –

- A through survey of the related literatures was carried out. The properties of the constituent materials of concrete, methods of investigation of materials, methods of proportioning of concrete mixes and properties of hardened concrete were covered in the literature review. The main points of this literature survey are already represented in Chapter 2 and Chapter 3.
- Investigations of the materials were done and relevant material characteristics were evaluated.
- Mix designs have been performed using broken brick chips as coarse aggregate and Sylhet Sand as fine aggregate for one batch and crushed stone as coarse aggregate and Sylhet Sand as fine aggregate for the other batch. Both batches were prepared according to the ACI method of Mix Design.
- Casting of Concrete was done according to the mix design results achieved in accordance with the ACI method.

The activities requiring laboratory work conformed to specifications stated by relevant regulatory agencies.

The details of this investigation are presented in the next sections of this chapter.

## 4.2 Material Investigation

- **Fine Aggregate**

- Material : Sylhet Sand

- Grain Size Analysis :

  Weight of Sample : 100 gm

Table 4.1 : Grain Size Distribution of Sand determined by ASTM Method

| Sieve Size | Sieve Opening | Amount Retained (gm) | % Retained | Cumulative % Retained | % Finer |
|---|---|---|---|---|---|
| #4 | 2.36 mm | 5.4 | 1 | 1 | 99 |
| #8 | 1.18 mm | 14.26 | 3 | 4 | 96 |
| #16 | 0.6 mm | 74.04 | 15 | 19 | 81 |
| #30 | 0.3 mm | 146.26 | 29 | 48 | 52 |
| #50 | 0.15 mm | 183.23 | 37 | 85 | 15 |
| #100 | 0.075 mm | 66.35 | 13 | 98 | 2 |
| Pan | | 10.46 | - | - | - |
| Total | | 500 | 100 | 255 | |

Fineness Modulus = 255 / 100

= 2.55

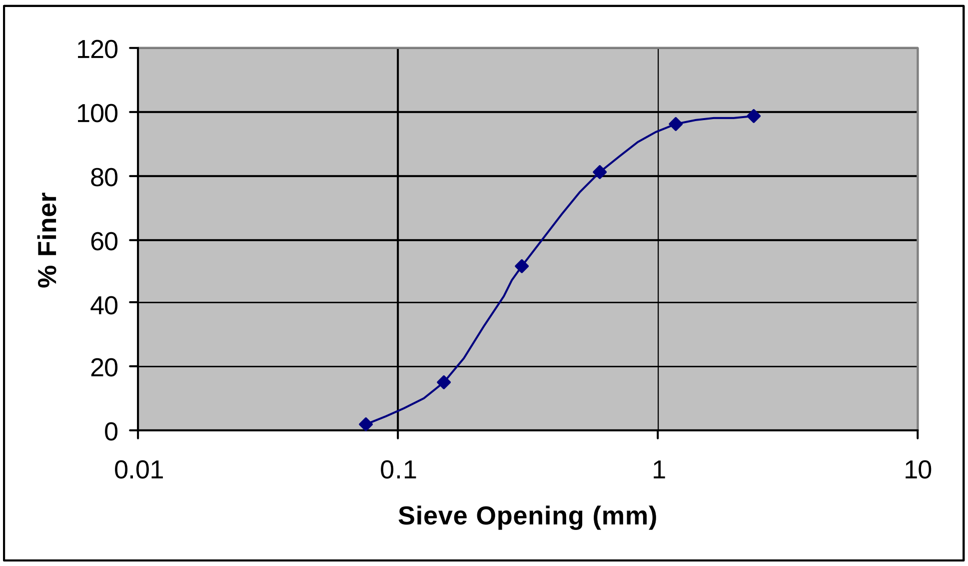



*Fig: Gradation Curve for Fine Aggregate – Sylhet Sand*

- Bulk Specific Gravity Determination :

  Weight of oven-dry specimen in air, A = 493 gm

  Weight of pycnometer filled with water, B = 1281 gm

Weight of saturated surface dry (SSD) specimen, S = 500 gm

Weight of pycnometer with specimen

and water to calibration mark, C = 1587 gm

Bulk Specific Gravity (SSD) = S / (B+S–C )

= 500 / (1281+500-1587)

= 2.58

Bulk Specific Gravity (OD) = A / (B+S–C )

= 493 / (1281+500-1587)

= 2.54

Absorption, % = [(S–A ) / A] * 100

= [(500-493) / 493] * 100

= 1.42

- Bulk Unit Weight Determination :

Weight of measure, A = 8.8 lb

Weight of measure

filled with specimen, B = 54.5 lb

Volume of measure, V = 0.5 cft

Unit Weight (SSD) = (B–A ) / V

= (54.5–8.8) / 0.5

= 91.4 pcf

➢ **Coarse Aggregate : Broken Brick Chips**

- <u>Grain Size Analysis :</u>

Weight of sample = 4 kg

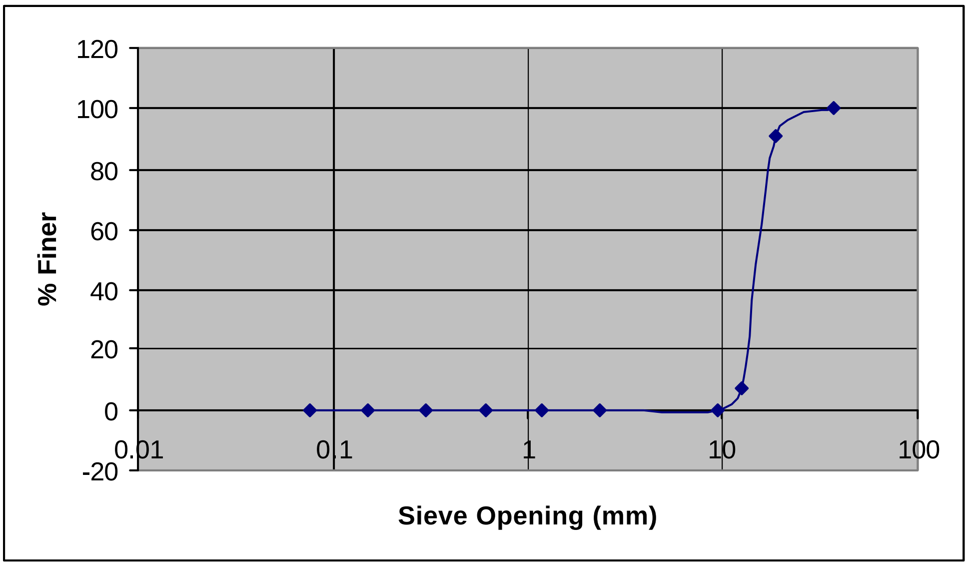
Nominal Maximum Size = 1” down

Table 4.2 : Grain size distribution of brick chips determined by ASTM method

| Sieve Size | Sieve Opening | Amount Retained (kg) | % Retained | Cumulative % Retained | % Finer |
|---|---|---|---|---|---|
| 1.5” | 37.5 mm | 0 | 0 | 0 | 100 |
| 3/4” | 19 mm | 0.366 | 9 | 9 | 91 |
| 1/2” | 12.7 mm | 3.375 | 84 | 93 | 7 |
| 3/8” | 9.5 mm | 0.259 | 7 | 100 | 0 |
| #4 | 2.36 mm | 0.005 | 0 | 100 | 0 |
| #8 | 1.18 mm | 0 | 0 | 100 | 0 |
| #16 | 0.6 mm | 0 | 0 | 100 | 0 |
| #30 | 0.3 mm | 0 | 0 | 100 | 0 |
| #50 | 0.15 mm | 0 | 0 | 100 | 0 |
| #100 | 0.075 mm | 0 | 0 | 100 | 0 |
| Total | | 4.000 | 100 | 802 | - |

Fineness Modulus = 802 / 100

= 8.02




*<u>Fig: Gradation Curve for Coarse Aggregate – Broken Brick Chips</u>*

- Bulk Specific Gravity Determination

Weight of oven-dry test sample in air, A = 4.68 lb

Weight of saturated surface dry test sample in air, B = 5.00 lb

Weight of saturated test sample in water, C = 3.00 lb

Bulk Specific Gravity (SSD) = B / (B–C)

= 5 / (5-3)

= 2.5

Bulk Specific Gravity (OD) = A / (B–C)

= 4.68 / (5–3)

= 2.34

Absorption, % = [(B–A ) / A] * 100

= [(5.00–4.68) / 4.68] * 100

= 6.7

- Bulk Unit Weight Determination

Weight of measure, A = 8.8 lb

Weight of measure filled with specimen, B = 47.3 lb

Volume of measure, V = 0.5 cft

Unit Weight (SSD) = (B–A) / V

= (47.3–8.8) / 0.5

= 77 pcf

➢ **Crushed Stone**

- Grain Size Analysis :

Weight of Sample : 6 kg

Nominal Maximum Size = 1”

Table 4.3 : Grain size distribution of crushed stone determined by ASTM method

| Sieve Size | Sieve Opening | Amount Retained (kg) | % Retained | Cumulative % Retained | % Finer |
|---|---|---|---|---|---|
| 1.5” | 37.5 mm | 0 | 0 | 0 | 100 |
| 3/4” | 19 mm | 2.421 | 41 | 41 | 59 |
| 1/2” | 12.7 mm | 1.558 | 26 | 67 | 33 |
| 3/8” | 9.5 mm | 0.903 | 15 | 82 | 18 |
| #4 | 2.36 mm | 1.086 | 18 | 100 | 0 |
| #8 | 1.18 mm | 0 | 0 | 100 | 0 |
| #16 | 0.6 mm | 0 | 0 | 100 | 0 |
| #30 | 0.3 mm | 0 | 0 | 100 | 0 |
| #50 | 0.15 mm | 0 | 0 | 100 | 0 |
| #100 | 0.075 mm | 0 | 0 | 100 | 0 |
| Total | | 6.000 | 100 | 790 | - |

Fineness Modulus = 790 / 100

= 7.90

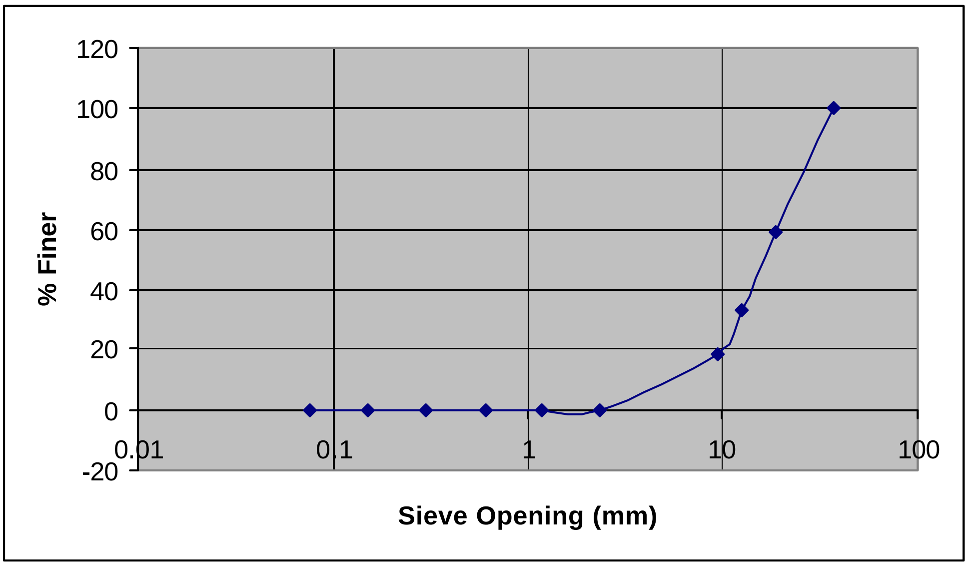



*Fig : Gradation Curve for Coarse Aggregate – Stone Chips*

- Bulk Specific Gravity Determination :

Weight of oven dry test sample in air, A = 4.75 lb

Weight of saturated surface dry test sample in air, B = 5.00 lb

Weight of saturated test sample in water, C = 3.05 lb

Bulk Specific Gravity (SSD) = B / (B–C)

= 5 / (5–3.05)

= 2.56

Bulk Specific Gravity (OD) = A / (B–C)

= 4.75 / (5.00–3.05)

= 2.44

Absorption, % = [(B–A) / A] * 100

= [(5.00–4.75) / 4.75] * 100

= 5.26

- Bulk Unit Weight Determinaion :

Weight of measure, A = 8.5 lb

Weight of measure filled with specimen, B = 58.5 lb

Volume of measure, V = 0.5 cft

Unit Weight (SSD) = (B–A) / V

= (58.5–8.5) / 0.5

= 100 pcf

## 4.3 Mix Design Computations and Preparing Concrete Specimen

Reference: ACI Manual of Concrete Practice – 1994

**A. Trial Mix 1**

Materials :

i) Coarse Aggregate – Crushed Stone

ii) Fine Aggregates – Sylhet Sand

iii) Portland Cement

Material Investigation Data :

Coarse Aggregate :

| | |
|---|---|
| Fineness Modulus | : 7.88 |
| Unit Weight | : 100 pcf (SSD) |
| Specific Gravity | : 2.56 (SSD) |
| | : 2.44 (OD) |

Fine Aggregate :

| | |
|---|---|
| Fineness Modulus | : 2.543 |
| Unit Weight | : 91.4 pcf (SSD) |
| Specific Gravity | : 2.58 (SSD) |
| | : 2.54 (OD) |

Design Strength at 28 Days : 4000 psi

Procedure :

Step – 1 : Choice of Slump

For construction of general purpose concrete: 1 ~ 2 inch

[From Table: 3.1]

Step – 2 : Choice of Maximum Aggregate Size

Maximum Aggregate Size : 1 inch

Step – 3 : Estimation of Mixing Water and Air Content

For Slump = 1 ~ 2 inch

Maximum Aggregate Size = 1 inch

Non Air Entrained Concrete,

Water Content = 300 $lb/yd^3$

Air Content = 1.5 percent [From Table: 3.2]

Step – 4 : Estimation of Water / Cement Ratio

For Design Strength = 4000 psi (28 days)

Moderate Exposure Level,

Water / Cement Ratio – 0.57 [From, Table: 3.3]

Step – 5 : Calculation of Cement Content

Cement Content $= {}^{300} / {}_{0.57}$

$= 526\ lb/yd^3$

Step – 6 : Estimation of Coarse Aggregate

For Fineness Modulus of Fine Aggregate = 2.543

Nominal Maximum Aggregate Size = 1 inch

Bulk volume of Coarse Aggregate (OD)

per unit volume of concrete = 0.6957

[From, Table 3.6]

Volume of Coarse Aggregate = 0.6957 * 27

= 18.7839 $ft^3/yd^3$

Unit weight of Coarse Aggregate (OD) = (2.44 / 2.56 ) * 100

= 95.3 pcf (OD)

Weight of Coarse Aggregate = 95.3 * 18.7839

= 1790 $lb/yd^3$

<u>Step – 7 : Estimation of Fine Aggregate</u>

For Maximum Aggregate Size = 1 inch

Non Air Entrained Concrete

Weight of Fresh Concrete = 4010 $lb/yd^3$ [From, Table 3.7]

Weight of Fine Aggregate = (4010 – 300 – 1790 – 526) $lb/yd^3$

= 1394 $lb/yd^3$

<u>Proportion By Weight</u>

Cement : F. A. : C. A. : Water = 526 : 1394 : 1790 : 300

= 1 : 2.65 : 3.40 : 0.57

## B. Trial Mix 2

Materials:

i) Coarse Aggregate – Brick Chips

ii) Fine Aggregate – Sylhet Sand

iii) Portland Cement

Material Investigation Data:

Coarse Aggregate :

| | |
|---|---|
| Fineness Modulus | : 8.02 |
| Unit Weight | : 77 pcf (SSD) |
| Specific Gravity | : 2.50 (SSD) |
| | : 2.343 (OD) |

Fine Aggregate :

| | |
|---|---|
| Fineness Modulus | : 2.543 |
| Unit Weight | : 91.4 pcf (SSD) |
| Specific Gravity | : 2.58 (SSD) |
| | : 2.54 (OD) |

Design Strength at 28 Days : 4000 psi

Procedure:

Step – 1 : Choice of Slump

For construction of general purpose concrete : 1 ~ 2 inch

[From Table: 3.1]

Step – 2 : Choice of Maximum Aggregate Size

Maximum Aggregate Size : 1 inch

Step – 3 : Estimation of Mixing Water and Air Content

For Slump = 1 ~ 2 inch

Maximum Aggregate Size = 1 inch

Non Air Entrained Concrete,

Water Content = 300 lb/yd$^3$

Air Content = 1.5 percent [From Table: 3.2 ]

Step – 4 : Estimation of Water / Cement Ratio

For Design Strength = 4000 psi (28 days)

Moderate Exposure Level,

Water / Cement Ratio – 0.57 [From Table 3.3]

Step – 5 : Calculation of Cement Content

Cement Content = $^{300} / _{0.57}$

= 526 lb/yd$^3$

Step – 6 : Estimation of Coarse Aggregate

For Fineness Modulus of Fine Aggregate = 2.543

Nominal Maximum Aggregate Size = 1 inch

Bulk volume of Coarse Aggregate (OD)

per unit volume of concrete = 0.6957

[From, Table 3.6]

Volume of Coarse Aggregate = 0.6957 * 27

= 18.7839 $ft^3/yd^3$

Unit weight of Coarse Aggregate (OD) = (2.343 / 2.5) * 77

= 72.16 pcf (OD)

Weight of Coarse Aggregate = 72.16 * 18.7839

= 1356 $lb/yd^3$

Modified weight of Brick Aggregate (Equivalent to stone aggregate)

= 1356 * (100 / 77)

= 1761 lb/yd3

<u>Step – 7 : Estimation of Fine Aggregate</u>

For Maximum Aggregate Size = 1 inch

Non Air Entrained Concrete

Weight of Fresh Concrete = 4010 $lb/yd^3$ [From Table 3.7]

Weight of Fine Aggregate = (4010 – 300 – 1761 – 526) $lb/yd^3$

= 1423 $lb/yd^3$

<u>Proportion By Weight</u>

Cement : F. A. : C. A. : Water = 526 : 1423 : 1356 : 300

= 1 : 2.71 : 2.58 : 0.57

**Proportion of Concrete Constituents ( 9 Cylinders of each batch)**

- <u>For Batch 1 : Stone Aggregate</u>

  Design Ratio –

  Cement : FA : CA : Water = 1 : 2.65 : 3.40 : 0.57

| Material | Oven Dry (OD) Basis | | Saturated Surface Dry (SSD) Basis | |
|---|---|---|---|---|
| | Actual Weight (lbs) | Weight to be taken (lbs) | Actual weight (lbs) | Weight to be taken (lbs) |
| Cement | 34.43 | 35.93 | 34.43 | 35.93 |
| F. A. | 91.24 | 95.21 | 92.68 | 99.70 |
| C. A. | 117.16 | 122.16 | 122.92 | 127.92 |
| Water | 19.63 | 20.48 | 19.63 | 20.48 |

- <u>For Batch 2 : Brick Aggregate</u>

  Design Ratio –

  Cement : FA : CA : Water = 1 : 2.70 : 2.58 : 0.57

| Material | Oven Dry (OD) Basis | | Saturated Surface Dry (SSD) Basis | |
|---|---|---|---|---|
| | Actual Weight (lbs) | Weight to be taken (lbs) | Actual weight (lbs) | Weight to be taken (lbs) |
| Cement | 34.43 | 36.37 | 34.43 | 36.37 |
| F. A. | 93.00 | 98.24 | 94.46 | 99.44 |
| C. A. | 88.75 | 93.75 | 94.70 | 99.70 |
| Water | 19.63 | 20.74 | 19.63 | 20.74 |

## 4.4 Test Results

The most common test of hardened concrete is the Compressive Strength Test. Concrete has very little tensile strength. It is primarily used in a compressive mode and therefore it has the compressive strength that is important in engineering practice. Also, it is assumed that most of the important properties of concrete are directly related; or at least, qualitatively related to its compressive strength. The structural design codes are also based mainly on the compressive strength of concrete. That's why, Compressive Strength Test is considered as the only necessary test for hardened concrete.

ASTM suggests some well defined standards to be maintained to test concrete for Compressive Strength. These includes :

| | |
|---|---|
| Specimen Diameter : | 6 inches |
| Specimen Height : | 12 inches |
| Tamping Rod Diameter : | 16 mm |
| No. of Tamping Per Layer : | 25 |
| Minimum Number of Layer: | 3 |
| Storage Temperature : | 16 – 27 $^{o}$c |
| Loading Rate : | 0.15 – 0.34 MPa / Sec |

Ends of the specimens have to be

capped by Gypsum Plastic or Sulpher Morter prior to loading.

Strength test at early ages are desirable during the first stages of concreting operations to aid in establishing the proper mix. Cylinder broken at 7 days will usually serve this purpose, although tests at even earlier ages often serve equally. Strength tests at higher ages are more indicative of the actual strength of concrete in the structure and are therefore more valuable for reference purpose.

In this case, two batches of concrete were casted in ACI method of mix design using Brick chips and Crushed stones as coarse aggregates. Each batch produced 9 cylindrical moulds as per ASTM standards. Three cylinders from each batch were tested for compressive strength at $7^{th}$ , $14^{th}$ and $28^{th}$ day. Failure pattern of the cylinder was also observed.

## 4.5 Presentation of Result

### A. Batch 1 : Crushed Stone as Coarse Aggregate

Design Strength : 4000 psi in 28 days

Casting Date : 30 – 06 – 2004

| Age (Days) | Specimen No. | Surface Area (sq. in) | Load (tons) | Compressive Strength (psi) | Average Compressive Strength (psi) |
|---|---|---|---|---|---|
| 7 | Cylinder 1 | 28.82 | 31 | 2151 | 2190 |
| | Cylinder 2 | 28.87 | 32 | 2217 | |
| | Cylinder 3 | 29.04 | 32 | 2204 | |
| 14 | Cylinder 1 | 29.02 | 44 | 3032 | 3080 |
| | Cylinder 2 | 28.94 | 44 | 3041 | |
| | Cylinder 3 | 29.04 | 46 | 3168 | |
| 28 | Cylinder 1 | 28.50 | 46 | 3228 | 3219 |
| | Cylinder 2 | 28.94 | 46 | 3179 | |
| | Cylinder 3 | 28.92 | 47 | 3250 | |

### B. Batch 2 : Broken Brick Chips as Coarse Aggregate

Design Strength : 4000 psi in 28 days

Casting Date : 30 – 06 – 2004

| Age (Days) | Specimen No. | Surface Area (sq. in) | Load (tons) | Compressive Strength (psi) | Average Compressive Strength (psi) |
|---|---|---|---|---|---|
| 7 | Cylinder 1 | 29.29 | 30 | 2049 | 2090 |
| | Cylinder 2 | 29.02 | 30 | 2068 | |
| | Cylinder 3 | 28.82 | 31 | 2151 | |
| 14 | Cylinder 1 | 28.97 | 36 | 2485 | 2546 |
| | Cylinder 2 | 28.50 | 36 | 2526 | |
| | Cylinder 3 | 28.94 | 38 | 2626 | |
| 28 | Cylinder 1 | 28.87 | 42 | 2979 | 2985 |
| | Cylinder 2 | 29.29 | 43 | 2936 | |
| | Cylinder 3 | 28.94 | 44 | 3041 | |

## 4.6 Discussion on Type of Failure

Most of the failures were observed to be of mortar failure type, which indicates the presence of excess sand in the concrete. Some specimen also showed combined type of failure, which indicates that the coarse aggregate in the concrete failed under loading. But the number of specimen showing combined failure was not that significant. Moreover, in those specimens where combined failure took place, mortar failure was predominant.

**Chapter 5**

# HIGH STRENGTH CONCRETE

## 5.1 Introduction

### 5.1.1 Historical Background

Although high-strength concrete is often considered a relatively new material, its development has been gradual over many years. As the development has continued, the definition of high-strength concrete has changed. In the 1950s, concrete with a compressive strength of 5000 psi (34 MPa) was considered high strength. More recently, compressive strengths approaching 20,000 psi (138 MPa) have been used in cast-in-place buildings. In recent years, the applications of high-strength concrete have increased, and high-strength concrete has now been used in many parts of the world. The growth has been possible as a result of recent developments in material technology and a demand for higher strength concrete.

### 5.1.2 Objective of the Study

High Strength Concrete is a special variety of High Performance Concrete. According to ACI Committee for High Strength Concrete,

> *Concrete that has a specified compressive strength for design of 6000 psi (41MPa) or more is known as High Strength Concrete or High Performance Concrete. This Concrete meets the special combination of performance and uniformity requirements that cannot be achieved routinely using conventional and normal mixing, placing and curing practice.*

The objective of this study was to focus specially upon the High Strength Concrete, its properties and constituents, decisive factors that controls its behavior in a construction and its potential and prospective as a construction material of the future, especially in context of Bangladesh.

As mentioned above, the definition of High Strength Concrete varies on a geographical basis. In regions where concrete with a compressive strength of 9000 psi (62 MPa) is already being produced commercially, High Strength Concrete might be in the range of 12,000 to 15,000 psi (83 to 103 MPa) compressive strength. However, in regions where the upper limit on commercially available material is currently 5000 psi (34 MPa) concrete, 9000 psi (62 MPa) concrete is considered as High Strength Concrete. Selection of material, concrete mix proportioning, batching, mixing, transporting, placing, and control procedures are applicable across a wide range of concrete strengths. The material properties and structural design considerations given in this report should be concerned with concretes having the highest compressive strengths.

## 5.2 Modern Breeds of Concrete

With the development of mankind, human are now capable of doing what he could not even dreamed of once. His knowledge, power, wisdom is at its best of all time. But yet, his quest for being better and better has never stopped. Whatever good he achieves does not satisfy him, it rather leaves him hungrier for a better achievement. In that process, old and conventional concrete is now out of date. Man now wants concrete with more and more capabilities. That’s why these new breeds of concrete have evolved for more specific operations, for helping mankind to continue its journey through time with more and more control and option. Combined these breeds constitutes the High Performance Concrete.

High Performance Concrete is one in which certain characteristics are developed for a particular application and environment, such as –

- Ease of placement
- Compaction without segregation
- Early age strength
- Long-term mechanical properties
- Permeability
- Density
- Heat of hydration

- Toughness
- Volume stability
- Long life in severe environments

Because many characteristics of high-performance concrete are interrelated, a change in one usually results in changes in one or more of the other characteristics.

### 5.2.1 High Workability Concrete

The workability of fresh concrete should be suitable for each specific application to ensure that the operations of handling, placing and compaction can be undertaken efficiently. The handling and placing properties of this sort of concrete mixes can be improved considerably by the use of cement replacement materials such as pulverized fuel ash or ground granulated blast-furnace slag. Further more, the use of admixtures such as water reducers and super plasticizers have beneficial effects on workability without compromising other concrete properties.

On site productivity can be greatly increased by utilizing Highly Workable Concretes. High Workability Concrete is especially suitable in the following applications:

- Inaccessible locations
- Large flat areas
- Underwater applications
- Pumping concrete over long distances

### 5.2.2 Self Compacting Concrete

SCC has been described as "the most revolutionary development in concrete construction for several decades". Originally developed to offset a growing shortage of skilled labor, it has proved beneficial economically because of a number of factors, including:

- faster construction
- reduction in site manpower
- better surface finishes
- easier placing

- improved durability
- greater freedom in design
- thinner concrete sections
- reduced noise levels, absence of vibration
- safer working environment

### 5.2.3 Foamed Concrete

Foamed concrete is a highly workable, low-density material which can incorporate up to 50% entrained air. It is generally self-leveling, self-compacting and may be pumped. Foamed concrete is ideal for filling redundant voids such as disused fuel tanks, sewer systems, pipelines, and culverts - particularly where access is difficult. It is a recognized medium for the reinstatement of temporary road trenches. Good thermal insulation properties make foamed concrete also suitable for sub-screeds and filling under-floor voids.

### 5.2.4 High Strength Concrete

The definition of High Strength Concretes is continually developing. Recently, compressive strengths approaching 138N have been used in cast-in-place buildings and are considered as High Strength Concrete. The major development in High Strength Concrete is it can withstand high compressive strength which further results in less concrete area. High-strength concrete columns can hold more weight and therefore be made slimmer than regular strength concrete columns, which allows for more useable space, especially in the lower floors of buildings.

### 5.2.5 Lightweight Concrete

Lightweight Concrete can be produced using a variety of lightweight aggregates. Lightweight aggregates originate from either:

- Natural materials like volcanic pumice
- The thermal treatment of natural raw materials like clay, slate or shale
- Manufacture from industrial by-products such as fly ash

- Processing of industrial by-products like FBA or slag

The required properties of the lightweight concrete will have a bearing on the best type of lightweight aggregate to use. If little structural requirement, but high thermal insulation properties are needed, then a light, weak aggregate can be used. This will result in relatively low strength concrete.

Lightweight aggregate concretes can however be used for structural applications, with strengths equivalent to normal weight concrete. The benefits of using lightweight aggregate concrete include:

- Reduction in dead loads making savings in foundations and reinforcement.
- Improved thermal properties.
- Improved fire resistance.
- Savings in transporting and handling pre-cast units on site.
- Reduction in formwork and propping

### 5.2.6 No-Fines Concrete

No-fines Concrete is obtained by eliminating the fine material sand, from the normal concrete mix. The single sized coarse aggregates are surrounded and held together by a thin layer of cement paste giving strength of concrete. The advantages of this type of concrete are –

- lower density
- lower cost due to lower cement content
- lower thermal conductivity
- relatively low drying shrinkage
- no segregation and capillary movement of water
- better insulating characteristics than conventional concrete because of the presence of large voids.

### 5.2.7 Waterproof Concrete

Water resistant concretes are impermeable to water and other fluids either above or below ground. They are high density concretes that incorporate fine particle cement replacements.

### 5.2.8 Autoclaved Aerated Concrete

Autoclaved Aerated Concrete was first commercially produced in 1923 in Sweden. Since then, AAC construction systems such as masonry units, reinforced floor/roof and wall panels and lintels have been used on all continents and every climatic condition. AAC can also be sawn by hand, sculpted and penetrated by nails, screws and fixings.

### 5.2.9 Fire Resistance Concrete

Concrete provides the best fire resistance of any building material. It does not burn, it cannot be 'set on fire' like other materials in a building and it does not emit any toxic fumes, smoke or drip molten particles when exposed to fire. Concrete and its mineral constituents enjoy the highest fire resistance classification.

This excellent fire performance is due in the main to concrete's constituent materials (i.e. cement and aggregates) which, when chemically combined, form a material that is essentially inert and has poor thermal conductivity. It is this slow rate of heat transfer that enables concrete to act as an effective fire shield not only between adjacent spaces but also to protect itself from fire damage.

The only potential risk to life safety from concrete in fire occurs in the form of spilling, which principally affects High Performance and Ultra High Performance Concrete. Even here, effective measures can be taken to reduce the probability of spilling.

## 5.3 Materials

The production of High Strength Concrete that consistently meets requirements for workability and strength development places more stringent requirements material selection than for lower strength concretes. Quality materials are needed and specifications require enforcement.

### 5.3.1 Cement

The choice of Portland cement for high-strength concrete is extremely important. Unless high initial strength is the objective, such as in pre-stressed concrete, there is no need to use Type III cement. Furthermore, within a given cement type, different brands will have different strength development characteristics because of the variations in compound composition and fineness. If the tri-calcium silicate content varies by more than 4 percent, the ignition loss by more than 0.5 percent, or the fineness by more than 375 cm2/g (Blaine), then problems in maintaining a uniform high strength may result. Sulfate (SO,) levels should be maintained at optimum with variations limited to ± 0.20 percent.

The effect of cement characteristics on water demand is more noticeable in High Strength Concretes because of the higher cement contents. High cement contents can be expected to result in a high temperature rise within the concrete. When the temperature rise is expected to be a problem, Type II (Low Heat of Hydration) cement can be used, provided it meets the strength-producing requirements. A further consideration is the optimization of the cement-admixture system. The exact effect of a water reducing agent on water requirement, for example, will depend on the cement characteristics. Strength development will depend on both cement characteristics and cement content.

### 5.3.2 Aggregates

#### 5.3.2.1 Fine Aggregate

**Grading**

Fine aggregates with a rounded particle shape and smooth texture have been found to require less mixing water in concrete and for this reason are preferable in high-strength concrete. Sand with a Fineness Modulus below 2.5 gives concrete a sticky consistency, making it difficult to compact. On the other hand, sand with a Fineness Modulus of about 3.0 gives best workability and compressive strength. Thus, it is sometimes useful to increase the fineness modulus of the fine aggregate. However, it has been seen that the sand gradation has no significant effect on early strengths but at later ages and consequently higher levels of strength, the gap-graded sand mixes exhibited lower strengths than the standard mixes.

#### 5.3.2.2 Coarse Aggregate

**Grading**

For optimum compressive strength with high cement content and low water-cement ratios, the maximum size of coarse aggregate should be kept to a minimum, within ½ inch (12.7 mm) to 1 inch (25.4 mm). The reason for this is the fact that, in high strength concrete, strength increases also for the reduction of average bond stress due to the increased surface area, contributed by individual aggregate. Also for smaller aggregates, stress concentration around the particles is less than average, which is caused by differences between the elastic moduli of the paste and the aggregate. Also, mechanical bond between the aggregate surface and concrete plays significant role.

**Absorption**

Curing is highly important in the production of High Strength Concrete. The general concept for High Strength Concrete is to keep the water-cement ratio as low as possible. This leads to the implementation of lowest possible amount of water in fresh concrete. But during the mixing, transporting, placing and by the time of early hydration, concrete loses some portion of this water (about 1/4$^{th}$ of total water). Thus, hydration of concrete during the late age is seriously hampered. If the coarse aggregate used in concrete has high water absorbing capability, it can act as small reservoir for concrete whenever there is a scare of water, and thus helping final stages of hydration of concrete, which farther results in more and more strength in concrete.

**Aggregate Strength**

It seems obvious that High Strength Concrete would require High Strength Aggregates and, to some extent, this is a fact. But, for some aggregates, a point is reached beyond which further increases in cement content produce no increase in the compressive strength of the concrete. This is due to having reached the limit of the bonding potential of that cement aggregate combination.

### 5.3.3 Water

The requirements for water quality for High Strength Concrete are no more stringent than those for conventional concrete. Usually, water for concrete is specified to be of potable quality. However, in case of scarce of fair quality of water at the construction site, test concretes should be made with the available water and the resulting concrete should be compared with concrete made with distilled water. In that case, specimens should be tested for compressive strength at 7 and 28 days. If those made with the available water are at least equal to 90 percent of the compressive strength of the specimens made with distilled water, the water then can be considered acceptable.

### 5.3.4 Admixtures

Admixtures are widely used in the production of High Strength Concretes. These materials include air-entraining agents and chemical and mineral admixtures. Selection of type, brand and dosage rate of all admixtures should be based on performance with the other materials being considered or selected for use on the project. Significant increases in compressive strength, control of rate of hardening, accelerated strength gain, improved workability, and durability are contributions that can be expected from the admixture or admixtures chosen.

#### 5.3.4.1 **Air–Entraining Admixtures**

Use of air-entraining admixtures is recommended to enhance durability of concrete subjected to freezing climate and thawing while wet. As compressive strengths increase and water-cement ratios decrease, air-void parameters improve and entrained air percentages can be set at the lower limits of the acceptable range. Entrained air has the effect of reducing strength, particularly in high-strength mixtures, and for that reason it has been used only where there is a concern for durability.

#### 5.3.4.2 Retarders

A retarder is frequently beneficial in controlling early hydration of fresh concrete. A retarder can control the rate of hardening in the forms to eliminate cold joints and provide more flexibility in placement schedules. An increase in retarder dosage to control the rate of hardening will provide some mitigation of the temperature induced reduction. Conversely, dosages should be decreased as temperatures decline.

#### 5.3.4.3 Normal Setting Water Reducers

Conventional water-reducing admixtures will provide strength increases without altering rates of hardening. Their selection should be based on strength performance. Increases in dosage above the normal amounts will generally increase strengths, but may extend setting times.

#### 5.3.4.4 High Range Water Reducers

High-range water reducing admixtures imparts high-strength performance, particularly at early ages (24-hour). Matching the admixture to the cement, both in type and dosage rate, is important. Use of a High Range Water Reducing Admixtures in high-strength concrete may serve the purpose of increasing strength at the slump or increasing slump.

#### 5.3.4.5 Accelerators

Accelerators are not normally used in High-Strength Concrete unless early form removal is critical. High Strength Concrete mixtures can provide strengths adequate for vertical form removal on walls and columns at an early age. Accelerators used to increase the rate of hardening will normally be counter productive in long-term strength development.

#### 5.3.4.6 Admixture Combinations

Combinations of High Range Water Reducing Admixtures with normal-setting water reducers or Retarders have become common to achieve optimum performance at lowest cost. Improvements in strength gain and control of setting times and workability are possible with optimized combinations. In certain circumstances, combinations of normal-setting or retarding water reducing admixtures plus an accelerating admixture have also been found to be useful.

## 5.4 Mix Proportions for High Strength Concrete

High-strength concrete mix proportioning is a more critical process than the design of normal strength concrete mixtures and has varied widely depending upon many factors, such as – strength level required, test age, material characteristics, and type of application influences mix proportions. In addition to that, economics, structural requirements, manufacturing practicality, anticipated curing environment, and even the time of year affect the selection of mix proportions.

### 5.4.1 Required Strength

High-strength concrete is recognized to be more difficult to test accurately than normal strength concretes. Testing difficulties may contribute to lower measured values or higher variability. The mean average of compressive strength test results should exceed the specified strength fc' by an amount sufficiently high to minimize the relative frequency of test results below the specified strength value. A high variance in test results will dictate a higher required average strength. A higher required average strength may be difficult or impossible to attain when producing high-strength concretes because mix proportions may already be optimized.

The most common design approach has been to limit the frequency of tests allowed to fall below the specified strength. The concrete has been judged acceptable if the following requirements are met:

- The average of all sets of three consecutive strength test results shall equal or exceed the required $f_c'$.
- No individual strength test (average of two cylinders) shall fall below $f_c'$ by more than 500 psi (3.4 MPa).

ACI Recommendations for concrete practice are established for concretes with strengths in the range of 3000 to 5000 psi (21 to 34 MPa). High-strength concretes continue to gain considerable strengths above and beyond design requirements with the passage of time, more than lower strength concretes. While the percentage gain of compressive strength of high-strength concretes from 7 days to 90 days may be equal to or lower than concretes in lower strength ranges, the order of magnitude of strength gain expressed in psi is actually much higher.

### 5.4.2 Test Age

The selection of mix proportions can be influenced by the testing age. This testing age has varied depending upon the construction requirements. For normal strength concrete, the test age is most often thought to be the age at which the acceptance criteria are established, for example at 28 days. For High Strength Concrete, the age might be slightly extended, likely at 56 or 90 days.

**Early Age**

Pre-stressed concrete operations may require high strengths in 12 to 24 hours. Special applications for early use of machinery foundations, pavement traffic lanes, or slip formed concrete have required high strengths at early ages. Post-tensioned concrete is often stressed at ages of approximately 3 days and requires relatively high strengths. Generally concretes which develop high later-age strengths will also produce high early-age strengths. Early-age strengths may be more variable due to the influence of curing temperature and the early-age characteristics of the specific cement. Therefore, anticipated mix proportions should be evaluated for a higher required average strength or a later test age.

**Twenty-eight days**

A very common test age for compressive strength of concrete has been 28 days. High-strength concretes gain considerable strengths at later ages and, therefore, are evaluated at later ages when construction requirements allow the concrete more time to develop strengths before loads are imposed. Proportions, notably cementitious components, are usually adjusted depending upon test age.

**Later age**

High-strength concretes are frequently tested at later ages such as 56 or 90 days. High-strength concrete has been placed frequently in columns of high rise buildings. Therefore, it has been desirable to take advantage of long-term strength gains so that efficient use of construction materials can be achieved. This has often been justified in high-rise buildings where full loadings may not occur until later ages.

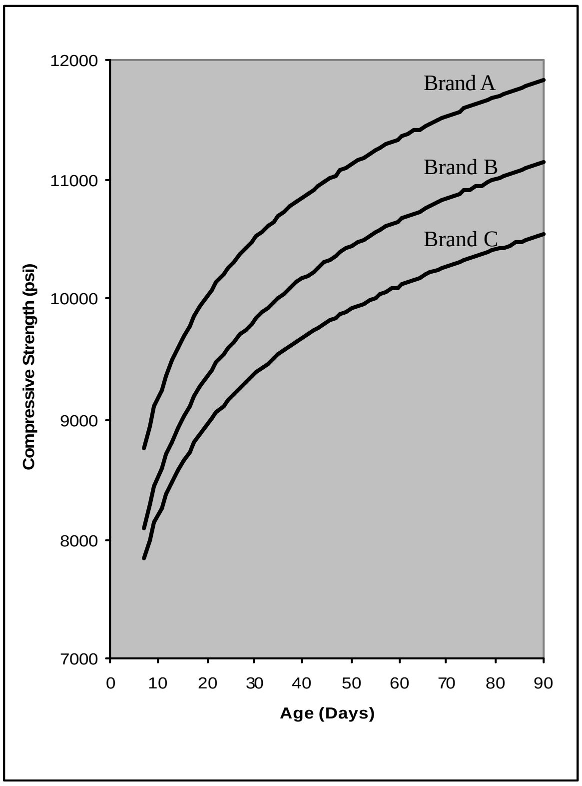



**Figure 1: Compressive Strength vs Test Age for Various Brands**

**Test age and curing correlation**

When selecting mix proportions, the type of curing anticipated should be considered along with the test age, especially when designing for high early strengths. Concretes gain strength as a function of maturity, which is usually defined as function of time and curing temperature.

## 5.4.3 Water Cement Ratio

The relationship between water-cement ratio and compressive strength developed for Low Strength Concretes has been found to be valid for High Strength Concretes also. Higher cement contents and lower water contents produces higher strengths in concretes. However, proportioning larger amounts of cement into the concrete mixture also increases the water demand of the mixture. Also, increase in cement content beyond a certain point does not increase compressive strength significantly. Other factors which may limit maximum cement content are–

- stickiness of the mixture
- workability
- Heat of hydration
- Curing Conditions
- Setting time of cement

Of course the slump of the concrete is related to the water-cement ratio and the total amount of water in the concrete. While concrete with 0 to 2 inch slump is widely being used in pre-cast operations, special consolidation efforts are required. Specified slumps for cast-in-place concretes without high-range water reducers range from 2½ to 4¼ inch (64 to 114 mm). Water cementitious ratios by weight for high-strength concretes

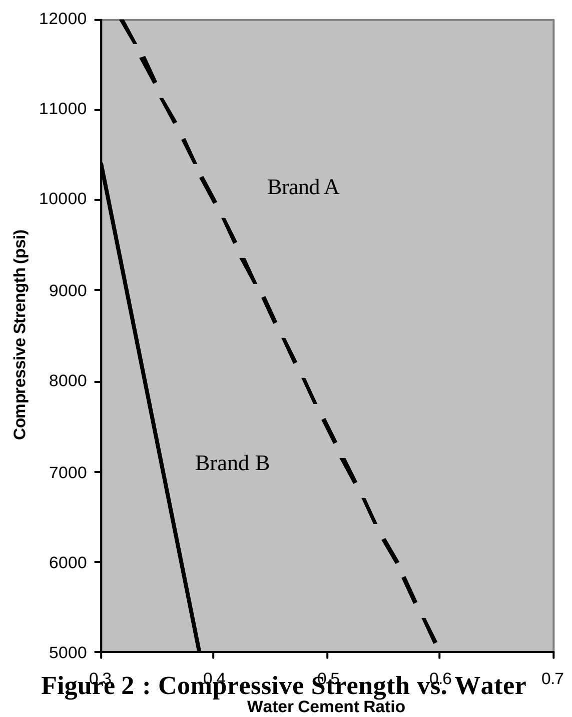



**Figure 2 : Compressive Strength vs. Water Cement Ratio for Various Mixtures**

typically range from 0.27 to 0.50. Also the quantity of liquid admixtures, particularly high-range water reducers, is sometimes included in the water-cementitious ratio.

### 5.4.4 Cement Content

For any given set of materials in a concrete mixture, there may be a cement content that produces maximum concrete strength. This is known as the Optimum Cement Content. The maximum strength may not always be increased by the use of cement added to the mixture beyond this optimum cement content. The strength for any given cement content will vary with the water demand of the mixture and the strength producing characteristics of that particular cement.

Higher cement contents in air entrained concrete have not been found to be useful in producing strengths equivalent to, or approaching, strengths attainable with non-air entrained concretes. Incorporation of entrained air may reduce strength at a ratio of 5 to 7 percent for each percent of air in the mix.

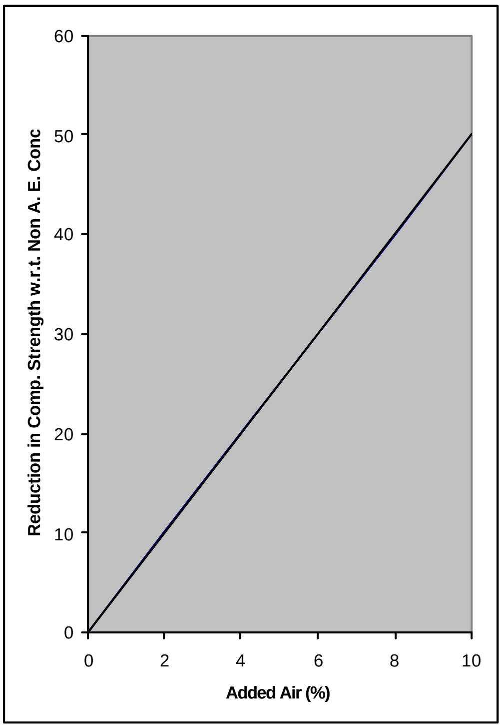



**Figure 3 : Strength Reduction in Air Entrained Concrete compared to Non Air Entrained Concrete of same w/c ratio**

### 5.4.5 Aggregate Proportions

Proportioning High Strength Concrete gives aggregates the important consideration since they occupy the largest volume of any of the ingredients in the concrete. Unless otherwise prescribed, normal weight aggregates are used in high strength concrete production.

**Fine aggregates**

Fine aggregates usually have more impact on mix proportions than the coarse aggregates. Fine aggregates contain a much higher surface area for a given weight than that of the larger coarse aggregates. Since the surface area of all the aggregate particles must be coated with a cementitious paste, the proportion of fine to coarse have a direct quantitative effect on paste requirements. Furthermore, the shape of these sand particles may either be spherical, sub-angular, or very angular. This property can alter paste requirements even though the net volume of the sand remains the same. Gradation of the fine aggregate also plays an important role in properties of the plastic as well as the hardened concrete. Low fine aggregate contents with high coarse aggregate contents results in a reduction in paste requirements and thus, proved to be economical. Such proportions also have made it possible to produce higher strengths for a given amount of cementitious materials. However, if the proportion of sand is too low, serious problems in workability become apparent.

**Coarse aggregates**

The optimum amount and size of coarse aggregate for a given sand will depend to a great extent on the characteristics of the sand. Most particularly it depends on the fineness modulus (FM) of the sand. This dependency is shown in Table 1.

| Max. size of aggregate, inch | Volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of sand | | | |
|---|---|---|---|---|
| | 2.40 | 2.60 | 2.80 | 3.00 |
| 3/8 | 0.50 | 0.48 | 0.46 | 0.44 |
| ½ | 0.59 | 0.57 | 0.55 | 0.53 |
| ¾ | 0.66 | 0.64 | 0.62 | 0.60 |
| 1 | 0.71 | 0.69 | 0.67 | 0.65 |
| 1 ½ | 0.75 | 0.73 | 0.71 | 0.69 |
| 2 | 0.78 | 0.76 | 0.74 | 0.72 |
| 3 | 0.82 | 0.80 | 0.78 | 0.76 |
| 6 | 0.87 | 0.85 | 0.83 | 0.81 |

**Table 1: Volume of coarse Aggregate per unit volume of concrete**

The proportion of coarse aggregate shown in Table 1 are suggested to be increased by up to 4 percent if sands with low void contents are used and decreased by up to 4 percent if the sand particles are very angular - in order to produce concretes of equivalent workability, although such changes will alter the water demand for given slump. When more or less water is needed to preserve the same consistency of paste, it is also necessary to adjust the amount of cement or cementitious materials if a given water/cement ratio is to be maintained.

## 5.4.6 Proportioning with Admixtures

Nearly all High Strength Concretes contain admixtures. Changes in the quantities and combinations of these admixtures affect the plastic and hardened properties of High Strength Concrete. Careful adjustments to mix proportions have been made when changes in admixture quantities or combinations have been made.

**Conventional Water Reducers and Retarders**

The amount of these admixtures used in High Strength Concrete mixtures vary depending upon the particular admixture and application. General practice is to use larger than normal or maximum quantities of these admixtures. Proportion of water in concrete can be reduced upto 10 percent by using admixture.

**Super Plasticizers or high-range water-reducing admixtures**

Same sort of adjustments are adoptable to super plasticizers similar to the adjustments for conventional water reducers in producing High Strength Concrete. Most often, they are simply added to existing mixtures without any adjustments to the mix proportions. Super plasticizers usually cause even larger amount of water reduction, approx. 12 to 25 percent.

However, High Range Water Reducers are used to lower the water/cement ratio; they are effective enough to lower the water/cement ratio as well as to increase the slump.

**Air-entraining agents**

Air-entraining agents are highly undesirable in High Strength Concretes due to the dramatic decrease in compressive strength. However, large dosage rates of air-entraining admixture have been found fruitful in high-strength concretes, especially in very rich low-slump mixtures and mixtures containing large quantities of some fly ashes.

**Admixture Combinations**

High Strength Concretes generally contain combinations of admixtures for better performance. High-range water reducers perform better when used in combination with conventional water reducers or retarders. This is because of the reduced rate of slump loss experienced. The proportions of the admixture combinations depends on the availability and performance required.

### 5.4.7 Workability

The property of freshly mixed concrete, which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished is known as Workability. Concrete should be discharged before the mixture becomes unworkable. Workability is needed in concrete practice in every stage of concreting. That’s why it’s been given the highest priority next to Proportioning and Material properties.

**Slump**

High-strength concrete performance demands a dense, void-free mass with full contact with reinforcing steel. Slumps should reflect this need and provide a workable mixture, easy to vibrate, and mobile enough to pass through closely placed reinforcement. Normally a slump of 4 inch (102 mm) will provide the required workability. Slumps less than 3 in. (76 mm) need special consolidation equipment and procedures.

**Placeability**

Without uniform placement, structural integrity could never be achieved. Cement fineness and particle size distribution influence the placing characteristics of the mixture. Certain admixtures may be used to improve the placeability of the mixture.

**Flow Properties**

Concrete must have sufficient flow properties to reach every portion of the concrete member. Elongated aggregate particles and poorly graded coarse and fine aggregates are examples of characteristics that have affected flow and caused higher water content for placeability with attendant strength reduction.

**Stickiness**

Stickiness is inherent in high fineness mixtures required for high strengths. Certain cements or Cement-Pozzolan or Cement-Admixture combinations causes undue stickiness that impairs flow ability.

### 5.4.8 Trial Batches

High Strength Concrete practice requires a large number of trial batches. In addition to laboratory trial batches, field-sized trial batches are also used to simulate typical

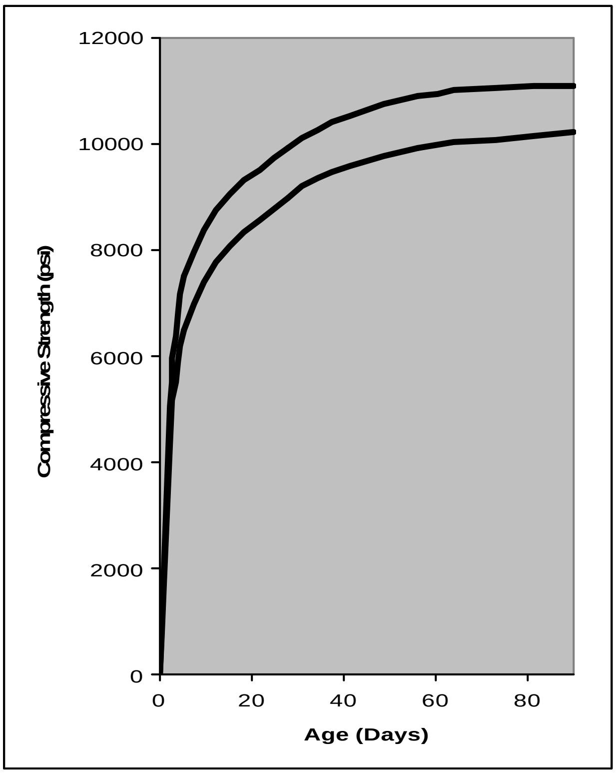



**Figure 4 : Laboratory molded concrete strengths vs. field molded concrete strengths**

production conditions.

**Laboratory trial batch investigations**

Laboratory trial Batches should be prepared according to Standard Method of Making and Curing Concrete Test Specimens in the Laboratory suggested by ASTM. Furthermore, timing, handling, and environmental conditions similar to the field should be simulated.

Once a promising mixture has been established, further laboratory trial batches may be required to quantify the characteristics of those mixtures, such as – Strength at various test ages, water demand, rate of slump loss, amount of bleeding, segregation, setting time, unit weight of the mixture and structural considerations like shrinkage and elasticity.

**Field-production trial batches**

Once a desirable mixture has been formulated in the laboratory, field testing with production-sized batches is recommended. Quite often laboratory trial batches exhibits a strength level significantly higher than that which can be reasonably achieved in production as shown in Fig. 4.

Actual field water demand, and therefore concrete yield, varies from laboratory design significantly. Ambient temperatures and weather conditions also affect the performance of the concrete.

## 5.5 Batching, Mixing, Transporting, Placing, Curing and Control Procedures

The batching, mixing, transporting, placing, and control procedures for high-strength concrete are not different in principle from those procedures used for conventional concrete. However, some changes, refinements, and emphasis on critical points are necessary. In addition to that, well-qualified concrete producers and testing laboratories are mandatory for quality production of High Strength Concrete.

### 5.5.1 Batching

**Control, handling and storage of materials**

Proper stockpiling of aggregates, uniformity of moisture in the batching process, and good sampling practice are essential. It may be prudent to place a maximum limit of 170 F (77 C) on the temperature of the cement as batched in warm weather and 150 F (66 C) in hot weather. The temperature of all ingredients should be kept as low as possible prior to batching. Delivery time should be reduced to a minimum and special attention paid to scheduling and placing to avoid having trucks wait to unload.

**Measuring and weighing**

Since speed and accuracy are the major concern in High Strength Concrete production, cements and aggregates can be weighed with automatic measuring equipments. Automatic weigh batchers or meters are recommended for water measurement. To maintain the proper water/cement ratios necessary to secure High Strength Concrete, accurate moisture determination in the fine aggregate is essential. In warm weather, a mixture with high cement content requires cooling of mixing water.

### 5.5.2 Mixing

High-strength concrete may be mixed entirely at the batch plant, in a central or truck mixer, or by a combination of the two. That is, High Strength Concrete can be mixed in all common types of mixers. However, it may prove beneficial to reduce the batch size below the rated capacity to insure more efficient mixing.

**Mixer performance**

The performance of mixers is usually determined by a series of uniformity tests made on samples taken from two to three locations. Due to the relatively low water content and high cement content and the usual absence of large coarse aggregate, the efficient mixing of high-strength concrete is more difficult than conventional concrete and special precautions and procedures are required. Thus, it becomes more important for High Strength Concrete to check mixer performance and efficiency prior to production mixing.

**Mixing time**

The mixing time required is based upon the ability of the central mixer to produce uniform concrete both within a batch and between batches. General specifications, such as 1 min for 1 $yd^3$ plus ¼ min for each additional $yd^3$ of capacity, are used as satisfactory guides for establishing mixing time. Otherwise, mixing times can be based on the results of mixer performance tests. Prolonged mixing may cause moisture loss and result in lower workability, which in turn may require re-tempering to restore slump, thereby reducing strength potential.

**Ready-mixed concrete**

Ready mixed concrete can be mixed at the job in a truck mixer. Close job control is essential for high strength ready-mixed concrete operations. Retarding admixtures are used to prolong the vibration respond time of concrete.

### 5.5.3 Transporting

High Strength Concrete can be transported by a variety of methods and equipment, such as truck mixers, stationary truck bodies with and without agitators, pipeline or hose, or conveyor belts. Each type of transportation has specific advantages and disadvantages depending on the conditions of use, mixture ingredients, accessibility & location of placing site, required capacity & time for delivery, and weather conditions.

**Truck Mixed Concrete**

Truck mixing is a process in which proportioned concrete materials from a batch plant are transferred into the truck mixer where all mixing is performed. The truck is then used to transport the concrete to the job site. This method is adaptable to the production of High Strength Concrete where it is desirable to retain the workability as long as possible.

**Stationary truck body with and without agitator**

Units used in this form of transportation usually consist of an open-top body mounted on a truck. The smooth, streamlined metal body is usually designed for discharge of the concrete at the rear when the body is tilted. However, water is not added to the truck body because adequate mixing cannot be obtained with the agitator.

**Pumping**

High-strength concrete will in many cases be very suitable for pumping. Pumps are available that can handle low-slump mixtures and provide high pumping pressure. High-strength concrete is likely to have a high cement content and small maximum size aggregate - both factors which facilitate concrete pumping. Continuous pumping is a prerequisite here because if the pump is stopped, movement of the concrete in the line may be difficult or impossible to start again.

**Belt Conveyor**

The conveyors must be adequately supported to obtain smooth, non-vibrating travel along the belt. The angle of incline or decline must be controlled to eliminate the tendency for coarse aggregate to segregate from the mortar fraction. Enclosures or covers are used for conveyors when protection against rain, wind, sun, or extreme ambient temperatures is needed to prevent significant changes in the slump or temperature of the concrete.

### 5.5.4 Placing Procedures

**Preparations**

Preparations for placing high strength concrete should include recognition at the start of the work that certain abnormal conditions will exist which will require some items of preparation that cannot be provided readily the last minute before concrete is placed. Workability time is expected to be reduced and preparations must be made to transport, place, consolidate, and finish the concrete at the fastest possible rate. Delivery of concrete to the job site must be scheduled to place it promptly on arrival. Equipment for placing the concrete must have adequate capacity to perform its functions efficiently. There should be ample vibration equipment and manpower to consolidate the concrete quickly after placement. Provision should be made for ample number of standby vibrators. A high strength concrete placing operation is in serious trouble, especially in hot weather, when vibration equipment fails and the standby equipment is inadequate.

#### Equipment

A basic requirement for placing equipment is that the quality of the concrete, in terms of water-cement ratio, slump, air content, and homogeneity, must be preserved. Selection of equipment should be based on its capability for efficiently handling of concrete. Concrete should be deposited at or near its final position in the placement. Buggies, chutes, buckets, hoppers, or other means may be used to move the concrete as required.

#### Consolidation

Proper internal vibration is the most effective method of consolidating high-strength concrete. The advantages of vibration in the placement of concrete are well established. The importance of full compaction cannot be overstated. Up to 5 percent loss in strength can be sustained from each 1 percent void space in concrete. Vibration almost to the point of excess may be required for high strength concrete to achieve its full potential.

### 5.5.5 Curing

#### Need for Curing

Curing is essential in the production of quality concrete; it is critical to the production of high strength concrete. The potential strength and durability of concrete will be fully developed only if it is properly cured for an adequate period prior to being placed in service.

#### Type of Curing

Water curing of high strength concrete is highly recommended due to the low water-cement ratios employed. At water-cement ratios below 0.4, the ultimate degree of hydration is significantly reduced if free water is not provided. Water curing will allow more efficient, although not complete, hydration of the cement. Moist curing for 28 days and thereafter in air is highly beneficial in securing high-strength concrete at 90 days.

#### Methods of Curing

The most thorough but seldom used method of water curing consists of total immersion of the finished concrete unit in water, is known as Ponding or Immersion. Fog spraying or sprinkling with nozzles or sprays provides satisfactory curing when immersion is not feasible. Lawn sprinklers are effective where water runoff is of no concern. Burlap, cotton mats, rugs, and other coverings of absorbent materials will hold water on the surface, whether horizontal or vertical. Liquid membrane-forming curing compounds retain the original moisture in the concrete but do not provide additional moisture.

### 5.5.6 Quality Control Procedures

The distribution of the compressive strength test results follows a normal distribution curve. A skew distribution may prevail due to the mean approaching a limit, especially for very high strength concrete with compressive strength of 15,000 psi (103 MPa) or higher. In the range of 6000 to 10,000 psi (41 to 69 MPa), normal distribution is achieved. Another point which needs consideration both in the quality control and the design phase is the age of concrete at the time of testing. A considerable strength gain may be achieved after 28 days in high-strength concrete. However, the specification for compressive strength of high strength concrete is modified from the typical 28-day criterion to either 56 or 90 days. High-strength concrete is generally used in high-rise structures; therefore, the extension of the time for compressive strength test results is reasonable since the lower portion of the structure will not attain full dead load for periods up to one year and longer.

**Method of evaluation**

The average strength of concrete must be in excess of fc', the design strength. The amount of excess strength depends on the expected variability of test results as expressed by a coefficient of variation or standard deviation. The standard deviation for high strength concrete becomes uniform in the range of 500 to 700 psi (3.5 to 4.8 MPa), and therefore, the coefficient of variation will actually decrease as the average strength of the concrete increases. Following equations are used to determine the average concrete strength of concrete found from test results -

$$f_{cr}' = f_c' + 1.34s$$

Or, $$f_{cr}' = f_c' + 2.33s - 500$$ where, s = standard deviation

However, a close check of the field results and maintenance of records in the form of control charts or other means are necessary.

### 5.5.7 Strength Measurement

Since much of the interest in high strength concrete is limited to strength only in compression, compressive strength measurements are of primary concern in the testing of high-strength concrete. Standard test methods of ASTM are followed except where changes are dictated by the peculiarities of the high strength concrete. Generally, compressive strengths at the age of 56 days and 90 days are tested. A minimum of two cylinders be tested for each age and each test condition.

**Specimen size and shape**

ASTM standards specify a cylindrical specimen 6 inch (152 mm) in diameter and 12 inch (305 mm) long. Recently some 4 x 8 inch (102 x 204 mm) cylinders are being used for determining compressive strength which exhibits a relatively higher strength and an increase in variability compared to the standard 6 x 12 inch.

**Testing apparatus**

Testing machine characteristics that may affect the measured compressive strength include calibration accuracy, longitudinal and lateral stiffness, stability, alignment of the machine components, type of platens, and the behavior of the platen spherical seating. Testing machines should meet the requirements of ASTM C 39 when used for testing compressive strength of cylindrical specimens.

**Type of mold**

The choice of mold materials, and specify construction of the mold regardless of the types of material used, can have a significant effect on measured compressive strengths. A given consolidation effort is more effective with rigidly constructed molds, and sealed waterproofed molds reduce leakage of mortar paste and inhibit the dehydration of the concrete. Rigid steel molds increase strengths approximately 13 percent in comparison with high quality paper molds, 6 percent in comparison with tin molds and approximately 16 percent in comparison with plastic molds.

**Specimen preparation**

Capping or grinding the ends of hardened concrete test specimens prior to testing for compressive strength is highly important. For high strength concrete the strength of the cap is another point to consider. If the compressive strength or modulus of elasticity of the capping material is less than that of the specimen, loads applied through the cap will not be transmitted uniformly.

Sulfur mortar is the most widely used capping material. Cap thicknesses in the range of $^1/_{16}$ to $^1/_8$ inch (1.5 to 3 mm) are desirable for use on high-strength concrete. However, caps consistently thinner than $^1/_8$ inch (3 mm) are difficult to obtain. The principal problems with thin caps are air voids at the specimen-cap interface and cracking of the cap under load. Caps with a thickness of ¼ inch (6 mm) are proved to be satisfactory. Concrete strengths up to 10,000 psi (69 MPa) could be determined using high strength capping materials, including sulfur mortar with a cap thickness of minimum ¼ in. (6 mm). For compressive strengths above 10,000 psi (69 MPa), the ends are usually formed or ground to tolerance.

## 5.6 Properties of High Strength Concrete

Properties of High Strength Concrete, such as, Stress–Strain relationship, Modulus of Elasticity, Tensile Strength, Shear Strength, Bond Strength, etc are frequently expressed in terms of the uniaxial compressive strength of 6 x 12 in. cylinders, same as Normal Strength Concrete. However, these properties vary in great extent compared to those of Normal Strength Concrete.

### 5.6.1 Stress-Strain Behavior in Uniaxial Compression

The shape of the ascending part of the stress–strain curve is more linear and steeper for High Strength Concrete, and the strain at the maximum stress is slightly higher than normal strength concrete. Also, the slope of the descending part becomes steeper for high-strength concrete.

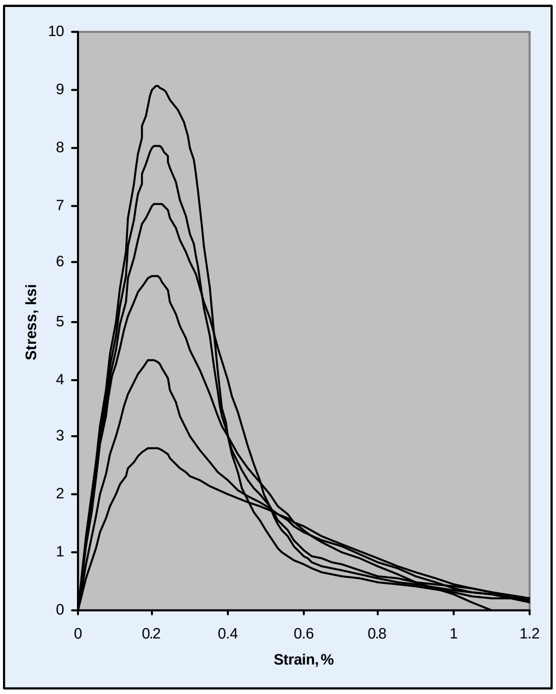



**Figure 5 : Compressive Stress-Strain Curves for Various Brands**

High Strength Concrete exhibits less internal micro-cracking than lower strength concrete for a given imposed axial strain. As a result, the relative increase in lateral strains is less for high strength concrete. The lower relative lateral expansion during the inelastic range may mean that the effects of triaxial stresses will be proportionally different for high strength concrete.

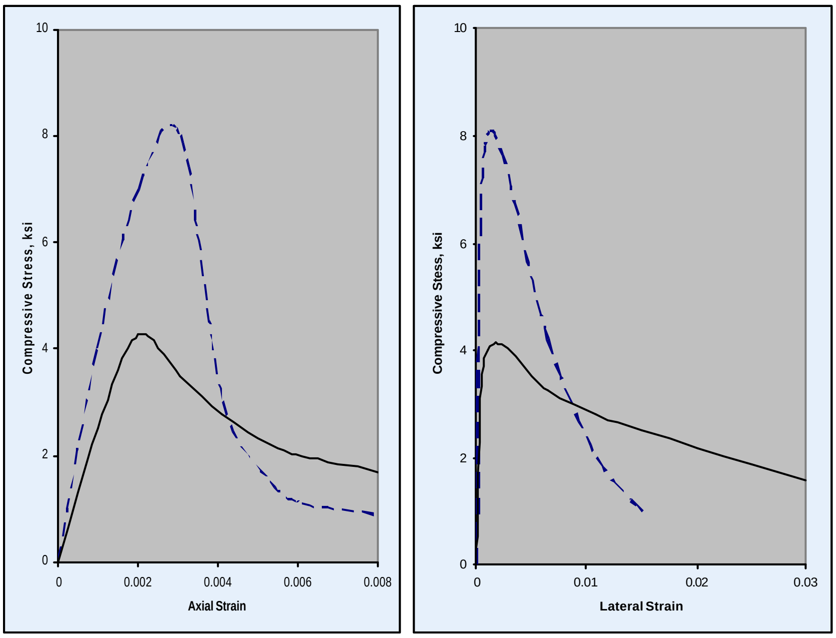



**Figure 6 : Axial Stress vs. Axial Strain and Lateral Strain**

### 5.6.2 Modulus of Elasticity

Values for the Modulus of Elasticity are determined as the slope of the tangent to the stress-strain curve in uniaxial compression. The values generally range from $4.2xl0^6$ to $5.2xl0^6$ psi (29 to 36 GPa) for concretes having compressive strengths ranging from 10,000 (69 MPa). However, values of the Modulus of Elasticity of High Strength Concretes depend mostly on the method used. A correlation between the Modulus of Elasticity $E_c$ and the compressive strength $f_c'$ is -

$$E_c = 40,000\ v f_c' + 1.0 \text{ x } l0^6 \text{ psi}$$

$$\text{for } 3000 \text{ psi} < f_c' < 12,000 \text{ psi}$$

$$\text{or} \quad E_c = 3320\ v f_c' + 6900 \text{ MPa}$$

$$\text{for } 21 \text{ MPa} < f_c' < 83 \text{ MPa}$$

### 5.6.3 Poison’s Ratio

Experimental data on values of Poisson’s ratio for High Strength Concrete is very limited. Values of Poisson’s ratio of lightweight aggregate High Strength Concrete with compressive strengths up to 10,570 psi (73 MPa) has been found to be 0.20 regardless of compressive strength, age, and moisture content. Values determined by the dynamic method were slightly higher. Values for Poisson’s ratio of normal weight High Strength Concretes with compressive strengths of 8000 to 11,600 psi (55 to 80 MPa) range between 0.20 and 0.28. It is generally believed that Poisson’s ratio tends to decrease with increasing water-cement ratio.

### 5.6.4 Modulus of Rupture

The Modulus of Rupture of both lightweight and normal weight High Strength Concretes fall in the range of $7.5v f_c'$ to $12v f_c'$ , both the Modulus of Rupture and the Compressive Strength expressed in psi. The following equation is recommended for the prediction of the tensile strength of normal weight concrete,

$$f_r' = 11.7\ v f_c' \text{ psi}$$

for 3000 psi < $f_c'$ < 12,000 psi

or, $f_r' = 0.94 \sqrt{f_c'}$ MPa

for 21 MPa < $f_c'$ < 83 MPa

### 5.6.5 Tensile Splitting Strength

At low strengths, the indirect tensile strength may be as high as 10 percent of the compressive strength but at higher strengths it may reduce to 5 percent. The tensile splitting strength is about 8 percent higher for crushed-rock-aggregate concrete than for gravel-aggregate concrete. In addition, the indirect tensile strength is found to be about 70 percent of the flexural strength at 28 days. The following equation is used to predict the tensile splitting strength $f_{sp}'$ of normal weight concrete -

$f_{sp}' = 7.4 \sqrt{f_c'}$ psi

for 3000 psi < $f_c'$ < 12,000 psi

or $f_{sp}' = 0.59 \sqrt{f_c'}$ MPa

for 21 MPa < $f_c'$ < 83 MPa

### 5.6.6 Fatigue Strength

The fatigue strength of High Strength Concrete is the same as that for concretes of lower strengths. However, lower values are found for the High Strength Concretes and for concrete made with the smaller-size coarse aggregate.

### 5.6.7 Unit Weight

The measured values of the unit weight of High Strength Concrete are slightly higher than lower strength concrete made with the same materials.

### 5.6.8 Thermal Properties

The thermal properties of High Strength Concretes fall within the approximate range for lower strength concretes. Quantities those usually measured are specific heat, diffusivity, thermal conductivity, and coefficient of thermal expansion.

### 5.6.9 Heat Formation due to Hydration

The temperature rise within concrete due to hydration depends on the cement content, water-cement ratio, size of the member, ambient temperature, environment, etc. The heat rise of High Strength Concretes is approximately 11 to 15 F per l00 lb of cement/yd3 (6 to 8 C per 59 kg/m3 of cement).

### 5.6.10 Strength Gain with Age

High Strength Concrete shows a higher rate of strength gain at early ages as compared to lower strength concrete. But at later ages the difference is not significant. Typical ratios of 7 day to 95 day strengths are 0.60 for low strength, 0.65 for medium strength, and 0.73 for high strength concrete. It seems likely that the higher rate of strength development of high-strength concrete at early ages is caused by –

- an increase in the internal curing temperature in the concrete cylinders due to a higher heat of hydration, and
- shorter distance between hydrated particles in high-strength concrete due to low water-cement ratio.

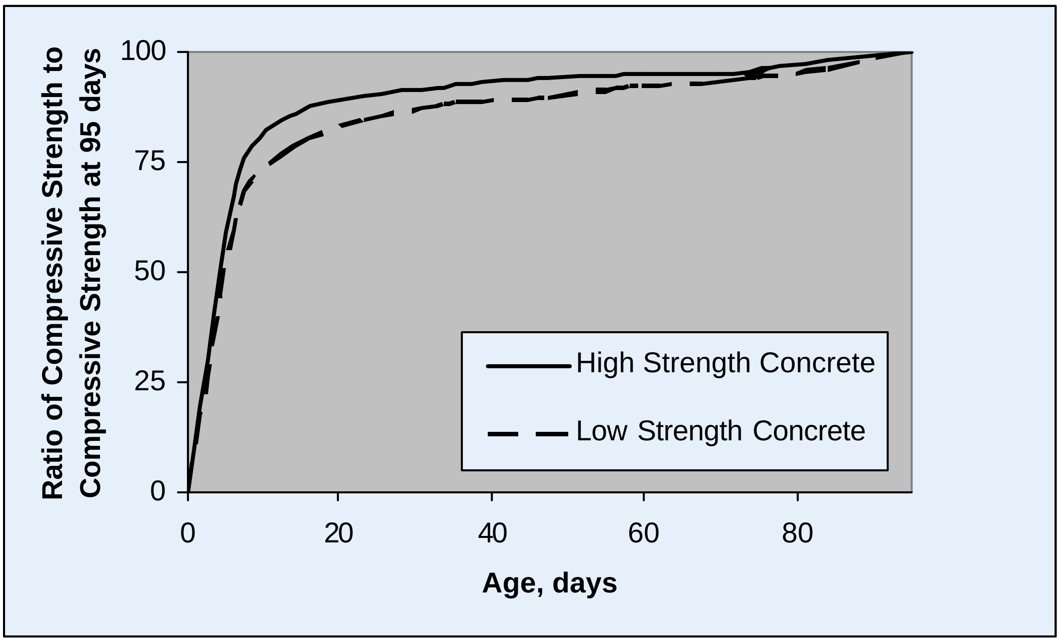



**Figure 7 : Normalized strength gain with age for moist cured concretes**

### 5.6.11 Freeze Thaw Resistance

Information about air content requirement for high strength concrete to produce adequate durability is contradictory. If High Strength Concrete is to be frozen under wet conditions, air entrained concrete should be considered despite the loss of strength due to air entrainment.

### 5.6.12 Shrinkage

High Strength Concrete usually have a relatively high initial rate of shrinkage, but after drying for 180 days there is little difference between the shrinkage of high strength and lower strength concrete. Reducing the curing period may cause a slight increase in the shrinkage. However, shrinkage is unaffected by changes in water-cement ratio, but is approximately proportional to the percentage of water by volume in the concrete.

### 5.6.13 Creep

The total strain observed in sealed High Strength Concrete under a sustained loading of 30 percent of the ultimate strength is more or less same as that of lower strength concrete. But under drying conditions, this ratio is 25 percent lower than that of lower strength concrete. The creep of High Strength Concrete made with High Range Water Reducers seems to be decreased significantly. The maximum specific creep was less for High Strength Concrete than for lower strength concrete loaded at the same age.

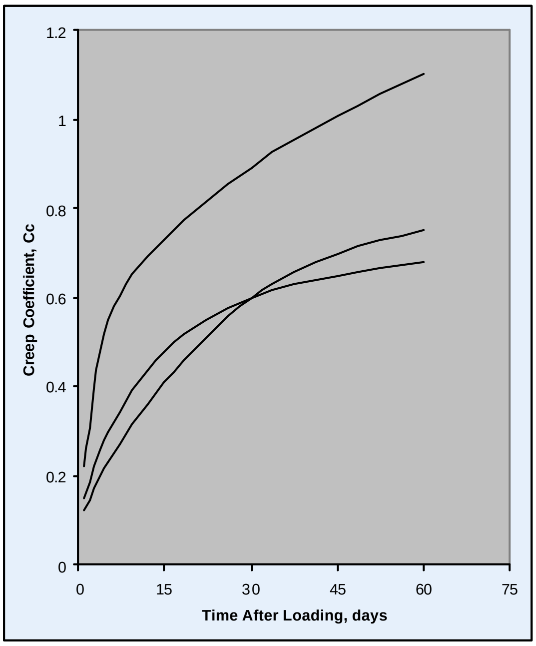



**Figure 8 : Relationship between Creep Coefficient and Time**

However, High Strength Concretes are subjected to higher stresses. Therefore, the total creep will be about the same for any strength concrete.

# 5.7 Economic Considerations

## 5.7.1 General Considerations

High strength Concrete is a state-of-the-art material and commands a premium price. In some instances, the benefits are well worth the additional effort and expense; in others they are not. In most areas and for most uses, the benefits of High Strength Concrete more than compensate for the increased costs of raw materials and quality control. Although the concrete itself is more costly than lower strength mixtures, the cost differential is offset by significant reduction in the given member size. This capability is particularly attractive for its use in columns. Since column size is so important for architectural and rental reasons, the ability to limit the sizes for taller structures often allows the use of a concrete solution in lieu of one of structural steel.

### 5.7.2 Quality Control

One more exclusive result of the use of High Strength Concrete is the cost of the increased testing, quality control, and inspection that the use of High Strength Concrete requires. The quality and consistency of the concrete is crucial, and additional steps must be taken to insure that quality and consistency.

### 5.7.3 Remarks

The economic benefits of High Strength Concrete are just now becoming fully apparent. Certainly as the use of High Strength Concrete increases, additional and possibly even greater benefits will be realized. In any case, those projects that have led the way in the use of High Strength Concrete have clearly demonstrated its distinct advantages. For now, it allows the profession to engineer most cost effectively and space effectively. In the future, those considerations may tip the balance on whether certain projects are constructed at all.

## 5.8 Areas of Application

The economic advantages of High Strength Concrete are most readily realized when the concrete is used in the columns of high-rise buildings. In this application, engineers may take full advantage of its increased compressive strength: reducing the amount of steel, reducing column size to increase usable floor space, or allowing additional stories without detracting from lower floors. These benefits overshadow the increased quality control costs and possible higher cost of raw materials discussed earlier. Yet the use of high-strength concrete has also spread to other applications, primarily slabs, beams, and long-span bridges.

### 5.8.1 Buildings

Parking garages, bridge decks, and other installations requiring improved density, lower permeability and increased resistance to freeze-thaw and corrosion and have good scopes for using High Strength Concrete.

The primary advantage of High Strength Concrete in slabs is the resulting reduction in dead load. However, significant economies can be achieved only by reducing the thickness that is required for stiffness; the additional reinforcement required may offset the concrete savings. Used for rectangular beams, T-beams, and one-way slabs, High Strength Concrete yields reduced section width or thickness and allows for longer spans.

**Table 2 : Buildings over the World with High Strength Concrete**

| Building | Location | Year* | Total Stories | Maximum Design Concrete Strength, psi |
|---|---|---|---|---|
| S.E. Financial center | Miami | 1982 | 53 | 7000 |
| Petrocanada Building | Calgary | 1982 | 34 | 7250 |
| Lake Point Tower | Chicago | 1965 | 70 | 7500 |
| 1130 S. Michigan Ave. | Chicago | | | 7500 |
| Texas Commerce Tower | Houston | 1981 | 75 | 7500 |
| Helmsley Palace Hotel | New York | 1978 | 53 | 8000 |
| Trump Tower | New York | | 68 | 8000 |
| City Center Project | Minneapolis | 1981 | 52 | 8000 |
| Collins Place | Melbourne | | 44 | 8000 |
| Larimer Place Condominium | Denver | 1980 | 31 | 8000 |
| 499 Park Avenue | New York | | 27 | 8500 |
| Royal Bank Plaza | Toronto | 1975 | 43 | 8800 |
| Richmond-Adelaide Center | Toronto | 1978 | 33 | 8800 |
| Mid-continental Plaza | Chicago | 1972 | 50 | 9000 |
| Water Tower Place | Chicago | 1975 | 79 | 9000 |
| River Plaza | Chicago | 1976 | 56 | 9000 |
| Chicago Mercantile Exchange | Chicago | 1982 | 40 | 9000 |
| Columbia Center | Seattle | 1983 | 76 | 9500 |
| Interfirst Plaza | Dallas | 1983 | 72 | 10,000 |
| Eugene Terrace | Chicago | 1987 | 44 | 11,000 |
| 311 S. Wacker Drive | Chicago | 1988 | 70 | 12,000 |
| 900 N. Michigan Annex | Chicago | 1986 | 15 | 14,000 |
| Two Union Square | Seattle | 1987 | 62 | 14,000 |
| 225 W. Wacker Drive | Chicago | 1988 | 30 | 14,000 |
| Scotia Plaza | Toronto | 1988 | 68 | 10,000 |

* year in which concrete was cast

## 5.8.2 Bridges

Long span bridges are another area where the qualities of High Strength Concrete are proving themselves economically attractive. Comparatively greater compressive strength per unit weight and unit volume of High Strength Concrete allows lighter, more slender bridge piers. This provides improved horizontal clearances. In addition, the increased stiffness of High Strength Concrete is advantageous when deflections or stability govern the bridge design. Also, increased tensile strength of High Strength Concrete is helpful in service load design in pre-stressed concrete.

**Table 3 : Bridges over the World with High Strength Concrete**

| Bridge | Location | Year | Maximum Span, ft | Maximum Design Concrete Strength, psi |
|---|---|---|---|---|
| Willows Bridge | Toronto | 1967 | 158 | 6,000 |
| Houston Ship Canal | Texas | 1981 | 750 | 6,000 |
| San Diego to Coronado | California | 1969 | 140 | 6,000 |
| Linn Cove Viaduct 8.13 | North Carolina | 1979 | 180 | 6,000 |
| Pasco-Kennewick Intercity | Washington | 1978 | 981 | 6,000 |
| Coweman River Bridges 8.14 | Washington | | 146 | 7,000 |
| Huntington to Proctorville | W. Va. to Ohio | 1984 | 900 | 8,000 |
| Annicis Bridge | British | 1986 | 1526 | 8,000 |
| Nitta Highway Bridge | Columbia | 1968 | 98 | 8,500 |
| Kaminoshima Highway Bridge | Japan | 1970 | 282 | 8,500 |
| Tower Road | Japan | 1987 | 161 | 9,000 |
| Fukamitsu Highway Bridge | Washington | 1974 | 85 | 10,000 |
| Ootanabe Railway Bridge | Japan | 1973 | 79 | 11,400 |
| Akkagawa Railway Bridge | Japan | 1976 | 150 | 11,400 |

## 5.8.3 Potential Applications

Most applications of High Strength Concrete have used the strength property of the material so far. However, High Strength Concrete may possess other characteristics that could be used advantageously in concrete structures.

Use of High Strength Concrete is satisfying enough for the need for a high modulus of elasticity. Similarly, High Strength Concrete can be used in slabs to allow early removal of formwork and avoid reshoring. This takes advantage of both the high modulus of elasticity and lower creep of High strength Concrete. The low creep of High Strength Concrete should be taken into account when considering pre-stress losses. Since most of the pre-stress loss is attributable to creep and shrinkage, pre-stress losses for High Strength Concrete members should be less than for lower strength concrete members.

The maximum span capability of solid-section girders can be increased by 15 percent when the concrete compressive strength is increased from 5000 to 7000 psi (34 to 48 MPa). Finally, the relationship between High strength Concrete and High Quality Concrete may make High Strength Concrete attractive not for its strength but for its long-term service performance.

More recently, High Strength Concrete has been specified for applications in warehouses, foundries, parking garages, bridge deck overlays, dam spillways, and heavy duty industrial floors. In these applications, High Strength Concrete is being used to provide a concrete with improved resistance to chemical attack, better abrasion resistance, improved freeze-thaw durability, and reduced permeability.

## 5.9 High Strength Concrete : From Local Point of View of Bangladesh

Concrete practice in Bangladesh has never been upto the mark. For the past years, only low strength concretes are being used in concrete constructions. Concrete used in local structures seldom exceeds a compressive strength of 4000 psi or so. The major reasons for such condition in concreting in Bangladesh are several, such as –

- Material Quality
- Poor Workmanship
- Lack of Supervision
- Poor knowledge on ever-changing concrete practice

Quality of materials used in concrete production is most important factor of all. But unfortunately, this is the most neglected side in local concrete production. The negligence starts right from the very beginning, while selecting the coarse aggregate. As stone is scarce in Bangladesh and budget for construction is relatively low for most cases, local people or engineers have adopted the use of brick chips in lieu of crushed stones. Brick is a light weight aggregate having lesser unit weight, more porosity and absorption qualities compared to stone and most importantly, brick is way too weak in strength properties when compared with stone. So, quite obviously, when a concrete is designed using ACI recommendations assuming that stone aggregates will be used and in field, brick is used instead of stone, it can never render the anticipated strength for which it was designed. The quality of the major ingredient of concrete, Cement, is also not pleasant. The constituent materials of cement limit its strength dependent on its age. That is, fresh cement will show much more strength than old or stocked cement. Due to some reasons, many construction uses stocked, old cement.

Also, the quality of fine aggregate and water used in local concrete is questionable. All these facts only leads to lessen the quality of concrete locally produced.

The next important factor in concrete practice, workmanship and supervision is also neglected. Concrete needs to be dealt with patience and care right form the beginning to the end, through proper mixing, transporting, placing and curing, if the best result is expected of it. This is a raw fact from the point of view of Bangladesh that almost all the workers are illiterate and do not have any background in concreting. More importantly, the instructors or supervisors literally know very little and inadequate about concrete. Thus, it goes like this – concrete is being produced in Bangladesh with ignorant workers and they are being supervised by ill-learned supervisors. As a result, the demand of the actual designer is never fulfilled.

### 5.9.1 Present Status of Concrete Practice in Bangladesh

For the last few years, the concrete practice in Bangladesh has improved a lot. Though stone is still scarce in Bangladesh, use of brick chips in concrete has diminished quite a lot. Most of the constructions now use stone chips as coarse aggregate. Use of good quality cement is another turn about in recent concrete practice in Bangladesh. In recent few years, many cements factories are established in our country those are producing good quality of cement adequate for us.

For construction, workmanship, supervision and maintenance, the situation is better than any other time in past. Workers, mastered only in concrete construction, are available now. New and improved technologies for mixing or carrying are available. Masterful devices, specially built for concrete placing or maintenance are now present and so are their skilled operators. Most importantly, interest and knowledge about concreting and better concrete practice is increasing every single day now, resulting us a better and improved concrete community.

For High Strength Concrete, the picture is not yet that much fair. Bangladesh still uses low strength concrete for general construction purpose. For special constructions, concretes with medium strength range are being used. So far published, concrete used in Bangladesh with maximum compressive strength is about 6000 psi. Though it is quite fair for Bangladesh point of view, it is certainly poor in international standards where concretes with 9000 psi to 12000 psi of compressive strength are being used quite frequently.

| Stucture | Location | Year* | Max. Span (ft) or Total Stories | Maximum Design Concrete Strength, psi |
|---|---|---|---|---|
| Bashundhara City | Dhaka | 2004 | 13 | 6000 |
| Bridge to Pres. Zia'r Graveyard | Dhaka | 2004 | -- | 6000 |
| Keari Center (not completed) | Chittagong | -- | 8 | 5000 |

* year in which construction was completed

### 5.9.2 Scope for High Strength Concrete in Bangladesh

Scope for High Strength Concrete in Bangladesh is really high. First of all, Bangladesh is a developing country, which means Bangladesh is developing and yet there are many places to develop in days to come. And the infrastructural development is at the base of all sorts of development projects. New structures need to be erected, new bridges need to be constructed, new roads to be laid, and more new cities need to be planned, designed and built. As we are going for all new constructions, it should be our motto to go for the best constructions, both in architectural and structural point of view, and show the world our potentials. High Performance Concrete, especially High Strength Concrete can be a great tool for such an enormous operation.

## 5.10 Conclusion

The objective of this chapter was to present state-of-the-art information on concrete with strengths in excess of about 6000 psi (41 MPa) but not including concrete made using exotic materials or techniques. Although High Strength Concrete is often considered a relatively new material, it is becoming well known and more accepted in all parts of the world. As with developments in the realm of materials, research data supporting the growth are also being available day by day. Though some research projects are already underway to satisfy these needs, further work is needed to fully use the advantages of High Strength Concrete and to affirm its versatile capabilities. This report is a document of the existing knowledge on High Strength Concrete so that the direction for future development may be ascertained.

## Chapter 6

# Conclusion

## 5.1 General

The prime objective of this research work was to study the ACI Method of Mix Design employing both Brick aggregate and Stone aggregate and to identify anomalies, if any, in context of Bangladesh. In this study, an analysis is done on the design of a concrete mix for a particular strength and observed the effect of ACI design methods. The ACI method of mix design is based for coarse aggregate as stone. It cannot rationally design the mixes for the cases where coarse aggregates of lighter unit weights are to be used. The present study covers only non air-entrained concrete. The amount of entrapped air was, however, incorporated as required by the ACI method.

## 5.2 Findings from the Study and Reasons Behind the Discrepancy:

In some design broken brick chips was used as a cheap substitute for crushed stone coarse aggregate. But recent laboratory investigations have shown that all such design practices do not conform to the strength requirements. Best effort was given to ensure SSD condition of aggregates and for proper mixing and preparation of cylinders and cubes. Water/cement ratio is the prime factor in determining concrete strength, so it was tried to keep the quantity of water exactly the same found from the computation. Mixing machine was used for concrete mixing and vibrator was used for better compaction.

Experience shows that quality of cement, aggregate, water and the process of nixing and curing are involved in the production of concrete. As concrete failure can be actuated either by crushing of coarse aggregate or by the mortar failure, strength of coarse aggregate plays an important role.

It has already been found out by tests, the ACI method fails to design normal mixes with lighter coarse aggregates. In such cases the design suggests for huge fine aggregate content, which obviously in turn increases the total surface area. The situation worsens further when designer goes for designing low slump or low strength mixes; uses fine aggregates of higher specific gravity or greater fineness modulus. Contrary to this, the ACI method, in such cases gives lower cement content, which further deteriorates the situation.

It has been stated previously that the amount of cement should be sufficient to cover the entire surface area of the aggregate. When the amount fine aggregates increases, corresponding cement content should also increase to maintain an efficient binding of the concrete ingredients into the concrete mass. In the ACI method of mix design the surface area of fine aggregate has been accounted for in terms of fineness modulus but that of the coarse aggregate has been completely ignored. Coarse aggregate size mattered only in determining the water quantity and in determining the coarse aggregate content. But for the determination of the amount of cement, it is entirely dependent on the water-cement ratio, with no reference to aggregate surface area. Moreover the cement content is determined at an earlier stage, when the properties of aggregate have not yet come into action. This is why, if the fine aggregate content increases due to some properties of the aggregates at a later part of design, the same amount of cement is available to cover up the aggregates. This system is thus subjected to failure. The method thus fails to give logical results for aggregates having finer fine aggregate as well as they have a larger surface area, with corresponding larger fineness modulus.

## 5.3 Suggestions and Recommendations

In Bangladesh the brick chips (Khoa) is the more available & economical coarse aggregate than the stone chips. But the ACI method of mix design is based by using the stone chips as coarse aggregate. As the brick chips is lighter material than the stone chips, the results give larger amount of fine aggregate which makes the ACI method inaccurate.

So the modification factor should be used to reduce the excessive fine aggregate for making the method more accurate.

Based on this study the following recommendations can be made for effective quality control of concrete:

- All the ingredients should conform to the required strength and other parameters in order to get the desired strength of the mix. If any of one ingredients do not exhibit required property the effect is cumulatively counted on other ingredients. In this study, in spite of the high strength of cement the poor performance of aggregate counted on the overall result.

- It should always be tried to have field adjustment of the mix proportion, because the ideal SSD condition of aggregates, on which the theoretical proportioning is based, is quite rare in actual construction sites.

- Neither workability should be hampered through the reduction of water in order to increase strength nor excess water should be provided to improved workability. If possible, it is better of improving workability by using admixtures instead of adding extra water which will reduce strength.

- Continuous curing is the best way to achieve higher strength close to the designed value.

- The mix proportions should be checked by using modified factor. Because, the concrete mix design methods are not blindly applicable for local lightweight aggregate like brick khoa.

- The diameter of a cylinder specimen should not less than three or four times the maximum size of the aggregate, in order to avoid undue influence of boundary conditions and other irregularities.

- Insufficient compaction results in pockets and reduce strength; excessive working results in segregation and likewise reduces strength.

- Care must be taken to avoid partial drying of specimens waiting for test.
- Temperature at every steps in concrete has a great effect on indicated strength.
- It is important that loading of concrete specimens be applied uniformly over the bearing area.
- To avoid delays two or more initial mixes with the same water content but with different w/c ratios may be prepared.

## 5.4 Scope for Future Study

The present study has just established the limitations of the ACI method with reference to various mix design parameters. The actual reasons behind this behavior could not be specifically ascertained, through a logically justified explanation was given. Researchers interested in pursuing further exploration in this field may investigate the following areas:

- The present study covers only normal, non air-entrained concrete mix designs by ACI method. Air-entrained concrete mixes should also be explored, this might give some interesting results, as air-entrained concrete is more workable than the non air-entrained one, which will give a lower water content and cement content as well.
- Mix designs by other methods; especially British method may also be explored for its various design parameters. Mix design methods by aggregate surface area should be investigated thoroughly as surface area is very, very important factor in mixes.
- It is interesting to note that even if the surface area of brick aggregate and stone aggregate be the same, still brick will give a higher FA content/CAcontent because of its lower unit weight. What is important here is that the available cement is constant and so is the available surface area. So the design may produce a satisfactory result. Therefore, FAcontent/CAcontent may not be the only criteria to judge the ACI method of mix design.
- The range of parameter values can be extended beyond which the ACI method fails to give a logical result.
- When this range has been established, empirical correction factors may be proposed for the parameter values for which ACI method fails to produce a satisfactory mix.
- The ACI mix design of lightweight aggregate could be experimented to design concrete mixes with broken brick aggregates and compared with the results of normal mix design procedure.

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