CONCRETE MIX DESIGN PROCEDURE USING LOCALLY AVAILABLE MATERIALS

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Warda Bint Ashraf

Warda Bint Ashraf

DEDICATION

to

My Parents & My Teachers

who built me up

ACKNOWLEDGEMENT

The preparation of the thesis was undertaken to meet the need for the partial fulfillment of the Degree of Master of Science in Civil Engineering (Structural) from BUET. All praise to The Omnipresent All-pervading Allah for blessing with potency and merit, to lead this thesis work towards completion.

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ABSTRACT

Concrete is the most popular and widely used construction material in Bangladesh. It can be produced form locally available materials which make the product-cost lower than the others. Concrete mix design works as a major determining factor for the properties of concrete, but at present there is no concrete mix design guideline for Bangladesh using locally available materials. There are already some conventional methods of concrete mix design, such as, ACI 211and BS 812. But subsequent aggregate gradations (i.e. ASTM C33, BS 882) may not be achievable through these standard methodologies due to possible variation in aggregate characteristics of this particular geographic region. Thus, in this research a comprehensive methodology has been developed for the suitable gradation of locally available aggregates as well as for concrete mix design.

In order to determine the most suitable aggregate gradation method, different existing methodologies have been compared via laboratory experiments in terms of fresh concrete workability (slump) and 28 days concrete compressive strength. The test results signify that concrete compressive strength and slump can vary up to 21 MPa and 65 mm respectively, at particular mix content because of the differences in aggregate gradations. Effectiveness of different parameters of aggregate gradation namely fineness modulus (FM) of fine aggregate (fa), FM of total aggregate (ta), coarseness factor, workability factor etc. have also been analyzed along with the test results. It has been found that contemporary 'band gradations' of aggregates result in somewhat better properties of concrete when compared with conventional gradations (ASTM C33, BS 882). Accordingly, two band aggregate gradations- '5-10-14-18' and '5-10-18-22' have been developed; for which the ranges of materials retaining on individual sieve sizes are specified in a way that any aggregate gradation falling within the range will also have their FM and fa/ta within a range.

In the next step, compatibility and other features of the '5-10-14-18' and '5-10-18-22' aggregate gradation bands have been examined via another set of laboratory experiments. Variations of concrete properties (compressive strength and slump) due to various possible aggregate gradations within the particular band have been found to follow some specific patterns. To incorporate these variations of concrete compressive strength and slump into mix design, two FM vs. fa/ta charts have been introduced where percentage of variations in these concrete properties are given for various FM and fa/ta values. Finally, these '5-10-14-18' and '5-10-18-22' aggregate gradation bands are applied to prepare a wide array of concrete mixes which are then used to prepare a concrete mix proportioning guideline. Two most available cement types in Bangladesh, CEM I and CEM II/B-M have been used in this concrete mix design method. The proposed concrete mix design method has been found to be advantageous and user-friendly since it considers the effects of cement-water paste volume on concrete properties; and also, for a target strength and slump requirements it provides multiple mix proportions as alternative options to the user. This method can be used to prepare mixes with compressive strength form 2.5 MPa to 55 MPa.

Finally, to examine the performance of proposed concrete mix design method three sets of concrete mixes have been prepared with different target 28 days compressive strengths; 25 MPa, 35 MPa and 45 MPa. It has been found that in case of 28 days compressive strength the mix design method shows an appreciable performance with very low standard deviation (7%). But for concrete workability the mix design results in somewhat greater slump value than the target slump with 44% standard deviation. Apparently, concrete mixes prepared with this proposed method do not result in lower concrete properties (i.e. slump, compressive strength) than the target values.

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Chapter 1

INTRODUCTION

General

Concrete is the most popular and widely used construction material in Bangladesh. It is composed of cement as the main binder along with other materials such as fly ash and slag, aggregate, water and chemical admixtures when required. The cement and water form a paste that hardens and bonds the aggregates together. Concrete is often looked upon as "man-made rock". Concrete is a versatile construction material and adaptable to a wide variety of constructions. Reasons behind such popularity are its high strength, fire resistibility, durability and workability. Another important reason is that, concrete can be produced form locally available materials which makes concrete low cost compared to other construction materials. Mix design or mix proportioning is a method of selection the most economical and practical combination and proportions of the available materials to produce concrete in an optimized way that will satisfy the performance requirements under particular conditions of use. Thus, the intrinsic quality of a mix design method is its address to the locally available materials.

1.1 Background and Present State of the Problem

A prerequisite behind the vast popularity of concrete is to achieve the desirable fresh and hardened properties of concrete which is the consequence of a proper concrete mix design method. Concrete Mix Design is the process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of the required strength, durability, and workability as economically as possible. The proportioning of ingredient of concrete is governed by the required performance of concrete in two states, namely the plastic and the hardened states. Numerous researches already have been accomplished in many countries to find out the optimum proportions of concrete ingredients (Abrams, 1918a, 1918b, 1919a, 1919b, 1919c, 1922; Dunagan, 1940; Goldbeck, 1943, 1950, 1958; Holland, 1990; Kennedy, 1940; Kosmatka et al. 2002;; Richardson, 2005; Shilstone, 1990; Quiroga and Fowler, 2004 Walsh, 1933). As a result, many countries already have their own methods of concrete mix design such as- United states (ACI 211), England (BS 812), Australia (AIS 3600), Europe (EN 206), India (IS 456), Malaysia (MS 523), Japan (JIS) etc. But there is an exceptional scenario in case of Bangladesh. Although some researches were done for concrete materials but none of these were related to concrete mix proportioning using indigenous materials.

Ahmed (1989) attempted to produce a guideline for quality control of concrete. Kaosar (2006) made a study on brick aggregate concrete with varying amount of fly ash content. Research work by Islam (2010) featured the strength gain of concrete mix prepared with locally available Portland composite cements (PCC). It was observed by Islam (2010) that concrete made with locally available PCC cement brands and following ACI method of concrete mix design, neither of the mixes were able to achieve target strength within 28 days (tested with five local cement brands and three target strength). Shamsuddoha (2011) have analyzed the feasibility of making aircrete with autoclave using local materials in Bangladesh. Although, the objectives of the above mentioned studies were quite different from one another but all these studies pointed out the fact, that in Bangladesh it is difficult to achieve the 28-days target compressive strength of concrete particularly when the required strength is above 4000psi.

Noteworthy that, ACI method of concrete mix design is the most popular method in Bangladesh for concrete works. But one major problem lies in the fact that all requirements of these methods may not be possible to fulfill such as, aggregate gradation (i.e. ASTM C33, BS 882). It is still in question that, whether it is possible to achieve this gradation limits using local aggregates, moreover these aggregate gradation requirements and procedure to achieve these gradations are not much common in local concrete production fields in Bangladesh. Aggregate occupies 70 ~ 80% of the volume of the concrete, it is understandable that aggregate affects the various characteristics and properties of concrete (Shetty, 2002). Since required aggregate properties can not be ensured as per the code prerequisite, the concrete mixes as per ACI or BS may not confirm the mix requirements (i.e. strength, workability).

An optimum aggregate gradation and optimum concrete mix ensure the proper utilization of materials and also reduces the cost of concrete production. Thus, there should be proper aggregate gradation and mix design method of concrete which will give better durability, workability and strength properties.

From synthesis of available researches on concrete in Bangladesh, it is understandable that the country still lag far behind in finding an appropriate gradation for locally available aggregates. Also an optimum user-friendly mix design procedure with a view to achieve desired strength as well as other concrete properties has never been proposed particularly for Bangladesh.

1.2 Objectives with Specific Aims and Possible outcome

a) Comparative analysis of different aggregate gradation methodology including some recent aggregate gradation and code suggested gradations.

b) Parametric study of different aspects of concrete mix design methods.

The outcomes of the thesis are a suitable aggregate gradation methodology and a mix design procedure using locally available materials.

1.3 Outline of Methodology

For the ease of research purpose total work was divided into three distinct phases. Each of these phases contains different types of mix proportions and number of mixes based on the particular objectives of that phase. These phases are explained in following sections.

Phase-1: Selection of the Suitable Aggregate Gradation Methodology

Large numbers of aggregate gradation methods are available for concrete mixtures. Various researchers, specifications and codes have suggested different types of aggregate gradations. Along with conventional aggregate gradation procedure (i.e. use two distinct portion-fine aggregate and coarse aggregate), recently many researcher giving an extra emphasis on combined aggregate gradation (Crouch et al. 2000; Shilstone, 1990; Taylor, 1986). Primary objective of this phase of the research have been confined on to the comparison of different existing aggregate gradation methodologies to find out a comparatively better one using locally available aggregates in Bangladesh.

At the end of this phase, two aggregate gradations have been found to give better concrete properties compared to other aggregate gradation methodologies in terms of concrete workability and compressive strength. These aggregate gradations are “5-10-14-18” and “5-10-18-22” band gradations. Details of these band gradations are described in chapter 4. These aggregate gradation bands are also newly proposed through this research work.

Phase-2: Suitability of Selected Aggregate Gradation Bands

This stage of the research mainly focused on the suitability of preliminary selected aggregate gradation methodologies. That is, whether these selected aggregate gradation bands are consistent enough to provide similar kind of concrete properties if the mix proportions are same and aggregate gradation falls anywhere within the prescribed band limits.

From this phase of the research it has been found that, practically it is not possible to achieve the extreme boundary cases of the 5-10-14-18 and 5-10-18-22 gradation bands using locally available aggregates. Thus, the theoretical boundaries of these gradation bands were found to be different from those of practical boundaries. Moreover, since there are only a limited number of sources of fine aggregates in Bangladesh and these sources are also dependent on climatic conditions of this country, large variation of aggregate gradations within a band will not be possible. Thus, any aggregate gradation that falls within the band will exhibit similar kind of concrete properties without much variation. Test results are also evident for this phenomenon.

Phase-3: Laboratory Experiments for Concrete Mix Design

The objective of this stage of the research has been to conduct extensive experimental works to collect the data sets which are prerequisite to produce a concrete mix design method. Thus in this phase, a large number of concrete mixes have been prepared using a wide variation of concrete mix proportions. Two types of local cement brands and aggregate gradations have been employed for the experimental purpose of this phase. Total fifty two concrete mixes have been prepared and tested for density, workability, compressive strength and permeability of concrete in this phase of the research.

1.4 Organisation of the Thesis

The total research work is described in various chapters of this book. Following section briefly explains the content of the chapters –

Chapter 2 describes literature review about concrete, components of concrete, types of cement and aggregates, properties and compositions of cement which affect concrete properties, aggregate gradation and other properties which have effect on concrete properties.

Chapter 3 features the test procedure and results which have been conducted for the source materials (i.e. aggregates and cements) of concrete, test plans and mix proportions of concrete samples at different stages of the research, preparation and testing of the specimens.

Chapter 4 presents different types of gradation methodologies for aggregates. Test results have shown and analyzed to evaluate the performance of different gradation methodologies along with two newly proposed aggregate gradation bands for concrete in terms of concrete compressive strength, density and workability.

Chapter 5 describes the experiments which have been conducted to check the compatibility of "5-10-14-18" and "5-10-18-22" band gradations for concrete mix design. Practical application of the recommended aggregate gradations has also been discussed in this chapter.

Chapter 6 illustrates the test results and analyzes the concrete properties prepared with "5-10-14-18" and "5-10-18-22" band gradations. Finally, based on the test results, a new method of concrete mix design has been proposed in this chapter.

Chapter 7 describes the significant outcomes of the research and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

General

Concrete is a composite construction material, composed of cement (commonly portland cement) and other cementitious materials such as fly ash and slag cement, aggregate (generally a coarse aggregate made of gravels or crushed rocks such as limestone, or granite, plus a fine aggregate such as sand), water and chemical admixtures. The strength, durability and other characteristics of concrete depend upon the properties of its ingredients, proportion of the mix, the method of compaction and other controls during placing, compaction and curing. Concrete solidifies and hardens after mixing with water and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a robust stone-like material.

The word concrete comes from the Latin word "concretus" (meaning compact or condensed), the perfect passive participle of "concresco", from "com-" (together) and "cresco" (to grow).

2.1 Elements of Concrete

The properties of concrete depend on the quantities and qualities of its components. The following sections of this chapter discuss the major elements of concrete and their effects on concrete properties.

2.1.1 Aggregates

Aggregate, the main constituent of concrete, constitutes 60 to 80% of the total volume of concrete. Proper selection of the type and particle size distribution of the aggregates affects the workability and the hardened properties of the concrete. There are two main reasons for increasing the amount of aggregates in concrete. The first is that cement is more expensive than aggregate, so using more aggregate reduces the cost of producing concrete. The second is that most of the durability problems, e.g. shrinkage, freezing and thawing of hardened concrete are caused by cement. Generally, concrete shrinkage increases with increase in cement content; aggregates, on the other hand, reduce shrinkage and provide more volume stability.

2.1.1.1 Effects of Aggregate Characteristics on Concrete Properties

Aggregate characteristics have a significant effect on the behavior of fresh and hardened concrete. Although these effects of aggregate characteristics change continuously as a function of particle size, the following classification usually made in common practice: material retained in the No. 4 sieve named as coarse aggregate, material passing No. 4 sieve and retained in the No. 200 sieve (75 μm) considered as fine aggregate, and material passing No. 200 sieve as microfines. This classification is summarized in Table 2.1. The impact of particle characteristics on the performance of concrete is different for microfines, fine and coarse aggregates as well as the characterization tests required for each of these fractions.

Table 2.1: Classification of Aggregates Based on Particle Size

Aggregate Fraction	**Size Range**
Coarse	Retained in No. 4
Fine	Passing No. 4 – Retained in No. 200
Microfines	Passing No. 200

The main characteristics of aggregate that affect the performance of fresh and hardened concrete are:

- Grading
- Maximum size
- Shape
- Texture
- Absorption
- Mineralogy and coatings
- Strength and stiffness
- Specific gravity or relative density
- Soundness
- Toughness

Some of these important characteristics and their effects on fresh and hardened properties of concrete have been discussed in this chapter.

2.1.1.2 Effects of Maximum Size of Aggregate

Maximum size of aggregates (MSA) influences workability, strength, shrinkage, and permeability. Mixtures with large maximum size of coarse aggregate tend to produce concrete with better workability because of the decrease in specific surface (Washa, 1998). There is an optimal maximum size of coarse aggregate that produces the highest strength for a given consistency and cement content (Popovics, 1998; Washa, 1998). For example, in high-performance concrete (HPC) with low water-cement ratio and high cement content, a high value of MSA tends to reduce strength. This can be explained by the observation that bond with large particles tends to be weaker than with small particles due to smaller surface area-to-volume ratios. Mixtures with coarse aggregate with large maximum size tend to have reduced shrinkage and creep (Washa, 1998). Finally, for a given water-cement ratio, the permeability increases as the maximum size of the aggregate increases (Helmuth, 1994).

2.1.1.3 Effects of Aggregate Grading

Grading or particle size distribution affects significantly some characteristics of concrete like packing density, voids content, workability, segregation, durability and some other characteristics of concrete. Particle size distribution of fine aggregate plays a very important role on workability, segregation, and pumpability of fresh concrete. Many authors claim that uniformly distributed mixtures produce better workability than gap-graded mixtures (Golterman, 1997; Glavind, 1993; Johansen, 1989; Johansson, 1979), although higher slumps can be achieved with gap-graded mixtures. Some properties of hardened concrete are also affected by grading. Uniformly distributed mixtures generally lead to higher packing resulting in concrete with higher density and less permeability (Golterman, 1997; Glavind, 1993; Johansen, 1989), and improved abrasion resistance (Mehta, 1993). Consequently, uniformly distributed mixtures require less paste, thus decreasing bleeding, creep, and shrinkage (Washa, 1998; Shilstone, 1999). Finally, Aitcin (1998) emphasizes that although an excess of coarse aggregate could decrease drying shrinkage it will increase the amount of microcracks within the paste.

The scarcity or excess of any size fraction could result in poor workability and in poor durability of concrete (Galloway, 1994; Shilstone, 1990). The amounts of coarse and fine aggregate must be in balance. For example, excess sand requires more cementitious materials, produces sticky mixtures, makes pumping difficult, causes finishing and crazing problems (Shilstone, 1999), and increases bleeding and permeability (Mindess, 1981). On the other hand, insufficient sand produces "bony" mixtures and other types of finishing problems (Shilstone, 1990; Mindess, 1981).

Both coarse aggregate and fine aggregate should be uniformly graded. If fine aggregate is too coarse it will produce bleeding, segregation and harshness, but if it is too fine, the demand for water will be increased (Galloway, 1994). Proper grading should depend on shape and texture of aggregates. For instance, suitable grading for natural sands could lead to bad results when using manufactured sands (Hudson, 1999; Johansson, 1979). Grading should also be changed depending on the construction procedures. For example, pumpable concrete requires a high fine aggregate content just as hand finishing requires more fines passing the No. 50 sieve than mechanical finishing does (Galloway, 1994).

The effect of grading on strength is controversial. Although, according to some authors, a given strength can be achieved with both well-graded mixtures and poorly graded mixtures (Shilstone, 1990), some studies indicate that increased strength concrete can be achieved with well-graded mixtures (Cramer, 1995).

Permeability, one of the most important factors affecting concrete durability, is significantly related to void content of aggregate mixture: the lesser the void content, the lesser the permeability. In reducing permeability, it is desirable to have the highest aggregate content possible. Consequently, well-graded mixtures produce concrete that is more durable.

Unfortunately, previous versions of ASTM C 33 may have contributed to problem concrete mixtures (Shilstone, 1994), since aggregate complying with ASTM C 33 could lead to gap grading or at least to an excess of one size and the specification did not address the use of blends. The current version of ASTM C 33 permits the use of blends, such that the resultant aggregate will have better characteristics than the original aggregates.

The particle size distribution of microfines may have an effect on concrete behavior. However, due to the inherent difficulties related to the characterization of such small particles, little research has been made to evaluate the effect of grading, shape and texture of microfines on concrete behavior. Ahn (2000) determined the size distribution of the microfines in his research using a laser diffraction scanner and a hydrometer, in terms of weight and in terms of volume, respectively. It was found that the effect of different types of microfines with distinct grading on fresh concrete behavior was clearly dissimilar. However, the effect of grading was not separated from the effect of shape and texture, and was not quantitatively determined.

2.1.1.4 Tools of Aggregate Gradation

(i) Fineness Modulus

In 1918 Abrams developed the method of aggregate gradation, Fineness Modulus (FM). Current practices involve the use of FM of fine aggregate for calculation of required amount of coarse aggregate. But still the total effects of FM of fine aggregate on concrete properties are not clear -

(i) Surface area of aggregates is the most important factor that affects concrete properties. But fineness modulus and surface area are not related (Abrams, 1918; Williams, 1922; Hewes, 1924; Besson, 1935)

(ii) For any single FM there could be numerous gradations of various aggregate contents.

(iii) Many researchers did not support FM as a useful tool (Edwards, 1918; Young, 1919; Young, 1921; Besson, 1935; Kennedy, 1940; Mercer, 1948)

(iv) Changes in gradation can render little change in calculated FM, but the workability of concrete could be significantly changed.

(ii) Coarseness Factor

Shilstone introduced coarseness factor derived from the aggregate gradation to predict the workability of the concrete mix. Coarseness Factor (CF) is the proportion of plus 3/8inch coarse particles in relation to the total coarse particles, expressed as a percent.

Shilstone divided the total gradation into three fractions-

(i) Coarse Fraction (Q): Materials retained on 3/8" sieve.

(ii) Intermediate Fractions (I) : Passing 3/8" sieve and retained #8

(iii) Fine Fraction (W): Passing #8 and retained on # 200.

Thus coarseness factor expressed as,

$$CF = \left[\frac{Q}{Q+I} \right] \times 100\%$$

A CF=100 would represent a gap-graded aggregate where there was no #8 to 3/8inch material. A CF=0 would be an aggregate that has no material retained on the 3/8inch sieve.

(iii) Workability Factor

This is another factor developed by Shilstone to asses the workability of concrete mix. Workability Factor (W) is the percentage of material passing #8 sieve.

An alternative designation is the "Adjusted workability factor (W-adj)". The W-adj factor reflects the influence of the amount of cementitious material on workability.

(iv) Mortar Factor

The mortar factor consists of all materials in the mix that passes the #8 sieve The key is to keep the paste at a minimum while having enough available to produce a durable finish. Specific mortar factor for various construction types and aggregate sizes are found in ACI 302.1R. The lowest mortar factor possible is recommended—52% to 54% for 1½ inch maximum-size aggregate and 53% to 55% for 1 inch maximum-size aggregate.

(v) Gradation Curve

In gradation curve the percent passing of aggregate is plotted against sieve opening sizes. Traditionally this curve is used to define good-graded, gap-graded and poorly-graded mix. Figure 2.1 shows the gradation curve of a uniformly graded aggregate sample.

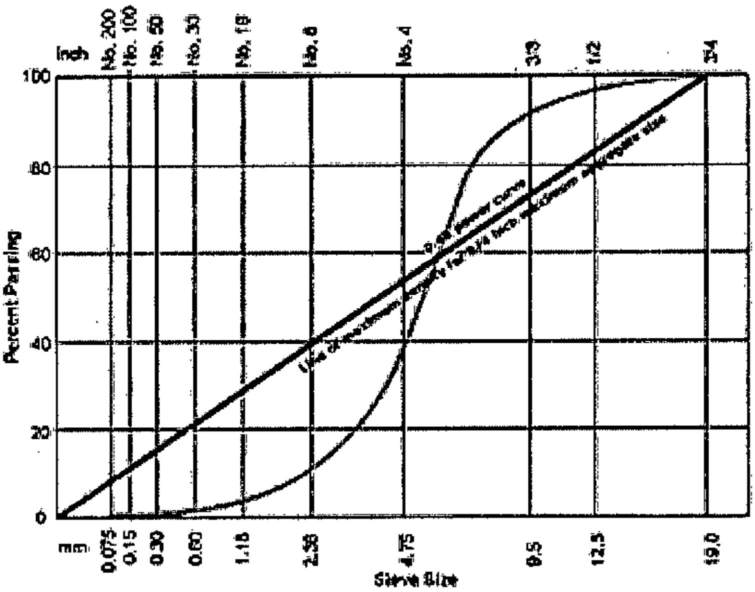


Figure 2.1: Uniformly Graded Aggregate in Gradation Curve (% Finer vs. Sieve Opening)

(vi)Individual Percent Retained Curve

Individual percent retained (IPR) vs. sieve sizes or sieve number is another method of representing the particle size distribution of an aggregate sample.

(i) Shilstone (1990) promoted the use of IPR curve, since it is very easy to determine which sizes are excessive or deficient.

(ii) The ideal IPR curve for uniformly distributed aggregate should be as shown in figure. But practically the IPR curve for such aggregate is nearly "haystack" in shape (Shilstone, 1990).

(iii) Whitten (1998) in a laboratory test adjusted the aggregate grading into a more "haystack" form and got nearly 5% increases in strength while preserving the slump at slightly lower cement content.

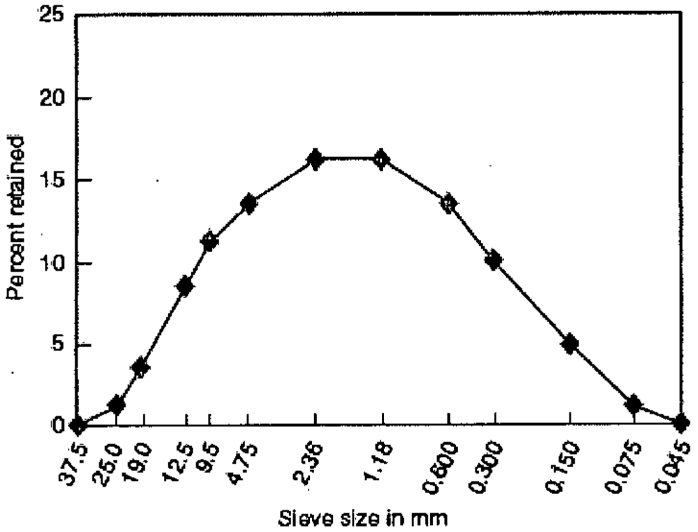


Figure 2.2: Uniformly Graded Aggregate in IPR Curve

(vii) 0.45 Power Chart

The Power Chart is a plot of the percent passing each sieve size and the sieve size in microns to the 0.45 power. A well graded, tight packing aggregate that produces a maximum density will approximately plot along a straight line. This straight line is the Power Chart line and may be plotted using the following equation.

0.45 power chart, commonly used for asphalt work.

$$\%\ Passing = \left(\frac{d}{D}\right)^{0.45} \qquad Power\ Chart\ Line$$

Where,

d = Square opening of the sieve size being considered.

D = Square opening of the nominal Maximum Sieve size.

(viii) Coarseness-Workability Factor Chart

Shilstone (1990) first introduced the coarseness- workability factor chart to show the relationship between CF, WF (or WF-adj), and characteristics of the mix, such as harshness, sandiness, excessive shrinkage, pumpability, finishing characteristics, degree of gap-grading, prone to segregation, and so forth.

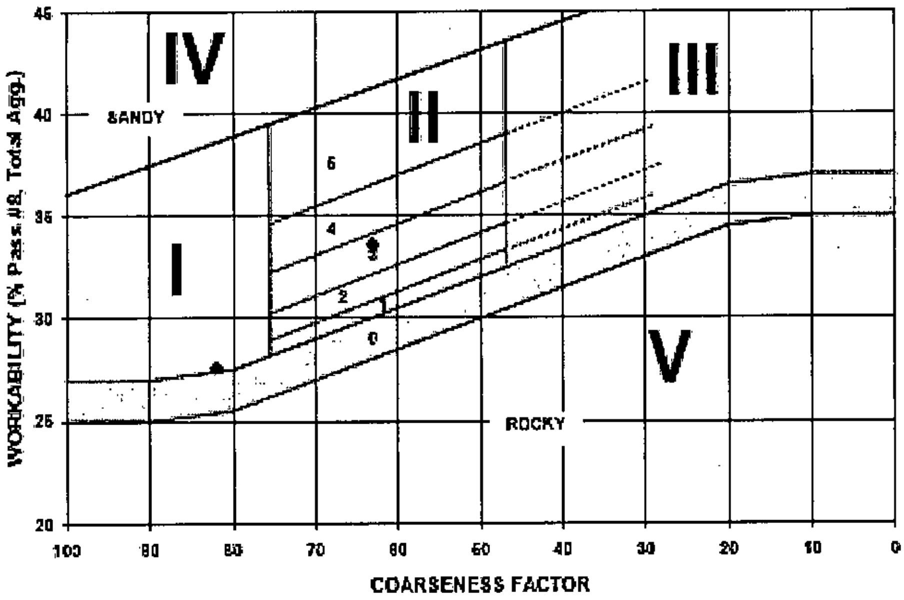


Figure 2.3: Coarseness Factor chart

Figure 2.3 shows a revised version of CF chart (Shilstone and Shilstone Jr. 1997). This version of the CF chart has additional delineation zones for prediction of properties:

Zone-I. Coarse, Gap-graded, tends to segregate.

Zone-II. Well-graded 1-1/2 inch, best spot for everyday mixes, depending on use. This zone again divided into five areas.

II-1. Excellent but caution.

II-2. Excellent paving and slip form.

II-3. High quality slab.

II-4. Good general.

II-5. Varies to materials and construction needs.

These trends cross into zone-III (Shilstone and Shilstone Jr. 1999)

Zone-III. 3/4 inch and finer (pea gravel mixes).

Zone-IV. Over sanded, sticky.

Zone-V. Rocky (suitable for mass concrete).

(ix) Combined fineness modulus

Abrams (1918) first introduced the idea of Fineness Modulus as a tool of aggregate gradation. The main drawback of FM is that for any single FM there could be numerous gradations of various aggregate contents (Besson 1935). Although the uses of fineness modulus of only fine aggregate are highly discouraging, but there have some recent interest in using the fineness modulus of combined (total) aggregate (Richardson 2005, Taylor 1986).

2.1.1.5 Effects of Aggregate Shape

The shape of the aggregate particles influences paste demand, placement characteristics such as workability and pumpability, strength and cost. (O'Flynn, 2000). Shape is related to sphericity, form, angularity, and roundness (Quiroga and Fowler, 2004; Galloway, 1994).

(a) The ***sphericity*** measures how nearly equal are the three principal axis of the aggregate (length *L*, width *W*, and height *H*). The sphericity increases as the three dimensions approach equal values. (Brzezicki and Kasperkiewicz, 1999; Quiroga and Fowler, 2004; Graves, 2006)

(b) The ***form or the shape factor***, describes the relative proportions of the three axes of a particle. It helps distinguish between particles that have the same sphericity (Quiroga and Fowler, 2004; Graves, 2006; Hudson, 1999).

(c) The ***angularity*** describes the proportions of the average radius of curvature of corners and edges to the radius of maximum inscribed circle (Quiroga and Fowler, 2004; Graves, 2006).

(d) The ***roundness*** describes the sharpness of the edges and corners (Lamond and Pielert, 2006; Quiroga and Fowler, 2004; Graves, 2006).

The descriptions of angularity and roundness are detailed here and illustrated in Figure 2.4

(a) ***Angular***: little evidence of wear on the particle surface.

(b) ***Subangular***: evidence of some wear, but faces untouched.

(c) ***Subrounded***: considerable wear, faces reduced in area.

(d) ***Rounded***: faces almost gone.

(e) ***Well rounded***: no original faces left.

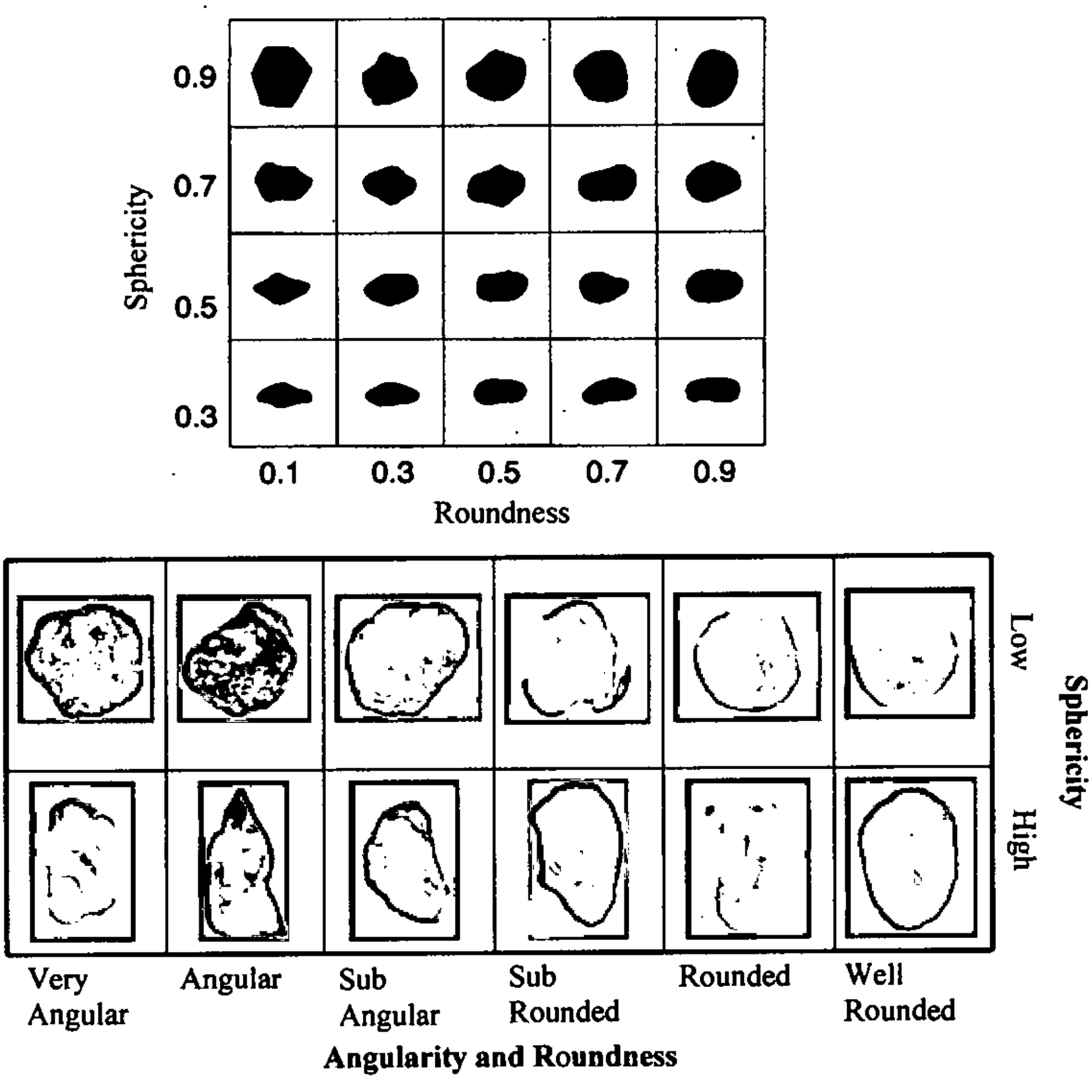


Figure 2.4: Visual Assessment of Particle Shape [Powers, 1953; Krumbein, 1963] (a) Derived from Measurements of Sphericity and Roundness (b) Based upon Morphological Observations

Round or nearly cubical shaped aggregates are desirable due to the ease in which they move in the mixing and handling process. However, aggregate can also contain flat or elongated shapes. Methods used to measure the shape of aggregates are the elongation factor and flatness factor (ASTM C 125). A flat particle has a width/thickness ratio greater than or equal to 3, while an elongated particle has a length/width ratio greater or equal to 3. Specifications usually define limiting elongation ratios of 3:1 or 5:1 to describe undesirable shapes of aggregates. The shape can modify the strength of the concrete, as in the case where a thin, flat particle is oriented in the hardened concrete where outside stresses are introduced (Graves, 2006).

The shape of natural aggregates depends on the strength, abrasion resistance, and on the degree of wear to which they have been subjected in their depositional environment. Natural aggregates tend to be more spherical and less angular. On the other hand, the shape of manufactured aggregate depends on the rock type and the crushing equipment. Manufactured aggregates are more angular when compared to natural aggregates.

The shape of an aggregate influences the workability of the mixture as well as the void content and packing density. For the same amount of paste, a mixture with round or cubical shaped aggregate will have better workability than a mixture with flaky and elongated aggregates. Moreover, for the same mass of aggregates, round and cubical aggregates produce mixtures with higher packing, which results in a lower void content. The decreased percentage of voids lowers the amount of cement paste required for that particular mixture. Some specifications, such as the Spanish or British standards (Quiroga and Fowler, 2004), limit the percent of use of flaky and elongated particles, but ASTM has no distinct limits. Some state transportation departments (DOTs) have set limits on the percentage of flaky and elongated particles ranging from 8 to 20%.

2.1.1.6 Effects of Aggregate Texture

Surface texture is the degree to which the surface may be defined as either: 1) being rough or smooth (referring to the height of asperities) or 2) coarse grained or fine grained (referring to the spacing between grains) (Graves, 2006). Again, Dolar-Mantuani defined the surface texture of particles (also called surface roughness) as the sum of their minute surface features (Dolar-Mantuani, 1983).

The surface texture influences the workability, quantity of cement and bond between particles and the cement paste. Two independent geometric properties are the roughness or rugosity (degree of surface relief) and the roughness factor (the amount of surface area per unit of dimensional or projected area) (Graves, 2006).

Natural aggregates have a smooth surface (Lamond and Pielert, 2006). Natural gravel subject to transport mechanisms tends to be smoother than manufactured aggregates. For instance, gravel would have a surface smoother than crushed limestone. Nevertheless, there is no reliable method to determine the surface texture of manufactured aggregate (Ahn and Fowler, 2001).

For Masad (2002), texture in an image is represented by the local variation in the pixel gray intensity values. Then wavelet theory is used for multi-scale analysis of textural variation on aggregate images. The original image is decomposed into low-resolution images by iteratively blurring the original image. As a result, images that contain information on fine intensity variation are obtained. The process could be repeated again with these images and texture quantification can be made at different scales. In this way, values for the coarser and finer texture of the sample can be obtained.

An improvement in the bond to the matrix is obtained as the surface roughness increases (Ahn and Fowler 2001). Rough-textured angular grains bond better with the cement paste to generate higher tensile strengths (O'Flynn, 2000). The strength of the bond between cement and aggregate increases as absorption increases, but the durability decreases with an absorption increase (Quiroga and Fowler, 2000). Although rougher textures lead to better bond between paste and aggregate, they also lead to harsher mixtures, as texture roughness increases, the internal friction increases between the aggregates, and therefore more paste is needed to achieve a given workability.

2.1.2 Cement

Cement is the most active component of concrete and usually has the greatest unit cost, hence, its selection and proper use are important in obtaining most economically the balance of properties desired for any particular concrete mixture.

Portland cement (often referred to as OPC, from Ordinary Portland Cement) is the most common type of cement in general use around the world because it is a basic ingredient of concrete, mortar, stucco and most non-specialty grout. It is a fine powder produced by grinding Portland cement clinker (more than 90%), a limited amount of calcium sulfate (which controls the set time) and up to 5% minor constituents as allowed by various standards such as the European Standard EN 197-1.

Portland cement clinker is a hydraulic material which shall consist of at least two-thirds by mass of calcium silicates ($3\,CaO{\cdot}SiO_2$ and $2\,CaO{\cdot}SiO_2$), the remainder consisting of aluminum- and iron-containing clinker phases and other compounds. The ratio of CaO to SiO_2 shall not be less than 2.0. The magnesium oxide content (MgO) shall not exceed 5.0 % by mass.

Portland cement clinker is made by heating, in a kiln, a homogeneous mixture of raw materials to a sintering temperature, which is about 1450 °C for modern cements. The aluminum oxide and iron oxide are present as a flux and contribute little to the strength. For special cements, such as Low Heat (LH) and Sulfate Resistant (SR) types, it is necessary to limit the amount of tricalcium aluminate (3 $CaO \cdot Al_2O_3$) formed. The major raw material for the clinker-making is usually limestone ($CaCO_3$) mixed with a second material containing clay as source of alumino-silicate. Normally, an impure limestone which contains clay or SiO_2 is used. The $CaCO_3$ content of these limestones can be as low as 80%. Second raw materials (materials in the raw mix other than limestone) depend on the purity of the limestone. Some of the second raw materials used are: clay, shale, sand, iron ore, bauxite, fly ash and slag. When a cement kiln is fired by coal, the ash of the coal acts as a secondary raw material.

2.1.2.1 Effects of Cement Compositions on Concrete Properties

Effects of cement on the most important concrete properties are presented in Table 2.2.Cement composition and fineness play a major role in controlling concrete properties. Fineness of cement affects the placeability, workability, and water content of a concrete mixture much like the amount of cement used in concrete does.

Cement composition affects the permeability of concrete by controlling the rate of hydration. However, the ultimate porosity and permeability are unaffected (ACI Comm. 225R 1985; Powers et al. 1954). The coarse cement tends to produce pastes with higher porosity than that produced by finer cement (Powers et al. 1954). Cement composition has only a minor effect on freeze-thaw resistance. Corrosion of embedded steel has been related to C_3A content (Verbeck 1968). The higher the C3A, the more chloride can be tied into chloro-aluminate complexes—and thereby be unavailable for catalysis of the corrosion process.

2.1.2.2 Effects of Cement Types on Concrete Strength

The ultimate compressive strength and rate of strength development of concrete is strongly influenced by the chemical reactivity of the cement. Varying hydration rates of the different cement compounds can help explain how the relative proportions of these compounds affect the rate of strength gain. For instance, the C_2S reacts slowly and contributes to long-term strength gain. C_3S, on the other hand, has a much faster hydration rate, and contributes to higher early-strength gain. Thus, cement with a higher proportion of C_3S – as is the case with most of today's cements – will tend to have a higher early strength, and allow for early form removal or post-tensioning. Figure 2.4 shows the strength gaining of cement mortars for different types of cements following the ASTM classification.

Table 2.2: Effects of Cements on Concrete Properties

Cement Property	**Cement Effects**
Placeability	Cement amount, fineness, setting characteristics
Strength	Composition (C_3S, C_2S and C_3A), loss on ignition, fineness
Drying Shrinkage	SO_3 content, cement composition
Permeability	Cement composition, fineness
Resistance to sulfate	C_3A content
Alkali Silica Reactivity	Alkali content
Corrosion of embedded steel	Cement Composition (esp. C_3A content)

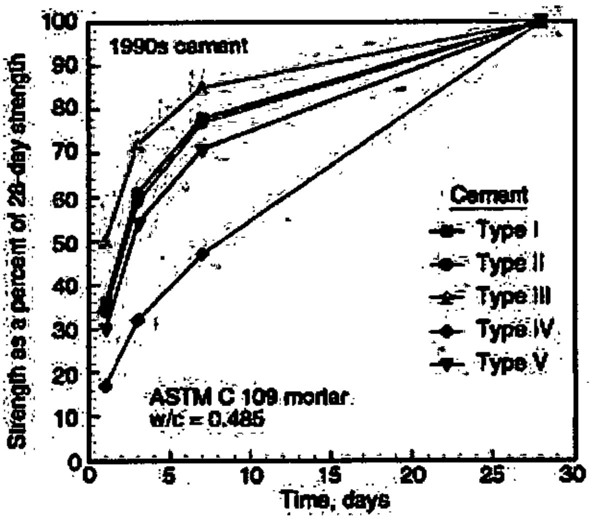


Figure 2.5: Strength Gaining with Time for Various Types of Cements (ASTM Classification)

2.1.2.3 Effects of Cement Types on Concrete Workability

Concrete slumps for various types of cements shown in figure 2.10. Highest slump range was observed for CEM II cements. The medium grade was observed for the rest normal setting CEM I type of cement. Since the water consumption is related to rates of hydration and heat evolution, it has been observed that grade 52.5 has high rate of hydration. The high slump of CEM II cement mixes can be correlated to low clinker content.

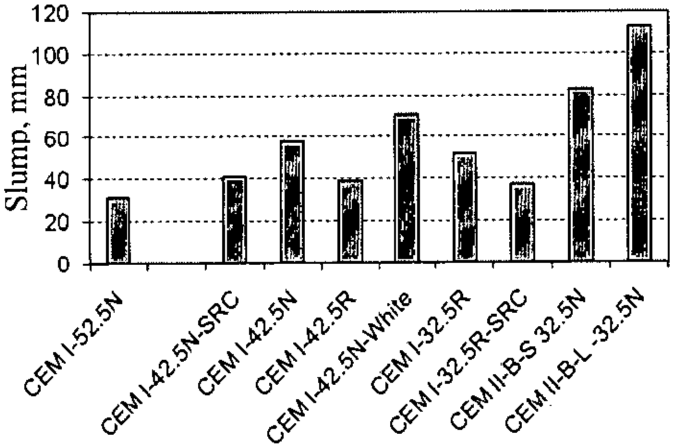


Figure 2.6: Slump Variations for Various Types of Cements (EN 197 Classifications)

2.1.3 Mineral Additives

2.1.3.1 Types of Mineral Additives

(I) Artificial Pozzolana

Artificial pozzolans are the by-products of various thermal treatments, such as burnt shale, silica fume, fly ash, slag, etc.

(II) Silica fume (D)

Silica fume, also called condensed silica fume and micro silica, is a finely divided residue resulting from the production of elemental silicium or ferrosilicon alloys that is carried from the furnace by exhaust gases (Nawy, 2008).

(III) Granulated Blast Furnace Slag (S)

In the production of iron, iron ore is smelted in a blast furnace. During this process, molten iron that is collected in the bottom of the furnace and liquid iron blast furnace slag floating on the pool of iron, are periodically tapped from the furnace at a temperature of 1400-1500°C (Hewlett, 2005). Granulated blast furnace slag is made by rapid cooling of a slag melt which contains at least two-thirds by mass of glassy slag and has hydraulic properties. It is stated in TS EN 197-1 that granulated blast furnace slag composition shall have at least two-thirds by mass of the sum of calcium oxide (CaO), magnesium oxide (MgO) and silicon dioxide (SiO_2). The rest of the composition is aluminiumoxide (Al_2O_3) together with small amounts of other compounds. Also, (CaO + MgO)/(SiO_2) ratio by mass shall exceed

1.0 (TS EN 197-1)

(IV) Fly Ash (V, W)

Fly ash is a finely divided residue that results from the combustion of pulverized coal and is carried from the combustion chamber of the furnace by exhaust gases. Commercially available fly ash is a by-product of thermal power plants (Nawy, 2008). TS EN 197-1 divides fly ashes into two groups; namely, siliceous and calcareous fly ashes.

(a) Siliceous fly ash (V)

Siliceous fly ash, a fine powder of mostly spherical particles having Pozzolanic properties, consists mainly of reactive SiO_2 and Al_2O_3 (TS EN 197-1).

(b) Calcareous fly ash (W)

Calcareous fly ash, a fine powder having both hydraulic and/or pozzolanic properties, consists mainly of reactive CaO, SiO_2 and Al_2O_3 (TS EN 197-1).

(V) Burnt Shale (T)

Burnt shale is another cementitious constituent used in cement production. Burnt shale is produced by burning of oil shale in fluidized bed furnace at temperatures between 600 and 800°C and composed of clinker phases, mainly dicalcium silicate and monocalcium aluminate.

(VI) Limestone (L, LL)

Limestone, a sedimentary rock, consists mainly of calcium carbonate; the most stable form is calcite. Limestone often contains Mg, Al and Fe combined as carbonates and silicates. It is stated in TS EN 197-1 that in order to use limestone as a constituent in cement, calcium oxide content should be at least 75% by mass. Moreover, limestone is divided into two groups in TS EN 197-1 according to its Total Organic Carbon (TOC) content. If TOC value does not exceed 0.20 % by mass, the limestone is demonstrated with LL. If TOC value does not exceed 0.50 % by mass, then the limestone is demonstrated with L (TS EN 197-1).

2.1.3.2 Effects of the Mineral Additives on Mortar and Concrete Properties

Mineral additives influence the properties of cements and concretes. The following subsections present the effects of main constituent of cement on water requirement, workability and strength.

(I) Water Requirement

The amount of mixing water required for a specified consistency of a mortar or concrete is called as water requirement, determined by mortars, of cement mortar or concrete. Adding excess or less amount of water can lead to adverse results on the strength of cement mortar or concrete. Therefore, it is required to determine how much water is sufficient for the cement mortar or concrete. Cementitious materials have different impacts on the water requirement of cement mortar or concrete since they have different particle size, shape, particle size distributions etc. For example, natural pozzolans have significant effect on water demand of concrete. Since the natural pozzolans increase the specific surface area, cements containing natural pozzolans have higher water requirement as compared to ordinary portland cement (Pan et al., 2003). The same effect is also observed when clinker is replaced with silica fume in cement. Therefore, there is a limit in water requirement in TS EN 197-1, because of the high fineness of silica fume.

However, for a given slump, water requirement of a cement containing fly ash may be less than the water requirement of Portland cement. Although the dosage of fly ash increases the water reduction, not all fly ash does the same effect on mortar. Brink and Halstead reported that the water demand increases as the carbon content of the fly ash increases (Brink, 1956).

(II) Workability

There are several factors affecting workability such as quantity and characteristics of cementing materials, and amount of water etc. The lubricant effect and morphology improvement on cement mortar or concrete of natural pozzolans increase with an increase in fineness of the cementitious materials (Pan et al., 2003). As a result, natural pozzolans improve the consistency and the workability of the concrete. Yijin et al. (2004) studied the usage of fly ashes having different fineness as a cementitious material replacing the clinker in cement and replacing cement in concrete (Yijin et al., 2004). They found out that fly ash improves the workability of cement mortar or concrete due to their spherical shape causing “ball bearing” effect. Also, the water requirement of concrete containing ground granulated blast furnace slag decreases with the increase in the amount of ground granulated blast furnace slag (Bartos, 1993).

(III) Strength

Supplementary cementitious materials such as fly ash, ground granulated blast furnace slag, burnt shale and silica fume contribute to the strength gain of concrete. However, the characteristics of the supplementary materials and replacement level limit them for the strength gain of concrete (Wesche, 1991). For example, pozzolanic reactivity of the fly ash is one of the limiting parameter. In addition to cementitious materials used, test type is another factor affecting the strength. As the size of the specimen, moisture content of the specimen, the rate of loading and type of test machine change, the strength results change.

2.2 Concrete Mix Design

The process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of the required, strength, durability, and workability as economically as possible, is termed the concrete mix design. The proportioning of ingredient of concrete is governed by the required performance of concrete in two states, namely the plastic and the hardened states. If the plastic concrete is not workable, it cannot be properly placed and compacted. The property of workability, therefore, becomes of vital importance.

The various factors affecting the mix design are:

(i) Compressive strength

It is one of the most important properties of concrete and influences many other describable properties of the hardened concrete. The mean compressive strength required at a specific age, usually 28 days, determines the nominal water-cement ratio of the mix. The other factor affecting the strength of concrete at a given age and cured at a prescribed temperature is the degree of compaction. According to Abraham's law the strength of fully compacted concrete is inversely proportional to the water-cement ratio.

(ii) Workability

The degree of workability required depends on three factors. These are the size of the section to be concreted, the amount of reinforcement, and the method of compaction to be used. For the narrow and complicated section with numerous corners or inaccessible parts, the concrete must have a high workability so that full compaction can be achieved with a reasonable amount of effort. This also applies to the embedded steel sections. The desired workability depends on the compacting equipment available at the site.

(iii) Durability

The durability of concrete is its resistance to the aggressive environmental conditions. High strength concrete is generally more durable than low strength concrete. In the situations when the high strength is not necessary but the conditions of exposure are such that high durability is vital, the durability requirement will determine the water-cement ratio to be used.

(iv) Maximum nominal size of aggregate

In general, larger the maximum size of aggregate, smaller is the cement requirement for a particular water-cement ratio, because the workability of concrete increases with increase in maximum size of the aggregate. However, the compressive strength tends to increase with the decrease in size of aggregate.IS 456:2000 and IS 1343:1980 recommend that the nominal size of the aggregate should be as large as possible.

(v) Grading and type of aggregate

The grading of aggregate influences the mix proportions for a specified workability and water-cement ratio. Coarser the grading leaner will be mix which can be used. Very lean mix is not desirable since it does not contain enough finer material to make the concrete cohesive.

The type of aggregate influences strongly the aggregate-cement ratio for the desired workability and stipulated water cement ratio. An important feature of a satisfactory aggregate is the uniformity of the grading which can be achieved by mixing different size fractions.

(vi) Quality Control

The degree of control can be estimated statistically by the variations in test results. The variation in strength results from the variations in the properties of the mix ingredients and lack of control of accuracy in batching, mixing, placing, curing and testing. The lower the difference between the mean and minimum strengths of the mix lower will be the cement-content required. The factor controlling this difference is termed as quality control.

2.3 Existing Concrete Mix Design Methods

Mix design is a process of specifying the mixture of ingredients required to meet anticipated properties of fresh and hardened concrete. Concrete mix design is a well established practice around the world. All developed countries, as well as many developing countries, have standardized their concrete mix design methods. These methods are mostly based on empirical relations, charts, graphs, and tables developed as outcomes of extensive experiments and investigations of locally available materials. All of those standards and methods follow the same basic trial and error principles.

There are many methods of concrete mix design. But each of methods will not be applicable for any countries, as the specific relationships constituting figures and tables are based on their materials (Maiti et al., 2006).

Some of the prevalent concrete mix design methods are:

- (i) ACI Mix Design Method,
- (ii) USBR Mix design practice,
- (iii) British Mix design Method, and
- (iv) ISI Recommended guidelines.

Rational proportioning of the ingredients of concrete is the essence of concrete mix design and its purpose is to ensure most optimum proportions of the constituent materials to meet the requirements of the structure being built. The mix design should ensure that, the concrete,

- (i) Complies with the specification of structural strength laid down, which is usually stated in terms of the compressive strength of standard test specimens.
- (ii) Complies with the durability requirements to resist the environment in which the structure will serve its functional life
- (iii) Be capable of being mixed, transported, compacted and placed as efficiently as possible
- (iv) Be as economical as possible

It should however be stressed that the data used in proportioning should be expected merely to serve as a guide; they should be backed up by personal experience and knowledge of basic principles of concrete mix design. Based on the observations made on the trial mixes, the mix proportions have to be adjusted and the refinement carried to the stage where the optimum proportion have been attained.

To sum up "concrete mix design" is still very much a problem of trial-and-error and any calculations based on design data are really only a means of providing, at best, a starting point so that the first test can be conducted.

2.3.1 American Concrete Institute Method of Concrcte Mix Design

This method of proportioning was published by ACI committee 613. In 1954 the method was revised to include the use of air entrained concrete among other modification. One method is based on the estimated weight of the concrete per unit volume. The other method is based on calculation of the absolute volume occupied by concrete ingredients. The ACI methods take into consideration the requirements for workability, consistency, strength and durability. It has the advantages of simplicity in that it applies equally well, and with more or less identical procedures to rounded or angular aggregate, to regular or light weight aggregates and to air entrained or non air entrained concretes. The methods suggested by the ACI Committee 211 (1969) are widely used in the USA.

Procedure

1. From the minimum strength specified, estimate the average design strength.
2. Find the water-cement ratio from the strength point of view, find also water- cement ratio from durability point of view from table.
3. Decide the maximum size of aggregate to be used.
4. Decide workability in terms of slump.
5. The total water in kg/m^3 of concrete is read from table, entering the table with selected slump and selected maximum size of aggregates.
6. Cement content is computed by dividing the total water content by the water-cement ratio.
7. From the table, the bulk volume of dry rodded coarse aggregates per unit volume of concrete is selected for the particular maximum size of coarse aggregate and fineness modulus of fine aggregate.
8. The weight of coarse aggregate per cubic meter of concrete is calculated by multiplying the bulk volume with bulk density.
9. The solid volume of coarse aggregate in one m^3 of concrete is calculated by knowing the specific gravity of coarse aggregate.
10. Similarly the solid volume of cement, water and volume of air is calculated in on cubic meter of concrete
11. The solid volume of sand is computed by subtracting from the total volume of concrete, the solid volume of cement, coarse aggregate, water and entrapped air
12. Weight of fine aggregate is calculated by multiplying the solid volume of fine aggregates by its specific gravity.

2.3.2 DOE Method of Concrete Mix Design

The DOE method was first published in 1975 and then revised in 1988.While the road note

No.4 or grading curve method was specifically developed for concrete pavements. The DOE method is applicable to concrete for most purposes, including roads. The method can be used for concrete containing fly ash.

Procedure

1. Find the target mean strength from the specified characteristic strength.
2. Calculate the water-cement ratio.
3. Decide the water content for the required workability expressed in terms of slump or vee bee time, taking into consideration the size of aggregates and its type from table.
4. Cement content is calculated simply by dividing the water content by water cement ratio.
5. Find out the total aggregate content. This requires an estimate of the wet density of the fully compacted concrete. This can be found out for approximate water content and specific gravity of aggregate.
6. Then proportion of fine aggregate is determined in the total aggregate knowing the workability, maximum size of aggregates and percent of fine aggregates passing through 600μ sieve. Once the proportion of fine aggregate is obtained, the amount aggregate content can be calculated by multiplying the proportion to the weight of total aggregate.
7. Then the water of coarse aggregate can be found out from total aggregate.

2.3.3 Indian Standard Recommended Method of Concrete Mix Design

The bureau of Indian standards, recommended a set of procedures for the design of concrete mix mainly based on the work done in national laboratories. The Mix design procedures are sentenced in IS 10262-1982.The methods given can be applied for both medium and high strength concrete.

Procedure

1. Target mean strength for mix design is calculated.
2. Water-cement ratio can be found out from a graph showing the relation between strength and water cement ratio.
3. The air content is estimated from table for the nominal maximum size of aggregate used.

4. The water content in percent of fines in total aggregate by absolute volume is determined by the maximum size of aggregates.
5. The cement content per unit volume of concrete may be calculated from free water cement ratio and cement content per unit volume.
6. Calculation of aggregate is done by the following two formulas

$$V = [w+(c/Sc) + (1/p)*(1/1000)$$

$$Ca = [(l-p)/p]* F.agr *(S_{ca} / S_{fa})$$

V = absolute volume of fresh concrete, which is equal to gross volume (m^3) - the volume of entrapped air.

W = mass of water (kg) per m^3 of concrete.

C = mass of cement (kg) per m^3 of concrete.

Sc = specific gravity of cement.

P = ratio of FA to total aggregate by absolute volume.

Actual qualities required for mix are calculated by adjusting the proportion for the water content and absorption of aggregates. The calculated mix proportions shall be checked by means of trial batches.

2.3.4 USBR Method of Concrete Mix Design

In USBR (United States Bureau of Reclamation) method of mix design, the water content of air entrained concrete and the proportions of fine and coarse aggregates are determined for a fixed workability and grade of fine aggregates.

Procedure

1. The water cement ratios for the target mean 28 day compressive strength of concrete is determined from table.
2. Approximate air and water contents and the percentages of coarse aggregate per cubic meter concrete are determined from the table, for concrete containing natural fineness modulus of 2.75 and having workability of 75 to 100mm.
3. Adjustment of values in water content and percentage of sand or coarse aggregate are made as provided in table for changes in the fineness modulus of sand, slump of concrete, air content, water-cement ratio and sand content.

4. The cement content is calculated using the selected water-cement ratio and the final water content of the mix is arrived after adjustments.
5. Proportions of aggregates are determined by estimating the quality of coarse aggregate from the table or by computing the total solid volume of sand and coarse aggregate in the concrete mix and multiplying the final percentage after adjustment.

CHAPTER 3

PREPARATION AND TESTING OF SPECIMENS

General

A wide variety of laboratory scale tests of aggregates and concrete have been conducted in this research. Nearly seventy concrete mixes have been prepared with different proportions and materials. This chapter describes test standards, procedures and results for the source materials that have been used in concrete production. For concrete specimens, gradations of aggregates, mix proportions, size, quantity and preparation of the specimens for different phases of the research are also featured in this chapter.

3.1 Materials Used

The main objective of this research has been to propose a concrete mix design method for Bangladesh using locally available materials. Thus for all concrete mixes locally available ingredients have been used. The ingredients which are of main concern –

- (i) Aggregate
- (ii) Cement

3.2 Aggregates

Aggregates are the major components in any concrete mixture. Thus, the properties of used aggregates are of high significance for fresh and hardened concrete properties. Crushed stone chips are used as coarse aggregate in this research. For proposing a new concrete mix design method, various properties of aggregates have been tested. Following section describes briefly the tests which have been conducted for aggregate samples.

1. Specific gravity and absorption capacity of fine aggregate.
2. Specific gravity and absorption capacity of coarse aggregate.
3. Unit weight and voids in aggregate.
4. Crushing strength test for coarse aggregate.
5. Sieve analysis of fine and coarse aggregate.

3.2.1 Tests of aggregates

(a) Specific gravity and absorption capacity of fine aggregate

Specific gravity of aggregate has significant effects on both concrete mix proportioning and theoretical yield of concrete. Bulk specific gravity is defined as the ratio of the weight of the aggregate (oven-dry or saturated-surface dry) to the weight of water occupying a volume equal to that of the solid including permeable pores. This test has been done as per the standard ASTM C128.

(b) Specific gravity and absorption capacity of Coarse aggregate

This test method conforms to the ASTM standard requirements of specification C 127. Figure 3.1 illustrates two main steps of the process. Figure 3.1 (a) shows the process of bringing the aggregates in air dry condition and figure 3.2 (b) explains the next step where the aggregates need to dry in oven.


(a) (b)

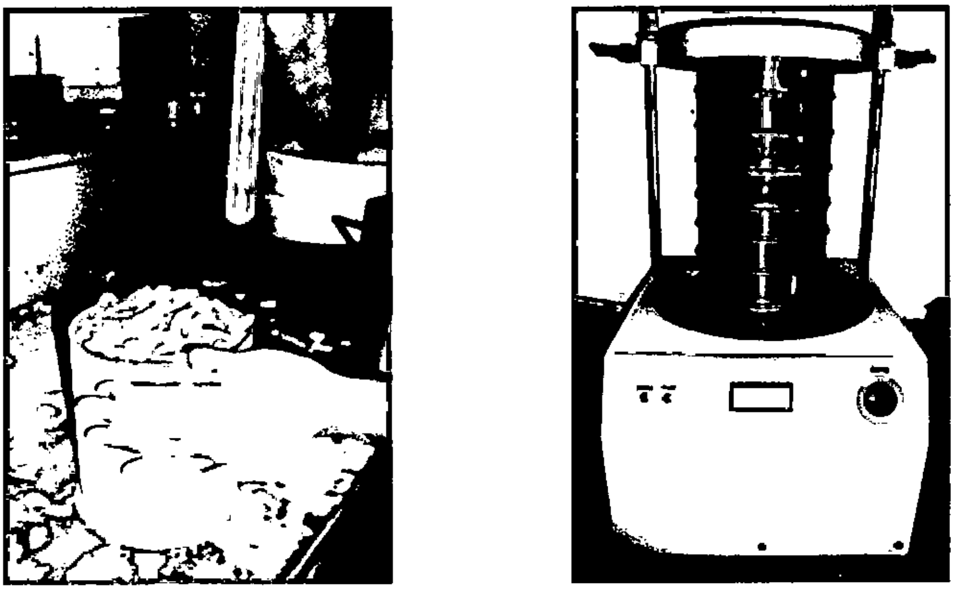
Figure 3.1: Specific Gravity and Absorption Test of Coarse Aggregates. (a) Samples Remove from Water and Roll in a Large Absorbent Cloth in order to bring it in Saturated Surface Dry Condition. (b) Oven Dry Sample and Weigh (nearest 0.5 gm or 0.05 % of the sample weight).

(c) Unit weight and voids in aggregate

Unit weight of aggregate plays an important role in selecting concrete mix proportions and also required for mass - volume conversion relation. Void content of aggregate measured here does not include the permeable or impermeable voids within the aggregate particles. Void contents act as indications of the amount of cement paste required for concrete mixture. This test method conforms to the standard ASTM C 29. As per the standard there are three procedures available for measuring the unit weight of aggregate. These are- i) shoveling procedure (provides loose unit weight), ii) rodding procedure (applicable for aggregates having a nominal maximum size of 1.5 inch or less), iii) jigging procedure (applicable for aggregates having a nominal maximum size greater than 1.5 inch). In this research the nominal maximum size of aggregates used has been 0.75 inch, thus for all aggregate samples the unit weight have been measured by rodding procedure. Figure 3.2 (a) shows the unit weight and void content test of coarse aggregates using rodding procedure.

(d) Sieve analysis of fine and coarse aggregate

The term sieve analysis is given to the simple operation of dividing a sample of aggregates into fraction each consisting of particles between specific limits. This test results plays a substantial role in concrete mix design. These tests also provide the Fineness Modulus of any aggregate samples, which is a significant parameter in concrete mix design. Moreover, it indicates the relative fineness or coarseness of aggregate samples when compared. These tests have been done as per the standard ASTM C 136. Sieve analysis of sand using mechanical sieve shaker has been illustrated in Figure 3.2 (b).



(a) (b)

Figure 3.2: (a) Unit Weight and Void Content Test of Coarse Aggregates Using Rodding Procedure. (b) Sieve Analysis of Aggregates Using Mechanical Sieve Shaker.

3.2.2 Aggregate samples

List of the source aggregates which have been used in this research purpose are described in following article.

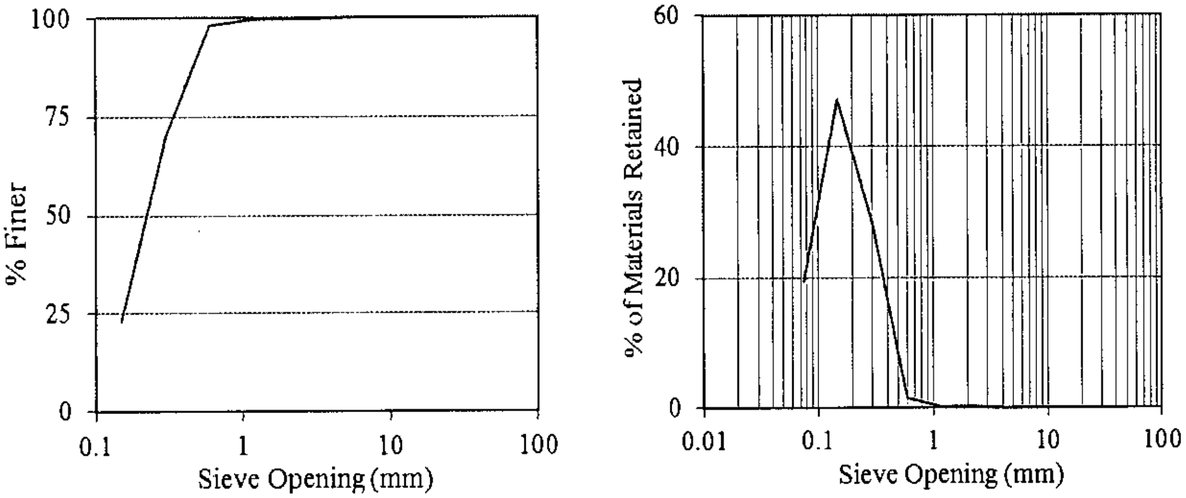
1. ¾ inch down grade aggregates.
2. Sylhet sand.
3. ½ inch downgraded aggregates.
4. Local Sand.
5. ¼ inch down grade aggregates.
6. Filler.

3.2.3. Aggregate Test Results

The total research has been accomplished in three distinct phases. In first phase the objective has been to select the suitable aggregate gradation methodology (Phase 1), in second phase the selected aggregate gradations have been further analyzed to verify their compatibility for normal weight concrete (Phase – 2) and at the last phase, concrete mixes have been prepared using selected aggregate gradations (Phase 3). Details of these phases of the research have also been elaborately discussed in Chapter 1 (Section 1.3). Source aggregate samples for these phases have been collected separately thus the aggregate properties of these samples found from test results have also been different. Gradation curves for source aggregate samples for different phases of the research have been shown in Figure 3.3 and Figure 3.4. Other properties of these aggregate samples have been given in Table 3.1 and Table 3.2.

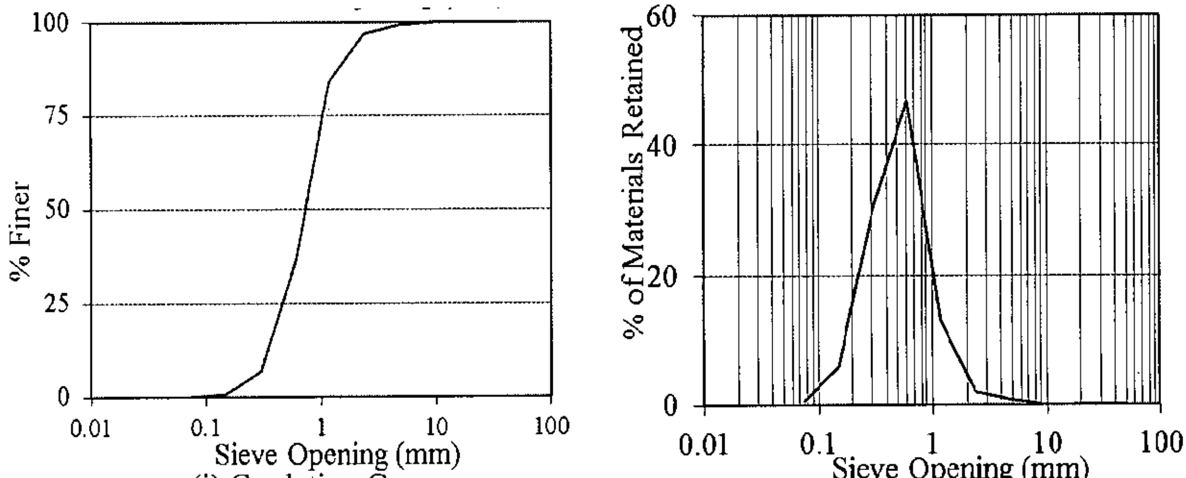
Table 3.1: Properties of Source Aggregates used in phase – 1 (selection of suitable aggregate gradation methodology)

	ID	**Type**	**Absorption Capacity, %**	**Moisture Content, %**	**FM**	**Specific Gravity (SSD)**
Fine Aggregate	FS-1	Sylhet Sand	1.67	4.3	2.75	2.7
	FS-2	Local Sand	1.18	5.0	1.13	2.69
Coarse Aggregate	CS-1	½ Inch down Grade	0.8	0.0	6.06	2.68
	CS-2	¼ Inch down Grade	1.4	1.5	4.72	2.69
	CS-3	¾ Inch down Grade	0.5	0.0	7.21	2.69



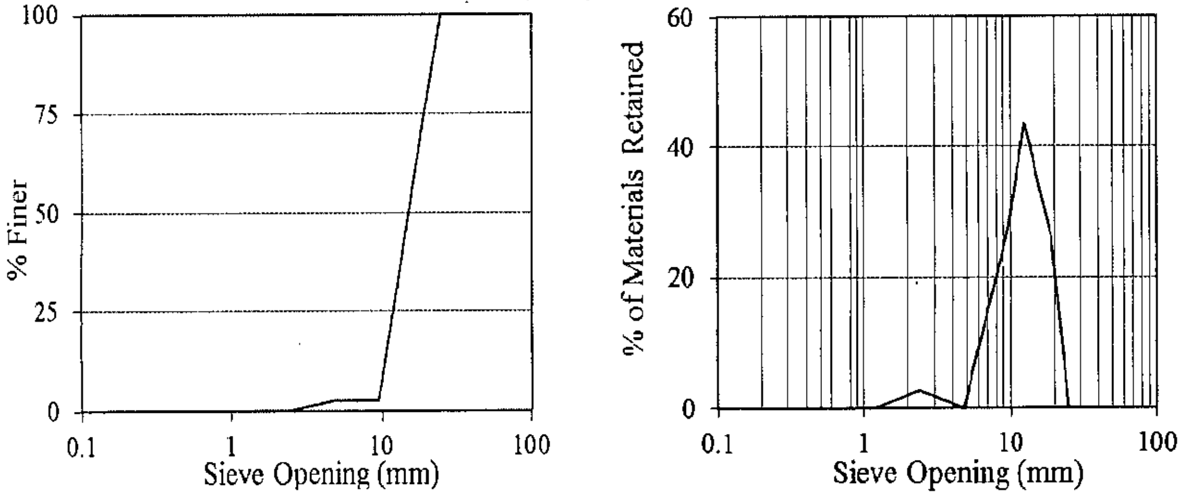
(i) Gradation Curve (ii) IPR Curve

(a) Local Sand



(i) Gradation Curve (ii) IPR Curve

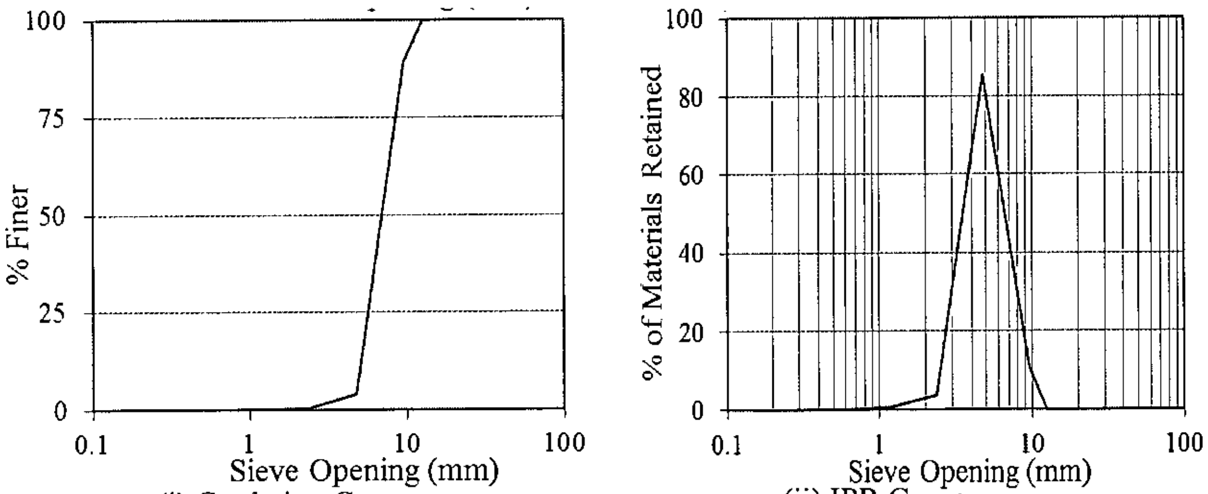
(b) Sylhet Sand



(i) Gradation Curve (ii) IPR Curve

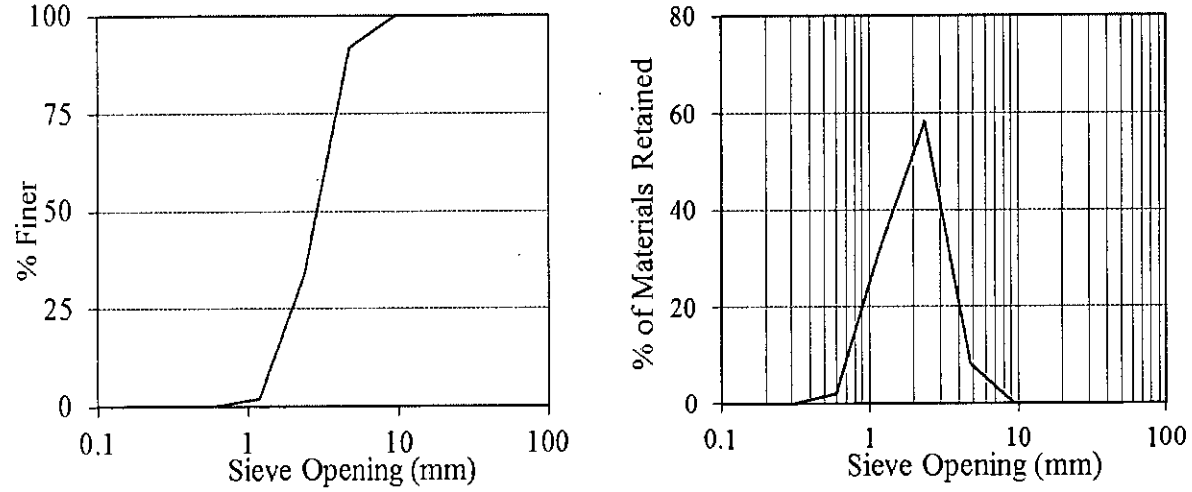
(c) ¾ Inch down Grade Aggregate Sample

Figure 3.3: Gradation Curves for Source Aggregates used in Phase -I (selection of suitable aggregate gradation methodology) (contd.)



(i) Gradation Curve (ii) IPR Curve

(c) ½ Inch down Grade Aggregate Sample



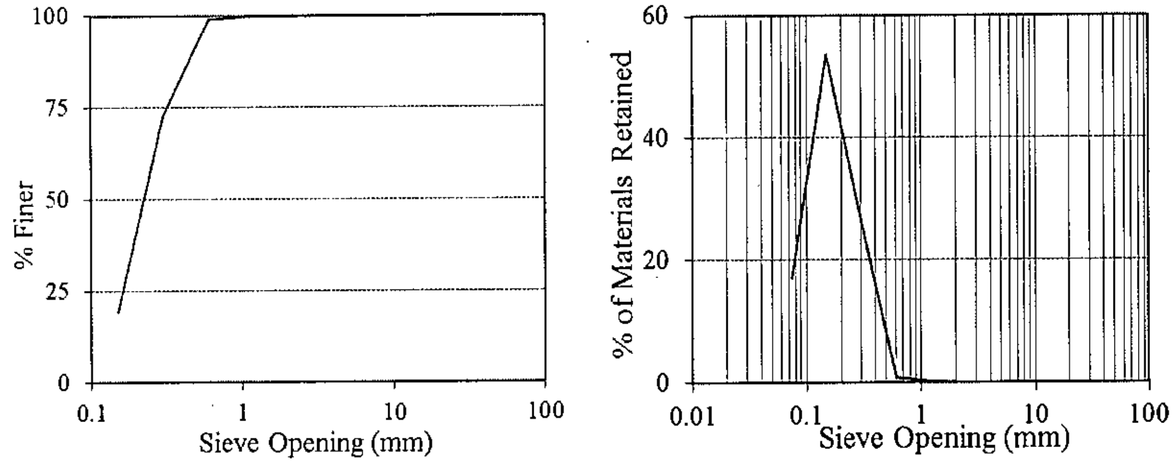
(i) Gradation Curve (ii) IPR Curve

(d) ¼ Inch down Grade Aggregate Sample

Figure 3.3: Gradation Curves for Source Aggregates used in Phase -1 (selection of suitable aggregate gradation methodology) (contd.)

Table 3.2: Properties of Source Aggregates used in phase – 2 and phase – 3

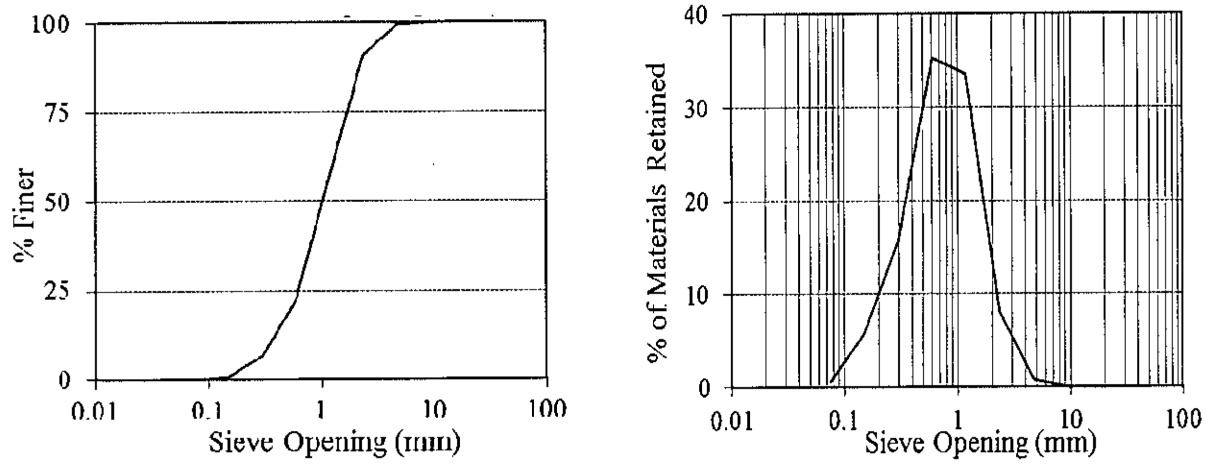
	Type	**Absorption Capacity, %**	**Moisture Content, %**	**FM**	**Specific Gravity (SSD)**
Fine Aggregate	Sylhet Sand	1.10	1.00	3.21	2.71
	Local Sand	0.90	1.20	1.11	2.71
	Filler	1.30	0.80	0.78	2.69
Coarse Aggregate	½ Inch down Grade	0.80	0.00	4.79	2.71
	¼ Inch down Grade	1.35	1.7	4.48	2.70
	¾ Inch down Grade	0.4	0.00	7.66	2.72



(i) Gradation Curve

(ii) IPR Curve

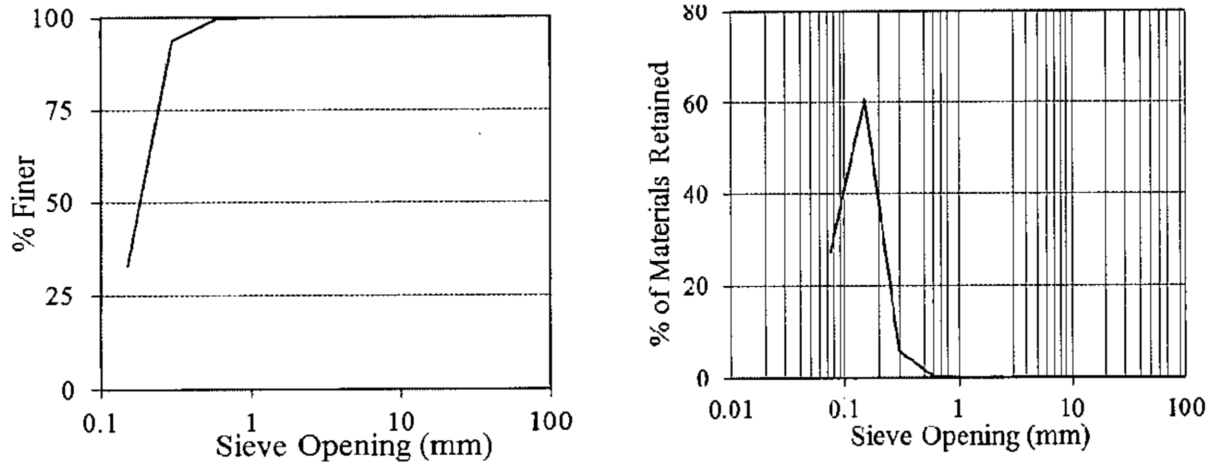
(a) Local Sand



(i) Gradation Curve

(ii) IPR Curve

(b) Sylhet Sand

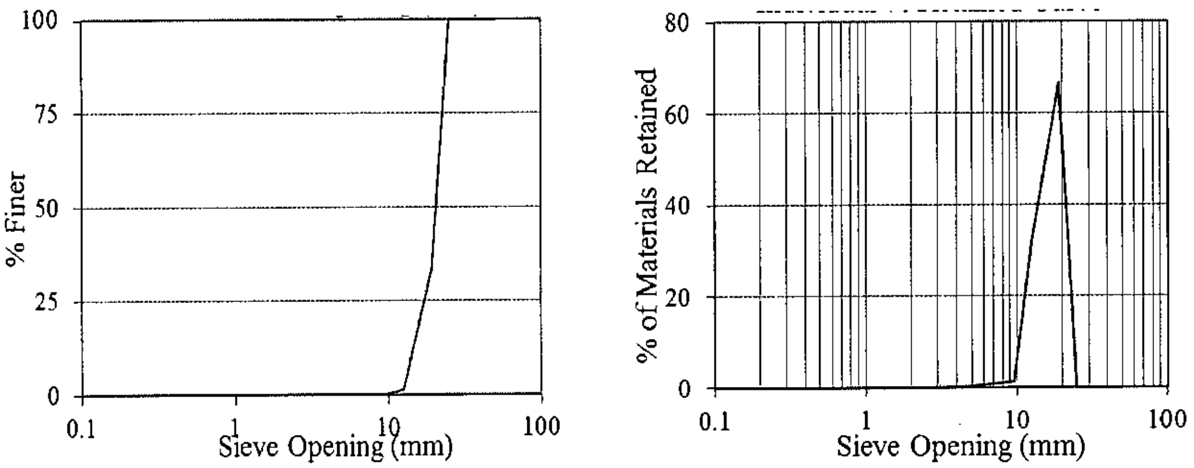


(i) Gradation Curve

(ii) IPR Curve

(c) Filler

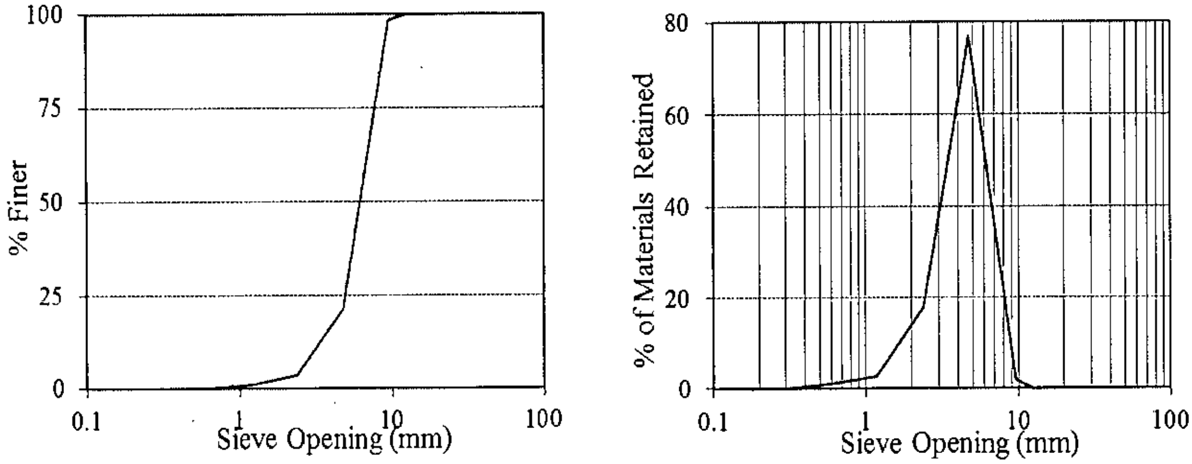
Figure 3.4: Grain Size Distribution for Curves Source Aggregates used in phase – 2 and phase – 3 (contd.)



(i) Gradation Curve

(ii) IPR Curve

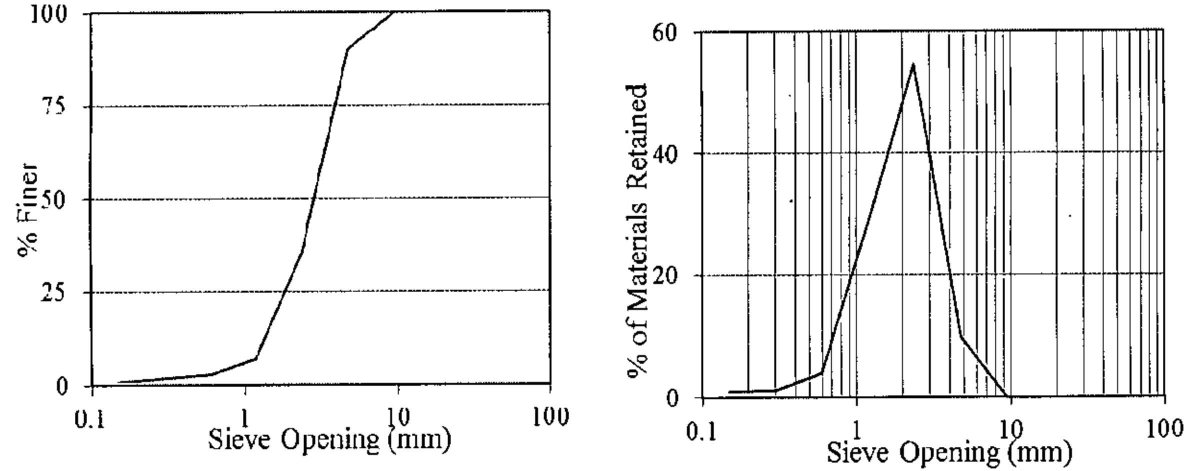
(d) ¾ Inch down Grade Aggregate Sample



(i) Gradation Curve

(ii) IPR Curve

(e) ½ Inch down Grade Aggregate Sample



(i) Gradation Curve

(ii) IPR Curve

(f) ¼ Inch down Grade Aggregate Sample

Figure 3.4: Grain Size Distribution Curves for Source Aggregates used in phase – 2 and phase – 3 (contd.)

3.3 Cement

Although various types of cement are being produced all over the world, but in Bangladesh mainly two types of cement are available - CEM-I and CEM-II B/M. Here, CEM I 42.5 N is a Ordinary Portland Cement (OPC) with ordinary early strength. In CEM I cements, the main constituents are Portland clinker (95-100%) and minor constituents only up to 5%. CEM II/ B-M 42.5N is a Portland composite cement (PCC) with ordinary early strength. According to SR EN 197-1:2011, the main constituents of CEM II/B-M Portland clinker (65-79%) and other components (slag and fly ash) (21-35%). For this research purpose locally available brands of these cements have been used.

3.3.1 Tests for Cement

Among the physical properties of cement compressive strength, initial setting time and final setting time have been tested.

(a) Compressive strength test

Compressive strength test of cements has been conducted as per the standard ASTM C150 for both CEM-I and CEM-II/B-M cement samples. 2 inch x 2 inch cement mortar cube specimens have been prepared and tested at 3, 7 and 28 days. Three samples have been tested at each case.

(b) Setting time test

Setting times of cement have been tested as per the standard ASTM C191. Both of initial and final setting time of cement play important role in determining the workability loss of concrete mixture due to time delay between mixing and casting of concrete.

(c) Normal consistency test

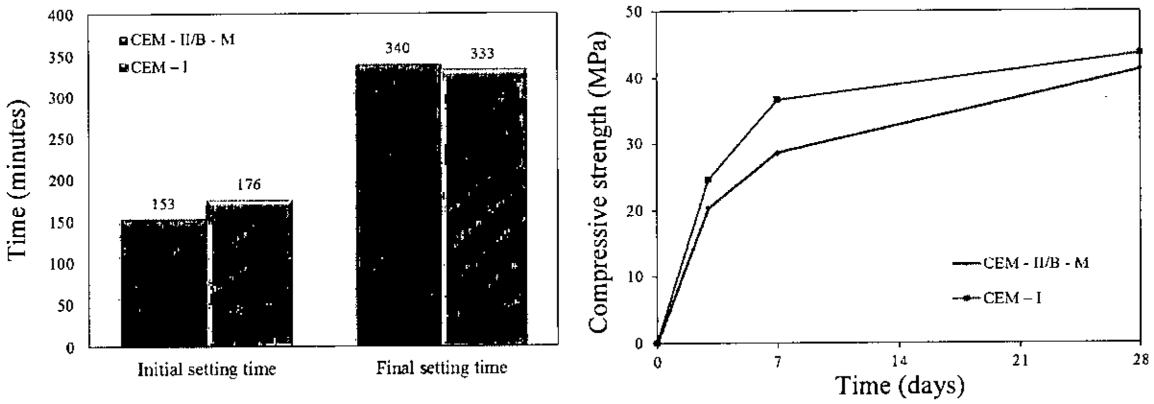
The amount of water content that brings the cement paste to a standard condition of wetness is called "normal consistency". Normal consistency of cement has significant effects on setting time of cements and the workability of concrete. Normal consistencies of cements have been tested as per the standard ASTM C 187.

3.3.2 Cement Test Results

Table 3.3 shows the test results for CEM I and CEM II/B-M cements which are used in this research. Figure 3.5(a) and Figure 3.5 (b) feature the comparison of setting times and rate of gain of strengths for used cements respectively.

Table 3.3: Test Results for Different Types of Cements used in This Research

Cement Type		**Normal consistency %**	**Initial setting time (Minute)**	**Final setting time (Minute)**	**Compressive strength (MPa)**		
					3 – days	**7 – days**	**28 – days**
CEM - II/B - M	Test results	28.5	176	333	20.3	28.6	41.2
	Standard Requirements	20 to 30	Not less than 45 min	Not more than 420 min	13.0	20.0	25.0
CEM – I	Test results	28	153	340	24.6	36.7	43.6
	Standard Requirements	20 to 30	Not less than 45 min	Not more than 375 min	12.0	19.0	28.0



(b) Setting Time

(a) Compressive Strength (MPa) vs. Time

Figure 3.5: Setting Times and Compressive Strength Test Results for Cements.

3.4 Preparation and Testing of Concrete Specimens

3.4.1 Preparation of Concrete Specimens

As mentioned earlier, total research work has been conducted into three different phase [discussed in chapter 1 (section 1.3)]. Each of these phases consists of different aggregate gradations, concrete mix proportions and number of specimens.

(a) Aggregate gradations

Since aggregate gradation significantly influences the concrete properties, at each phase of the research, specific aggregate gradations have been required. Moreover, aggregates those specific gradations have been not readily available in markets. Thus, locally available coarse aggregates have been first needed to segregate in particular sieve sizes and then again combine by weight to achieve the particular required aggregate gradation. Figure 3.6 shows the stacks of different sizes of coarse aggregates after sieving.

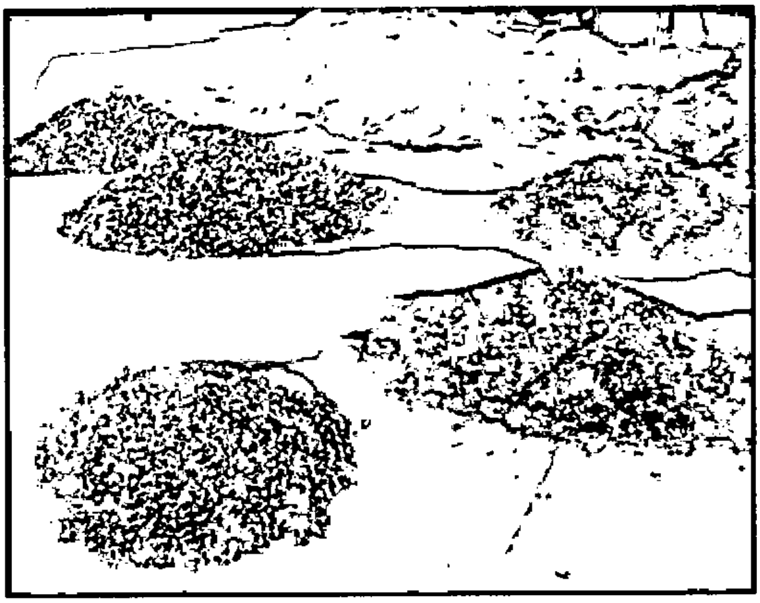


Figure 3.6: Different Sizes of Coarse Aggregates after Sieving.

For fine aggregate samples this procedure has not been possible because of large number of sieves. But as mentioned earlier, various types of fine aggregates have been available from various sources; these are Sylhet sand, local sand and filler. In order to achieve the required fine aggregate gradation, two or three types of fine aggregates needed to combine. Figure 3.7 shows the stacks of different types of fine aggregates.

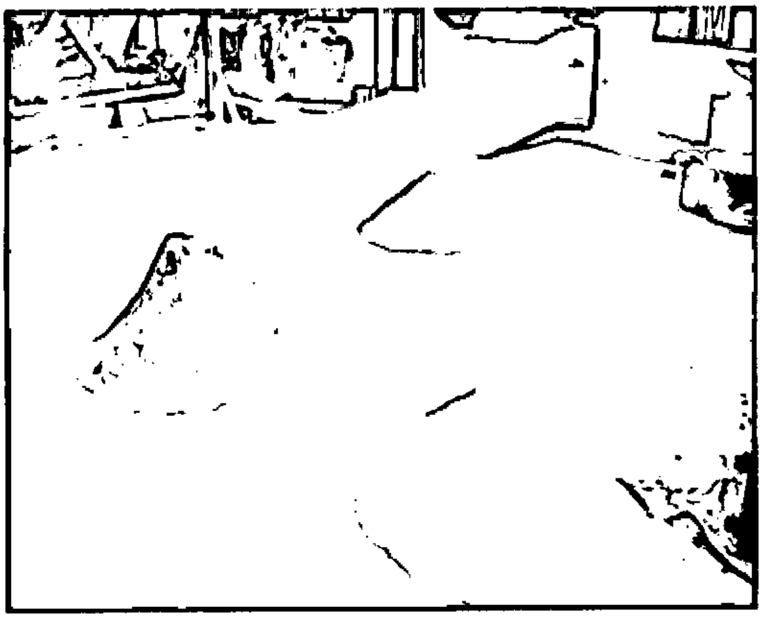


Figure 3.7: Different Samples of Fine Aggregates.

(b) Mix proportions

Phase 1: Selection of Aggregate Gradation Type

In this phase of the research total eight types of aggregate gradation methodologies have been compared. Since the main objective has been to observe the effect of aggregate gradation on concrete mix properties, the mix proportions have been kept same for all mixes. Thus total eight concrete mixes have been prepared in this phase for which water to cement (w/c) ratio, aggregate/cement (a/c) ratio have been kept unchanged only the aggregate gradations have been varied. To compare different aggregate gradation methodologies, a number of tests for aggregate gradations need to be conducted, these are – combined aggregate density test, measurement of aggregate void content etc. The selected aggregate gradations named as Gradation -1, Gradation – 2 and so on (Table 3.4). Concrete mixes have also been named in similar approach (i.e. mix – 1, mix – 2 etc). For better understanding details of these aggregate gradation bands have been discussed in chapter 4 along with the test results of each mixes. Table 3.4 shows the mix proportions for the trial concrete mixes of this phase for SSD condition of aggregates.

Nine 100 mm x 200 mm cylindrical concrete samples have been prepared for each mix. Concrete samples have been subjected to slump test, density test and compressive strength test. Compressive strengths of concrete tested at 7, 14 and 28 days. Thus the total number of concrete specimen prepared in this phase of the research is seventy two (72) - 100 mm x 200 mm cylinders.

Phase 2: Consistency Check of Selected Aggregate Gradation Bands

The main objective of this phase of the research has been to check the performance of concrete mixture for aggregate gradations within the selected aggregate gradation bands. Concrete mixtures have been prepared with same mix proportions but different aggregate gradations. Various source aggregates have been combined in a way so as to achieve the extreme cases of the selected aggregate gradation bands. In this phase, total eight concrete mixes have been prepared. Continuing from the previous phase, in this phase aggregate samples have been named as Gradation – 9, Gradation – 10 up to Gradation – 16 (Table 3.5). Concrete mixes have been identified in similar manner (mix – 9 to mix – 16). Details of these aggregate gradation band and concrete mixes have been described in chapter 5.

In this phase, for each concrete mix, nine 150 mm x 300 mm cylinder samples have been prepared. The concrete samples have been subjected to slump, fresh concrete density and compressive strength tests. In this phase of the research total seventy two concrete cylinders have been prepared. Table 3.5 represents the mix proportions at SSD condition of aggregates.

Table 3.4: Mix Proportions (SSD Condition) for Phase – 1 Trial Concrete Mixes

Mix ID	**Aggregate gradation**	**A/c ratio**	**w/c ratio**	**Water Content (kg/m^3)**	**Cement Content (kg/m^3)**	**Aggregate Content (kg/m^3)**
Mix – 1	Gradation – 1	4.073	0.44	180.00	410.00	1670.00
Mix – 2	Gradation – 2					
Mix – 3	Gradation – 3					
Mix – 4	Gradation – 4					
Mix – 5	Gradation – 5					
Mix – 6	Gradation – 6					
Mix – 7	Gradation – 7					
Mix – 8	Gradation – 8					

Table 3.5: Mix Proportions (SSD Condition) for Phase – 2 Trial Concrete Mixes

Mix ID	**Aggregate gradation**	**A/c ratio**	**w/c ratio**	**Water Content (kg/m^3)**	**Cement Content (kg/m^3)**	**Aggregate Content (kg/m^3)**
Mix – 9	Gradation – 9	4.54	0.50	190.00	380.00	1725.00
Mix – 10	Gradation – 10					
Mix – 11	Gradation – 11					
Mix – 12	Gradation – 12					
Mix – 13	Gradation – 13					
Mix – 14	Gradation – 14					
Mix – 15	Gradation – 15					
Mix – 16	Gradation – 16					

Phase 3: Laboratory Experiments for Concrete Mix Design

In this phase of the research large numbers of concrete mixes have been prepared for collecting the required information for concrete mix design method. The concrete mixes have been prepared into four categories based on the cement type and aggregate gradation used. These categories are named as; Category – A, Category – B, Category – C, Category – D (Table 3.6 to Table 3.9). These categories of concrete mixes have been discussed further in Chapter 6. Table 3.6 to 3.9 describe the mix proportions at SSD condition of aggregates for A, B, C and D category trial concrete mixes respectively. Total numbers of specimens prepared in this phase are: 468 cylinders (150 mm × 600 mm) and 60 cube (150 mm × 150 mm). Figure 3.8 shows some of the prepared concrete samples and figure 3.9 illustrated the curing procedure of these concrete samples that have been followed in this research.

Table 3.6: Mix Proportions for "category – A" Trial Concrete Mixes

Mix ID	**Water Content kg/m^3**	**Cement Content kg/m^3**	**Aggregate Content kg/m^3**	**w/c Ratio**	**A/c Ratio**	**Number of specimen prepared**
A1	180	360	1905	0.50	5.29	Nine Cylinders
A2	200	360	1851	0.56	5.14	Nine Cylinders
A3	220	360	1797	0.61	4.99	Nine Cylinders
A4	245	360	1730	0.68	4.81	Nine Cylinders
A5	180	400	1871	0.45	4.68	Nine Cylinders
A6	200	400	1817	0.50	4.54	Nine Cylinders
A7	220	400	1763	0.55	4.41	Nine Cylinders + Three Cube
A8	245	400	1696	0.61	4.24	Nine Cylinders + Three Cube
A9	180	440	1837	0.41	4.17	Nine Cylinders
A10	200	440	1783	0.45	4.05	Nine Cylinders + Three Cube
A11	220	440	1729	0.50	3.93	Nine Cylinders + Three Cube
A12	245	440	1661	0.56	3.78	Nine Cylinders
A13	180	500	1785	0.36	3.57	Nine Cylinders
A14	200	500	1731	0.40	3.46	Nine Cylinders + Three Cube
A15	220	500	1677	0.44	3.35	Nine Cylinders
A16	245	500	1610	0.49	3.22	Nine Cylinders

Table 3.7: Mix Proportions for "category – B" Trial Concrete Mixes

Mix ID	Water Content kg/m^3	Cement Content kg/m^3	Aggregate Content kg/m^3	w/c Ratio	A/c Ratio	Number of specimen prepared
B 1	180	360	1905	0.50	5.29	Nine Cylinders
B 2	200	360	1851	0.56	5.14	Nine Cylinders
B 3	220	360	1797	0.61	4.99	Nine Cylinders + Three Cube
B 4	180	400	1871	0.45	4.68	Nine Cylinders
B 5	200	400	1817	0.50	4.54	Nine Cylinders
B 6	220	400	1763	0.55	4.41	Nine Cylinders + Three Cube
B 7	180	440	1837	0.41	4.17	Nine Cylinders
B 8	200	440	1783	0.45	4.05	Nine Cylinders + Three Cube
B 9	220	440	1729	0.50	3.93	Nine Cylinders + Three Cube
B 10	180	500	1785	0.36	3.57	Nine Cylinders
B 11	200	500	1731	0.40	3.46	Nine Cylinders + Three Cube
B 12	220	500	1677	0.44	3.35	Nine Cylinders

Table 3.8: Mix Proportions for "category – C" Trial Concrete Mixes

Mix ID	Water Content kg/m^3	Cement Content kg/m^3	Aggregate Content kg/m^3	w/c Ratio	A/c Ratio	Number of specimen prepared
C 1	180	360	1905	0.50	5.29	Nine Cylinders
C 2	200	360	1851	0.56	5.14	Nine Cylinders
C 3	220	360	1797	0.61	4.99	Nine Cylinders + Three Cube
C 4	180	400	1871	0.45	4.68	Nine Cylinders
C 5	200	400	1817	0.50	4.54	Nine Cylinders
C 6	220	400	1763	0.55	4.41	Nine Cylinders + Three Cube
C 7	180	440	1837	0.41	4.17	Nine Cylinders
C 8	200	440	1783	0.45	4.05	Nine Cylinders + Three Cube
C 9	220	440	1729	0.50	3.93	Nine Cylinders + Three Cube
C 10	180	500	1785	0.36	3.57	Nine Cylinders
C 11	200	500	1731	0.40	3.46	Nine Cylinders + Three Cube
C 12	220	500	1677	0.44	3.35	Nine Cylinders

Table 3.9: Mix Proportions for "category – D" Trial Concrete Mixes

Mix ID	**Water Content kg/m^3**	**Cement Content kg/m^3**	**Aggregate Content kg/m^3**	**w/c Ratio**	**A/c Ratio**	**Number of specimen prepared**
D 1	180	360	1905	0.50	5.29	Nine Cylinders
D 2	200	360	1851	0.56	5.14	Nine Cylinders
D 3	220	360	1797	0.61	4.99	Nine Cylinders + Three Cube
D 4	180	400	1871	0.45	4.68	Nine Cylinders
D 5	200	400	1817	0.50	4.54	Nine Cylinders
D 6	220	400	1763	0.55	4.41	Nine Cylinders + Three Cube
D 7	180	440	1837	0.41	4.17	Nine Cylinders
D 8	200	440	1783	0.45	4.05	Nine Cylinders + Three Cube
D 9	220	440	1729	0.50	3.93	Nine Cylinders + Three Cube
D 10	180	500	1785	0.36	3.57	Nine Cylinders
D 11	200	500	1731	0.40	3.46	Nine Cylinders + Three Cube
D 12	220	500	1677	0.44	3.35	Nine Cylinders

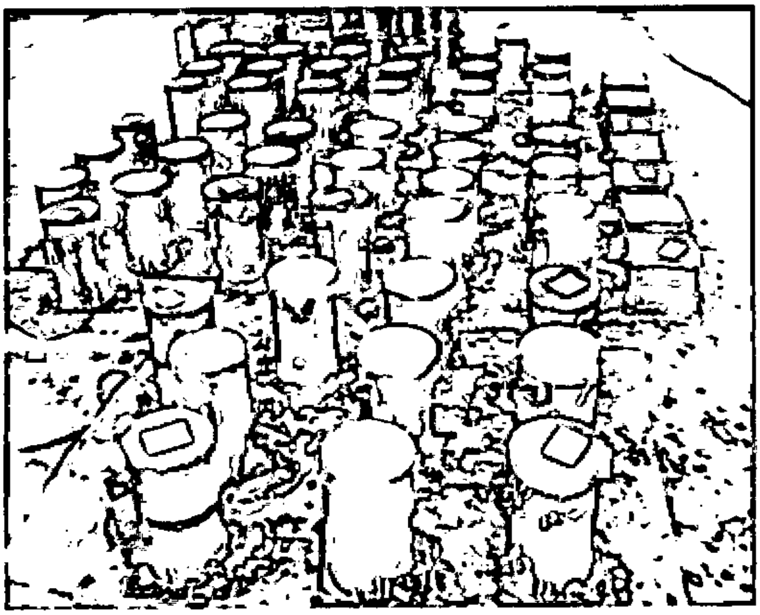


Figure 3.8: Some of the Concrete Cylinders and Cubes Prepared for Experiments

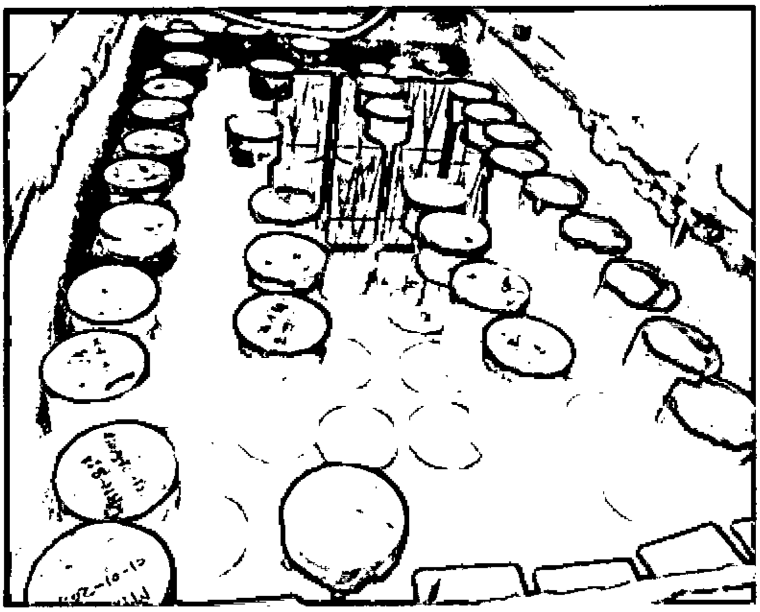


Figure 3.9: Curing of Concrete Specimens.

3.4.2 Tests of Concrete

(a) Slump test

Workability of each mix has been determined by measuring the slump of the mix as per the standard ASTM C 143. For measuring the loss of workability with time, slump of the mixes have been measured several times with certain time delays. Figure 3.10 illustrate different types of slump of fresh concrete mix and Figure 3.11 exemplify a slump measurement of this research.

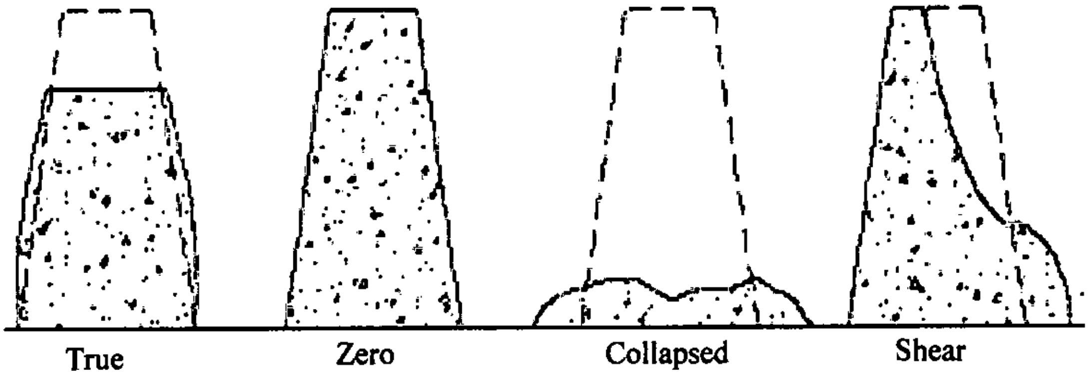


Figure 3.10: Types of Concrete Slump

Figure 3.11: Slump Test of Concrete Sample.

(b) Density test of fresh concrete

This test method conforms to the standard ASTM C 138. As per the standard, minimum size of the measure for aggregates having nominal maximum size lower than 1 inch is 0.2 m^3 and for ¾ inch nominal maximum size of aggregate the minimum measure size is 0.05 m^3. In this research, for density determination a measure used with a capacity of 0.05 m^3. Figure 3.12 illustrates the density measurement procedure of fresh concrete mix.

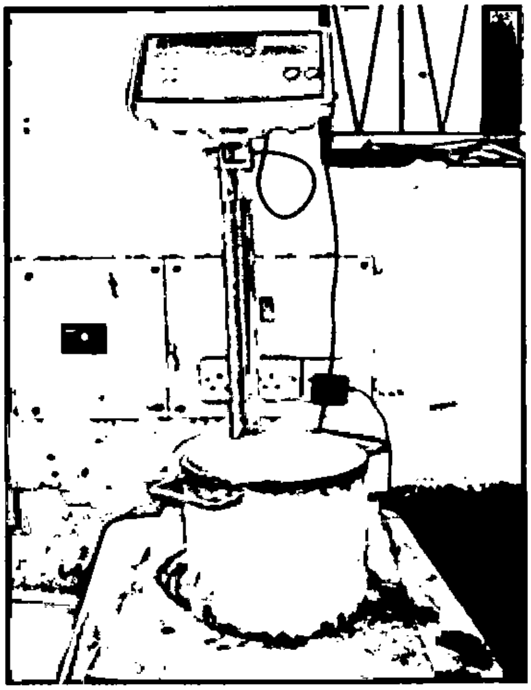


Figure 3.12: Fresh Concrete Density Test

(c) Concrete compressive strength test

Concrete compressive strengths have been tested as per the standard ASTM C 39. According to this standard, concrete compressive strength should be tested on cylindrical samples such as 6 inch x 12 inch or 4inch x 8 inch. In this research three 6 inch x 12 inch (150 mm x 300 mm) cylinder samples have been prepared for each day testing.

(d) Water penetration depth test

The penetration depth of water has been measured under pressure as per EN12390-8 standard. 150 mm x 150mm concrete cube have been prepared and cured for 28 days. The curing temperature has been around 20 – 25 °C. After the completion of 28 days curing, the concrete specimens have been removed from curing water and kept in a room for 24 hour, in order to bring the concrete specimens in air dry condition. Then the cube specimens have been placed in the equipment (Figure 3.13) and water has been introduced from bottom with a certain pressure (5 bar) in a way that the water forced to penetrate through the sample. As per the standard, the pressure has been applied for 72 ± 2 hour. After this specified time, the specimens have been removed from the apparatus and the face, on which water pressure has been applied, has been wiped to remove the excess water. To observe the water penetration depth, the specimens have been spliced into half perpendicularly to the face on which the water pressure has been applied. A sample of such halved concrete cube is shown in Figure 3.14. For each concrete mix, total three cube specimens have been prepared and tested for water penetration depth. The results used in this research are the average penetration depth for three samples. Figure 3.15 shows different types of test error that may occur during the testing.

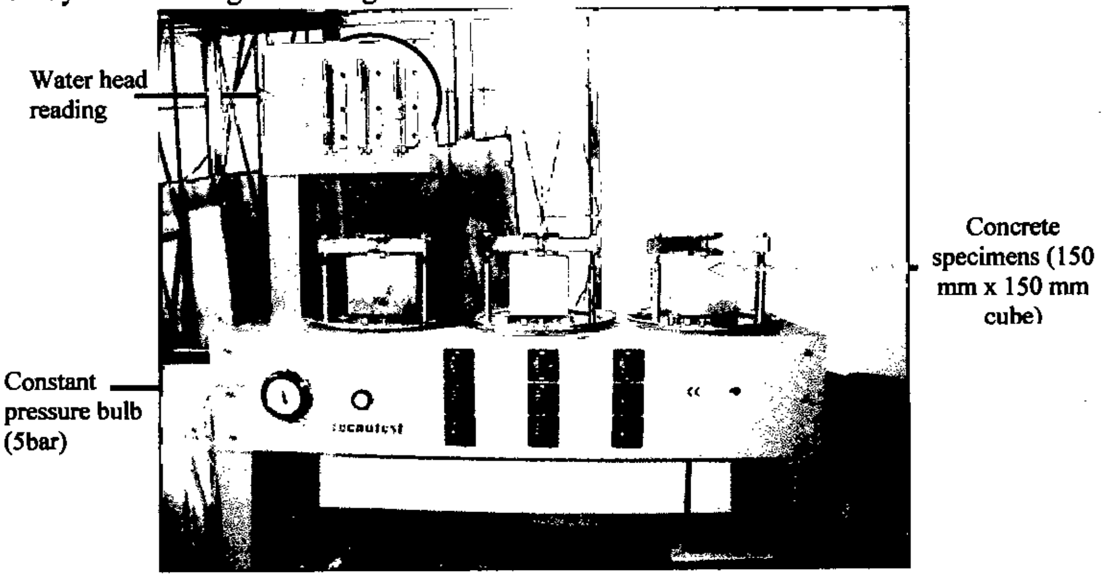


Figure 3.13: Water Penetration Depth Test for Concrete Cube Specimens.

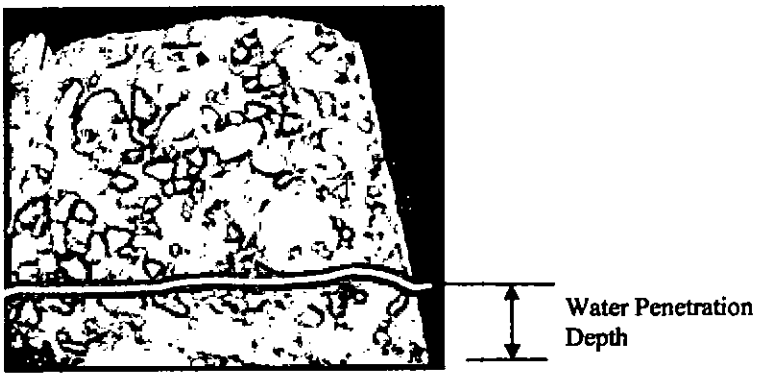
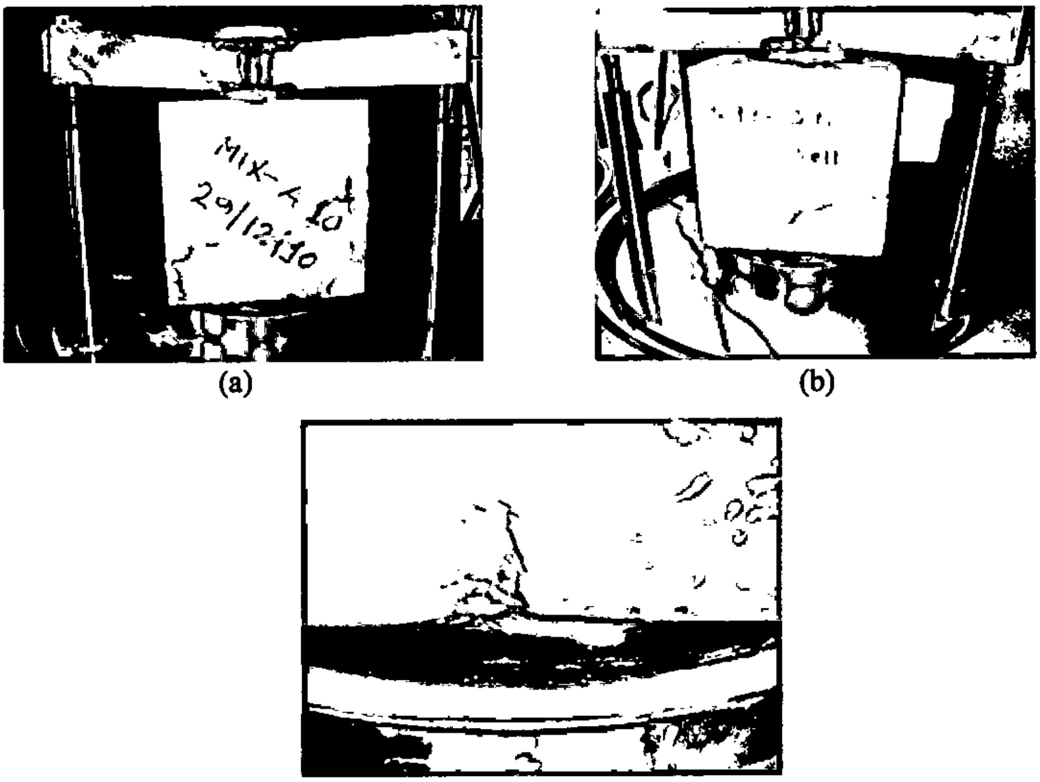


Figure 3.14: Measurement of the Water Penetration Depth



(a)

(b)

(c)

Figure 3.15: Source of Errors Which May Cause Cancellation of the Test Results. (a) Wet Surface of the Specimen. (b) Water Leakage (c) Un-Smoothed or Partially Cracked Surface of the Specimen.

The results of the water penetration depth test of concrete are given Table 3.10. Concrete mix ids are same as explained for phase – 4 of the research. The depth of water penetration can be used to determine the water permeability coefficient (Valenta, 1970). Moreover, the depth of water penetration itself can be considered as an indication of permeable and impermeable concrete (Neville, 2006).

Table 3.10: Water Penetration Depth Test Results for Phase – 3 Concrete Mixes.

Mix ID	w/c Ratio	Water Penetration Depth (cm)
A14	0.4	3.25
A10	0.45	9.25
A11	0.5	10.0
A7	0.55	12.5
A8	0.61	13.00
B14	0.4	2.85
B10	0.45	5.10
B11	0.5	8.00
B7	0.55	10.80
B 3	0.61	12.50
C14	0.4	2.33
C10	0.45	2.50
C11	0.5	5.20
C7	0.55	6.10
C3	0.61	8.50
D14	0.4	2.37
D10	0.45	2.67
D11	0.5	6.33
D7	0.55	9.00
D 3	0.61	12.00

Chapter 4

COMPARATIVE ANALYSIS OF AGGREGATE GRADATION METHODOLOGIES

General

It is already well established that aggregate gradation plays a fundamental function on fresh and hardened concrete properties. To improve concrete quality several aggregate gradation methods are present in the record of concrete and aggregate. But any comparison of these gradation methods in favor of better concrete properties has never been under taken. And it may be indubitable that conducting lab experiments is the best preference for comparing concrete properties. Thus in this phase of the research, a series of trial concrete mixes with different aggregate gradations have been prepared to find a comparatively better aggregate gradation method in requisites of main two concrete properties-(i) compressive strength and (ii) slump. There are various aggregate gradation tools or methods, such as-Fineness Modulus, Coarseness Factor, Workability Factor, Mortar Factor, Gradation curve, Individual Percent Retained (IPR) curve, "8-18" band and Combined Fineness modulus (fineness modulus of total aggregate) etc. In this chapter, focus has also given on the comparative analysis of various tools and methods of aggregate gradation along with two newly proposed gradations through a number of trial concrete mixes.

4.1 Existing Aggregate Gradation Methods

4.1.1 Types of Aggregate Gradation Methods

All of the existing aggregate gradation methodologies can be considered as two distinct type of aggregate gradations – i) gradation of fine aggregate (aggregate passing #4 sieve and below) and coarse aggregate (aggregate retained on #4 sieve and above) individually, such as, ASTM C 33, BS 882 etc. and ii) gradation of total aggregate. Although combined aggregate gradation became increasingly popular, but still, only a limited methods for achieving these types of gradations have been proposed, among which band gradations are quite remarkable.

(i) *ASTM C 33 and BS 882*

The ACI method considers the FM of fine aggregate and dry rodded unit weight (ASTM, 1991) of the coarse aggregate to select the proportion of coarse aggregate. It has been observed that there are still some limitations associated with current gradation specifications such as ASTM C 33 (Shilstone and Shilstone Jr. 1987, ASTM 1994) as mentioned below -

(i) Sands currently used are too fine. Thus because of bulking problem causes high water demand.

(ii) Poorly graded, tend to have lower coarse aggregate and greater sand contents. Thus the mix as per ACI 211, tend to be gap graded, highly sanded, and prone to segregation, when subjected to vibration.

(iii) Again, ASTM C 33 considers only fine and coarse fractions. Unfortunately, the intermediate size is often lacking in the fine and coarse fractions. And the voids are needed to be filled with mortars.

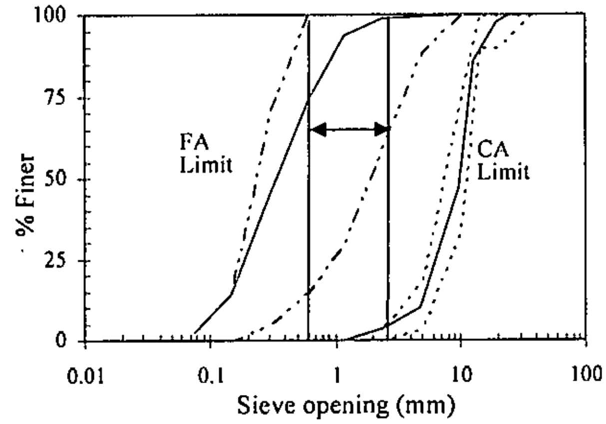


Figure 4.1 (a): FA and CA Gradation Limit as per BS 882

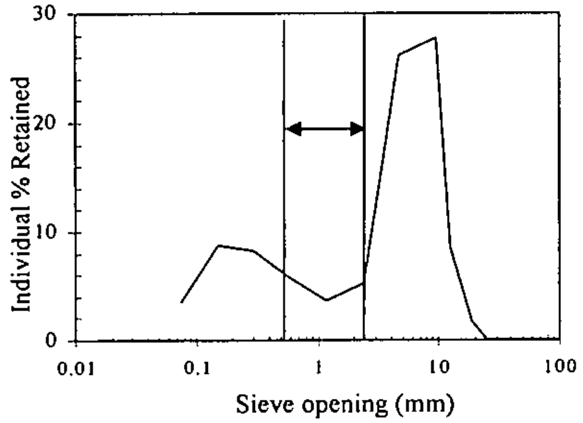


Figure 4.1 (b): Aggregate Gradation in IPR Curve after Combination (BS 882)

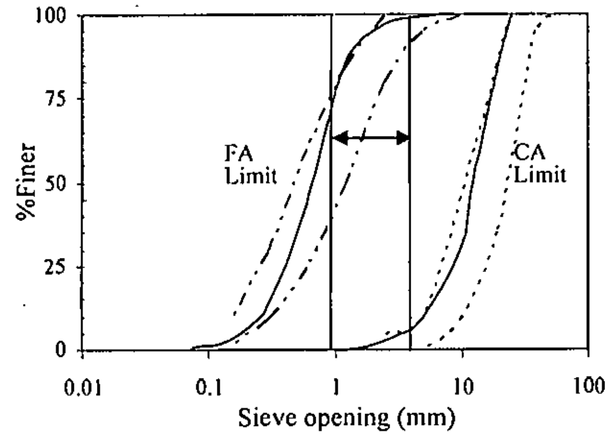


Figure 4.2 (a): FA and CA Gradation Limit as per ASTM C33

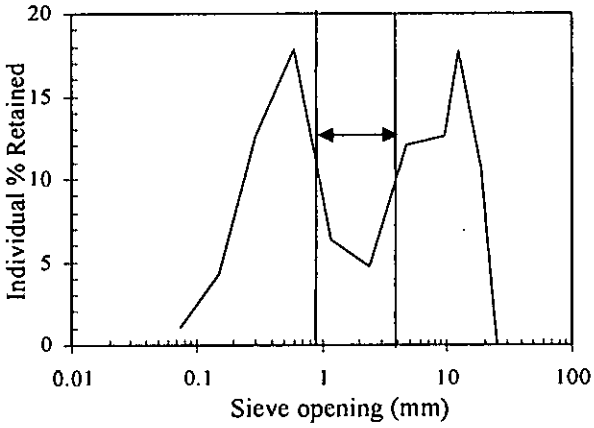


Figure 4.2 (b): Aggregate Gradation in IPR Curve after Combination (ASTM C33)

Similar drawbacks have also been observed for BS 882 gradations since it is also based on the individual requirements for fine and coarse aggregates. Thus both of the ASTM C33 and BS 882 gradation result in harsh mixes which are also difficult to finish. This phenomenon described in Figure 4.1 and in Figure 4.2 for ASTM C33 and BS 882, respectively.

(ii) ***Band gradations***

Holland (1990) is generally credited for the initiation of band gradation with the "8-18" band. "8-18" band requirement is that the total percentage of fine and coarse aggregate retained on any one sieve to be in between 8 and 18 percent (Figure 4.3). Later on many researchers also recommend "8-18" (or "6-22") band rule explaining that it reduces shrinkage by reducing water demand through optimized gradation (Harrison, 2004). After the huge support for band gradations, it has already been included in various codes and standards (ACI 1999; USAF 1997). However, for better controlling the mix properties, coarseness factor chart (Shilstone, 1990) is recommended to use along with the band gradations in these standards. The coarseness factor chart is a method of analyzing the size and uniformity of the combined aggregate distribution, balanced with respect to the fine aggregate content of the mix. A rectangular box within the chart represents the optimum zone for aggregate gradation (Harrison, 2004) (Figure 4.4).

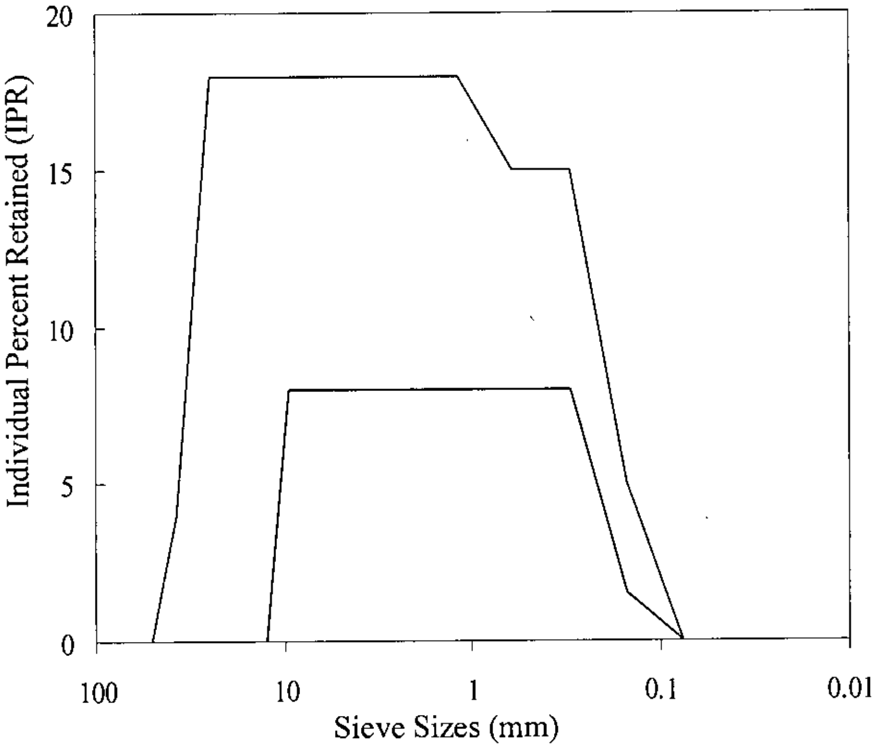


Figure 4.3: IPR Requirements for "8-18" Band Gradation.

Contradictorily, some researchers have found that "8-18" band gradations makes little or no-difference in water demand, shrinkage or compressive strength with the concrete made with normal proportion aggregates (Maccall et al., 2005). Moreover, another major drawback of "8-18" gradation is that, it covers a wide range of combined aggregate gradation, which allows fine aggregate to total aggregate (fa/ta) ratio from 0.28 to 0.65 and also a similar wide variation of FM (theoretically). This befuddling condition made the use of coarseness factor chart a mandatory along with the 8-18 or 6-22 band gradations. Coarseness factor chart shows the combined effect of WF and CF on mix properties, but surprisingly the relationships between various concrete properties with CF and WF are still unclear. Again, if any mix is found to have its position outside the optimum zone of coarseness factor chart, there is no recommendations or guidelines about what to adjust and how to adjust to get the optimum mix. In some researches, CF is found to have relationship with concrete compressive strength (Ashraf and Noor, 2011a), whereas; some researcher observed that these aggregate properties do not have any clear effects on hardened concrete properties (Maccall et al., 2005).

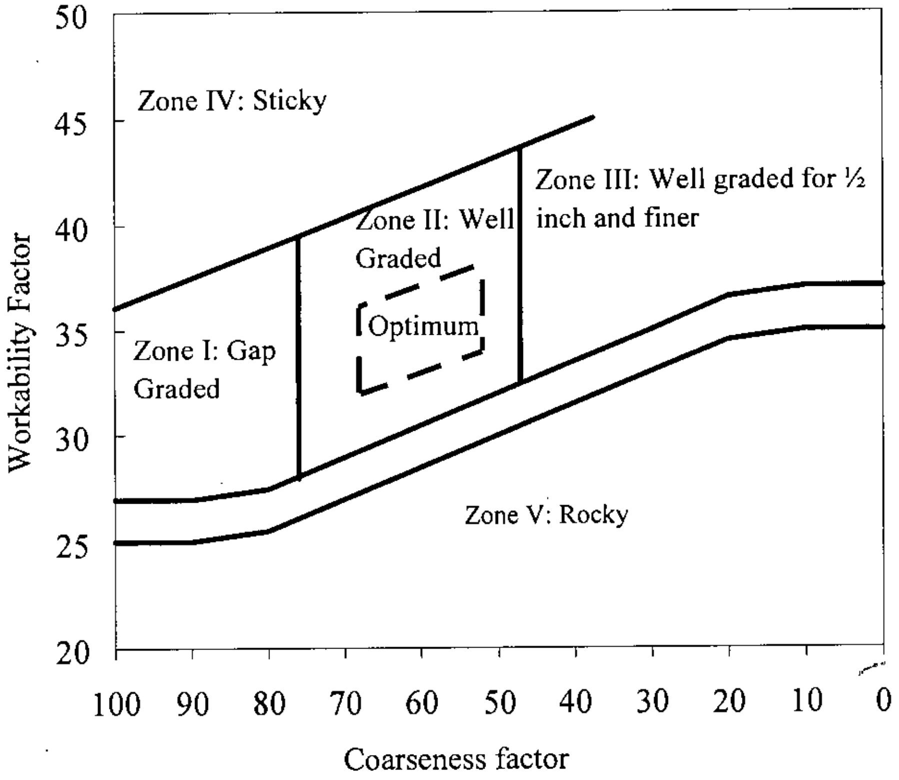


Figure 4.4: Different Zones of Coarseness factor Chart

(iii) Packing Models

The SHRP Packing Handbook (C-624) and the companion Guide (C-334) present a method for determining the optimum coarse/fine aggregate ratio for use in proportioning concrete, based on packing models (Anderson and Johanson, 1993; Roy et al., 1993). This model assumes dry packing of spherical particles. The contention of this method is that the workability of the concrete at a fixed cement content and w/c is mainly a function of the binary packing of the coarse and fine aggregate. The optimum workability was found to be when the sand-to-coarse aggregate ratio is equal to the densest packing of these two materials.

Cox et al. (1993) evaluated the Packing Handbook by comparing mixes and concluded that-

1) The Packing Handbook mixes had more coarse aggregate and less sand, therefore were harsher, harder to work, had lower slumps, had less air but the flexural strength were about 10% higher.

2) Packing Handbook has promise because concrete cost could be lower as a result of lower cement content and w/c, but workability and air issues needed to be overcome.

3) One of their references indicated that maximum packing density gives the best workability, minimum porosity, minimum permeability, and maximum compressive strength. Another of their reference stated that maximum density gives a harsh, somewhat unworkable mix.

4.1.2 Advantages of Combined Aggregate Gradation Methods

Here the term "Combine aggregate Gradation" represents the total aggregate gradation thus mainly focused on band gradations.

1. This provides a more thorough analysis of how the aggregates will perform in concrete (Richardson, 2005).
2. Sometimes mid-sized aggregate, around the 9.5 mm (3/8 in) size, is lacking in an aggregate supply, resulting in a concrete with high shrinkage properties, high water demand, poor workability, poor pumpability, and poor placeability. Strength and durability may also be affected (Richardson, 2005).
3. The combined gradation can be used to better control workability, pumpability, shrinkage, and other properties of concrete (Shilstone, 1990).
4. With constant cement content and consistency, there is an optimum for every combination of aggregates that will produce the most effective water to cement ratio and highest strength (Shilstone, 1990).
5. These gradations have the least particle interference and responds best to a high frequency, high amplitude vibrator (Shilstone, 1990).

6. Crouch (2000) found in his studies on air-entrained concrete that the water-cement ratio could be reduced by over 8% using combined aggregate gradation.
7. At any typical concrete batch plant, only two fractions of aggregate stocked; one fine aggregate and another coarse aggregate for the routine production of concrete. This creates the potential for gap graded mix associated with concrete behavioral problems (Richardson, 2005).

4.2 Modified Aggregate Gradation Bands

To overcome the drawbacks of 8-18 (or 6-22) gradations, two new band gradations for aggregates have been developed in this research; these are 5-10-14-18 and 5-10-18-22. As in initial stage these gradation bands are proposed for aggregates which nominal maximum size is 20 mm. The main criteria during developing these gradations was that, similar to the percentage of aggregate retained on a particular sieve, other aggregate properties (FM, fa/ta) should also fall into a range. Among the various properties of aggregates, focus has been particularly given on FM and fa/ta ratio. Although the importance of FM has been discarded by many researchers, but still it is the most well-known and easily calculable parameter of aggregates. Moreover these two parameters are directly linked with the aggregate grain size distributions.

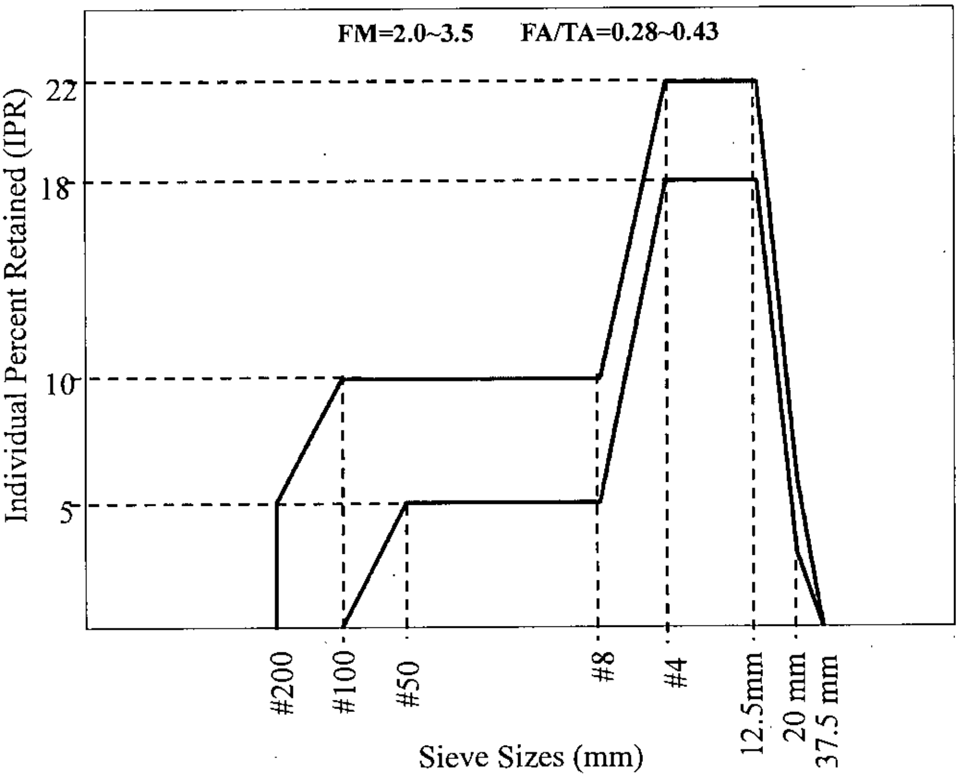


Figure 4.5: IPR Requirements for 5-10-18-22 Band Gradation

Figure 4.5 shows the requirements for different sieves for achieving 5-10-18-22 band gradations. Any aggregate gradation that falls within 5-10-18-22 band will confirm to have FM within 2 to 3.5 and fa/ta 0.28 to 0.43.

For 5-10-14-18 band gradation, requirements for different sieves sizes shown in Figure 4.6. Ranges of FM and fa/ta included in these band gradations are 2 to 3.5 and 0.4 to 0.55, respectively.

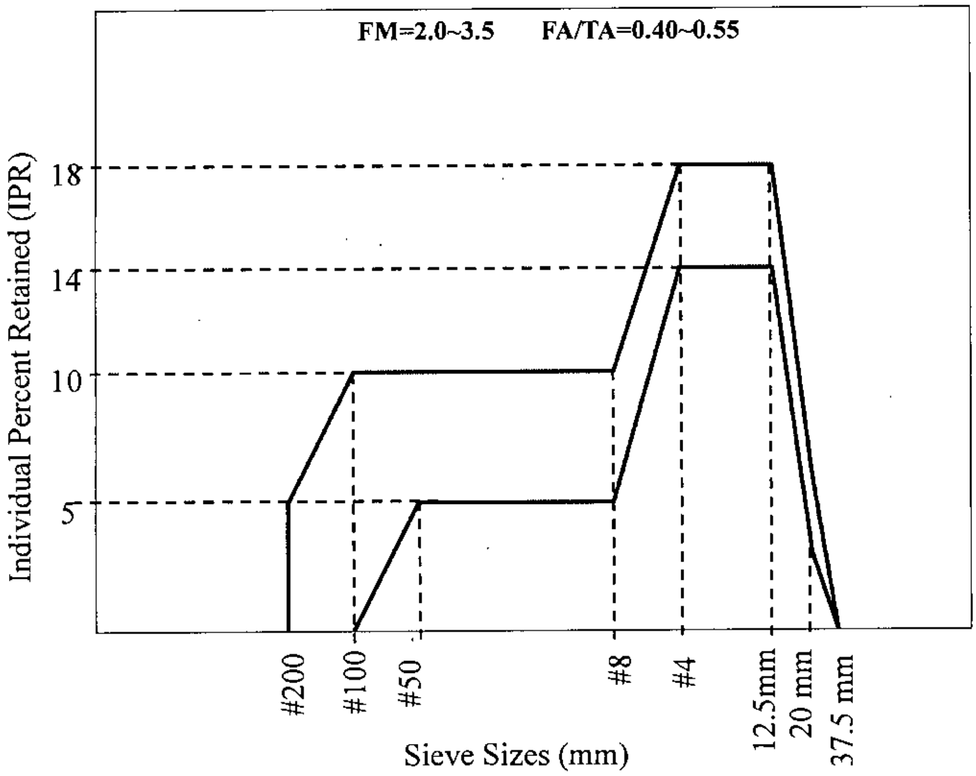


Figure 4.6: IPR Requirements for 5-10-14-18 Band Gradation.

4.3 Experiments

In this stage various existing aggregate gradation methods are compared to find out the most suitable aggregate gradation methodology in terms of concrete compressive strength and workability. In this part of the experimental set up, total eight types of aggregate gradations have been compared in terms of their resultant concrete compressive strength and workability.

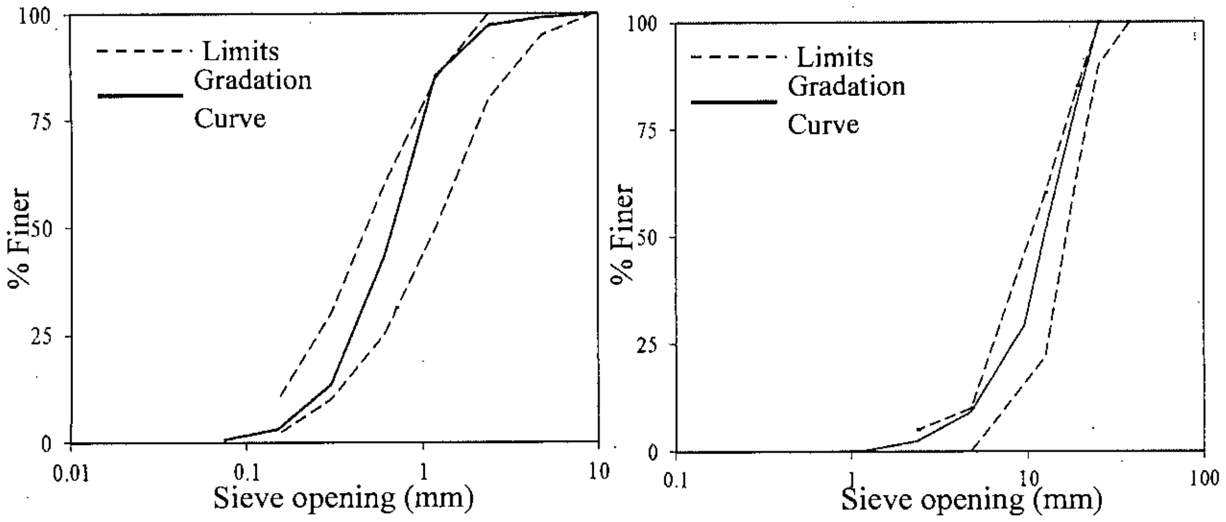
4.3.1 Aggregate Gradations

Gradation-1

It is the aggregate gradation as per ASTM C33. First Sylhet sand and Local sand has been combined to meet the fine aggregate gradation limits as per ASTM C33. Once the fine aggregate gradation is fixed, fineness modulus corresponding to this selected fine aggregate gradation has been determined. On the other side using available coarse aggregates, arbitrarily a coarse aggregate gradation has been selected which meets the ASTM C33 recommended coarse aggregate gradation. Using the fine aggregate FM and water content, mixing ratio of fine aggregate to coarse aggregate has been determined from ACI 211.

Figure 4.7(a) and 4.7 (b) represent the fine aggregate and coarse aggregate gradation curves. In these figures dashed lines represents the corresponding limits as per the standard ASTM C 33. The solid lines represent the selected gradations for fine aggregates and coarse aggregates.

Table 4.1 represents the required proportions of different source aggregates, which have been combined to achieve the code specified gradation. Here '¾ inch down grade', '½ inch down grade' and '¼ inch down grade' are the graded coarse aggregate samples which includes different sizes of aggregates. Details of these source aggregate samples are described in chapter 3 (section 3.3.2).



(a) Fine Aggregate

(b) Coarse Aggregate

Figure 4.7: Fine and Coarse Aggregate Gradation Curves for Gradation – 1

Table 4.1: Fine and Coarse Aggregate Properties for Gradation – 1

		Fine Aggregate	**Coarse Aggregate**
Proportions of Source aggregates	Sylhet sand	90%	-
	Local Sand	10%	-
	¾ inch down grade	-	70%
	½ inch down grade	-	23%
	¼ inch down grade	-	7%
Other Properties	Overall FM	3.57	6.86
	FM	2.57	4.72
	Particles passing #4	98.59%	9.26%
	Particles retained #4	0.84%	90.74%

Aggregate properties after combination

For FM of fine aggregate = 2.57 and w/c = 0.44, required ratio of fine aggregate to total aggregate has been found to be 0.42. After combining these FA and CA in this ratio, total aggregate gradation has been found. The total aggregate gradation curve is represented by the solid line in Figure 4.8.

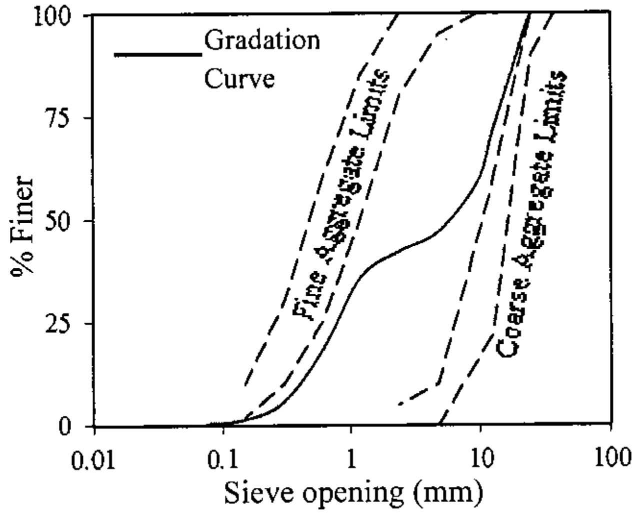


Figure 4.8: Combined Aggregate Gradation Curve for Gradation – 1

But since, coarse aggregate which has been shown above in Figure 4.3 (b) has certain portion of fine aggregate, after combination the actual Fa/Ta ratio becomes 0.47 and FM of fine aggregate becomes 2.82.

Gradation-2

20mm all-in aggregate gradation given in BS 882 selected as gradation – 2 for the experiment. It is a combined aggregate gradation. Different proportions of all source aggregate has been required to meet the gradation limits of 20 mm all-in aggregate gradation. Table 4.2 shows the required proportions of source aggregates for gradation – 2.

Table 4.2: Fine and Coarse Aggregate Properties for Gradation – 2

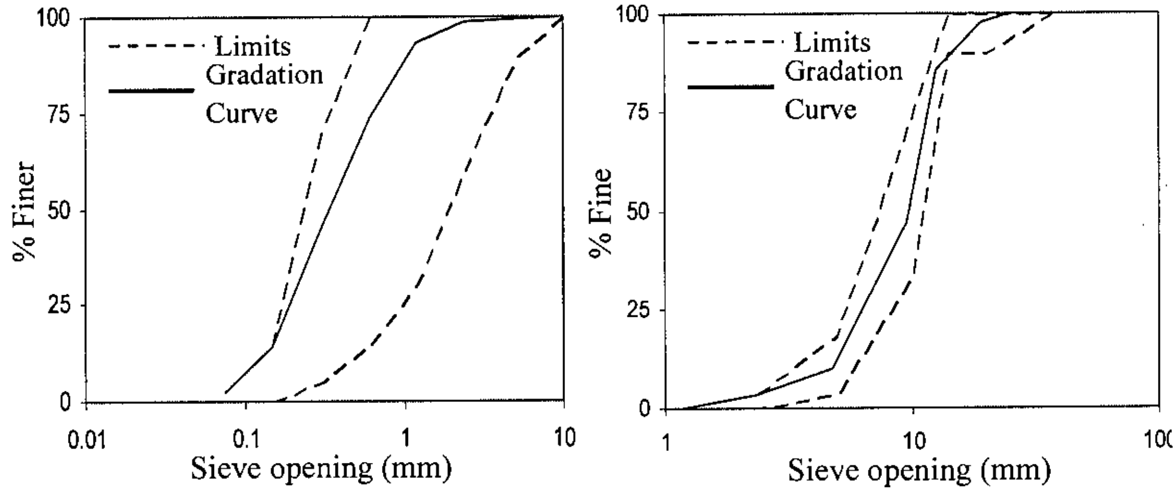
		Combined aggregate gradation	**Fine Aggregate**	**Coarse Aggregate**
Proportions of Source aggregates	Sylhet sand	20	53%	-
	Local Sand	18	47%	-
	¾ inch down grade	17	-	27 %
	½ inch down grade	20	-	32 %
	¼ inch down grade	10	-	16%
	1/2inch	7.5	-	12%
	3/4	7.5	-	12%
Other Properties	Overall FM	5.18	-	-
	FM	2.57	-	-
	Particles passing #4	47.57	-	-
	Particles retained #4	51.73	-	-

Gradation-3

Fine and coarse aggregate gradation

Overall fine aggregate gradation as per the standard BS 882 has also been selected for comparison. Again in concrete mix design procedure as per the standard BS 812, it is recommended that for coarse aggregate, suitable gradation may be achievable by mixing 20 mm and 10 mm single sized aggregate in 1:2 ratio. Moreover 20 mm and 10 mm single sized aggregate gradation limits for different sieves are defined in BS 882. Hence, the coarse aggregate gradation has been easily achieved simply by mixing the specified single sized aggregate at the recommended ratio.

Figure 4.9(a) and Figure 4.9(b) represent the fine aggregate and coarse aggregate gradation curves respectively for gradation – 3. In these figures the dashed line used to indicate the range of variation in grain size distribution which has been allowed by BS 882 and solid line represents the gradation used in this experiment. Table 4.3 shows the used proportions of source aggregates.



(a) Fine Aggregate (b) Coarse Aggregate

Figure 4.9: Fine and Coarse Aggregate Gradation Curves for Gradation – 3

Table 4.3: Fine and Coarse Aggregate Properties for Gradation – 3

		Fine Aggregate	**Coarse Aggregate**
Proportions of Source aggregates	Sylhet sand	40%	-
	Local Sand	60%	-
	¾ inch down grade	-	9 %
	½ inch down grade	-	42 %
	¼ inch down grade	-	9%
	Only ½ inch		8 %
	Only ¼ inch		32 %
Other Properties	Overall FM	2.73	6.52
	FM (considering particles passing #4)	1.8	4.66
	Particles passing #4	97.36%	10.2 %
	Particles retained #4	0.38%	89.8 %

Combined aggregate gradation:

Using the FM of fine aggregate and water content the mixing ratio of fine aggregate to coarse aggregate has been found from concrete mix design procedure as per BS 812. For FM of fine aggregate = 1.8 and w/c = 0.44, required ratio of fine aggregate to total aggregate has been found to be 0.286. After combination with coarse aggregate the actual Fa/Ta ratio becomes 0.35 and FM of fine portion of total aggregate becomes 2.37. Figure 4.10 shows the gradation curve of total aggregates after combination.

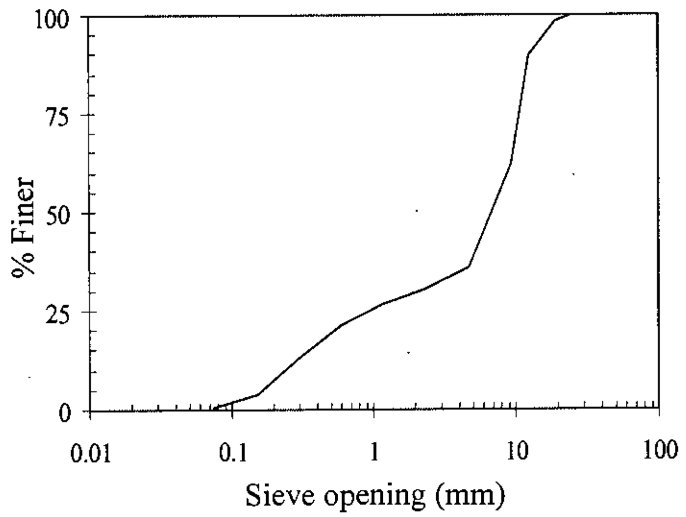


Figure 4.10: Combines Aggregate Gradation Curves for Mix-3

Gradation-4

Aggregate gradation – 4 has been selected as a band gradation in which proportions of all size particles remains within 10 to 15 percent of the total aggregate by weight. This gradation is known as "10-15" band gradation. Table 4.4 shows the required proportions of source aggregates used to achieve this gradation of aggregate.

Table 4.4: Proportions and Properties of Source Aggregates Gradation – 4

		Combined aggregate gradation	**Fine Aggregate**	**Coarse Aggregate**
Proportions of Source aggregates	Sylhet sand	30	86 %	-
	Local Sand	5	14 %	-
	¾ inch down grade	30	-	46%
	½ inch down grade	15	-	23 %
	¼ inch down grade	20	-	31 %
Other Properties	Overall FM	5.44	-	-
	FM	3.28	-	-
	Particles passing #4	54.27	-	-
	Particles retained #4	45.47	-	-

Gradation-5

For gradation – 5, aggregates have been graded so as to limit the percent of particles retained on any individual sieve is in between 8 to 18 percent. These is the now – a – days popular gradation methodology known as 8 – 18 band. Table 4.5 shows the proportions of source aggregates required to achieve this gradation. This table also features some parameters of total aggregates.

Table 4.5: Properties of Combined Aggregates for Gradation – 5

		Combined aggregate gradation	Fine Aggregate	Coarse Aggregate
Proportions of Source aggregates	Sylhet sand	30	100 %	-
	Local Sand	0	0 %	-
	¾ inch down grade	27	-	38 %
	½ inch down grade	18	-	26 %
	¼ inch down grade	25	-	36 %
Other Properties	Overall FM	5.58	-	-
	FM	3.59	-	-
	Particles passing #4	54.09	-	-
	Particles retained #4	45.84	-	-

Gradation – 6

Aggregates have been graded so as to limit the percent of particles retained on any individual sieve is in between 6 to 22 percent. Table 4.6 shows the properties of combined aggregate.

Table 4.6: Properties of Combined Aggregates for Gradation – 6

		Combined aggregate gradation	Fine Aggregate	Coarse Aggregate
Proportions of Source aggregates	Sylhet sand	21	81 %	-
	Local Sand	5	19 %	-
	¾ inch down grade	38	-	51 %
	½ inch down grade	25	-	34 %
	¼ inch down grade	11	-	15 %
Other Properties	Overall FM	5.78	-	-
	FM	3.15	-	-
	Particles passing #4	37.72	-	-
	Particles retained #4	62.05	-	-

Gradation-7

In this gradation the aggregates have been graded so as to follow the newly proposed gradation "5-10-14-18". Table 4.7 shows the proportions and properties of aggregates for gradation – 7.

Table 4.7: Properties of Combined Aggregates for Gradation – 7

		Combined aggregate gradation	**Fine Aggregate**	**Coarse Aggregate**
Proportions of Source aggregates	Sylhet sand	17	68 %	-
	Local Sand	8	32 %	-
	¾ inch down grade	24	-	32 %
	½ inch down grade	22	-	29 %
	¼ inch down grade	7	-	9 %
	Only ½ inch			15 %
	Only ¾ inch			15 %
Other Properties	Overall FM	5.81	-	-
	FM	2.83	-	-
	Particles passing #4	32.48	-	-
	Particles retained #4	67.19	-	-

Gradation-8

In this gradation the aggregates have been graded so as to follow the newly proposed gradation "5-10-18-22". Table 4.8 shows the proportions and properties aggregates for gradation – 8.

Table 4.8: Properties of Combined Aggregates for Gradation – 8

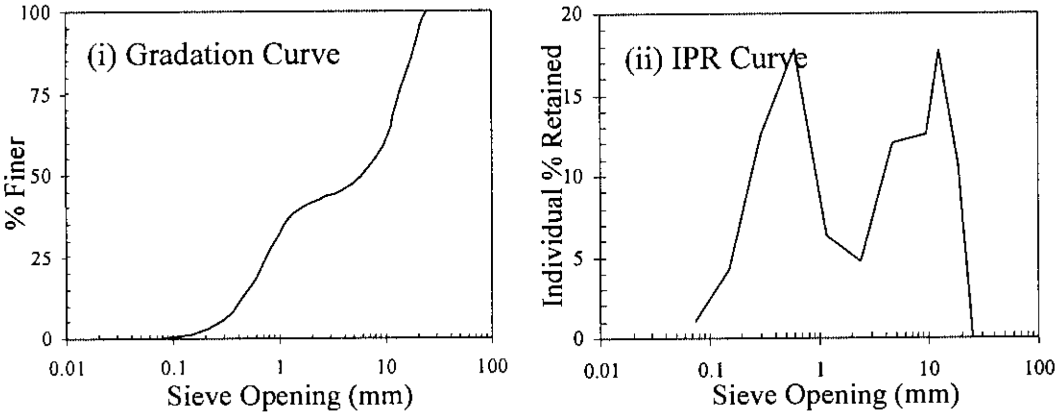
		Combined aggregate gradation	**Fine Aggregate**	**Coarse Aggregate**
Proportions of Source aggregates	Sylhet sand	20	57 %	-
	Local Sand	15	43 %	-
	¾ inch down grade	22	-	34 %
	½ inch down grade	16	-	25 %
	¼ inch down grade	14	-	21 %
	Only ½ inch	5.6		9 %
	Only 3/8 inch	7.2		11 %
Other Properties	Overall FM	5.81	-	-
	FM	2.83	-	-
	Particles passing #4	32.48	-	-
	Particles retained #4	67.19	-	-

Table 4.9 summarizes the different types of aggregate gradations which have been used in this research for comparison in terms of concrete properties.

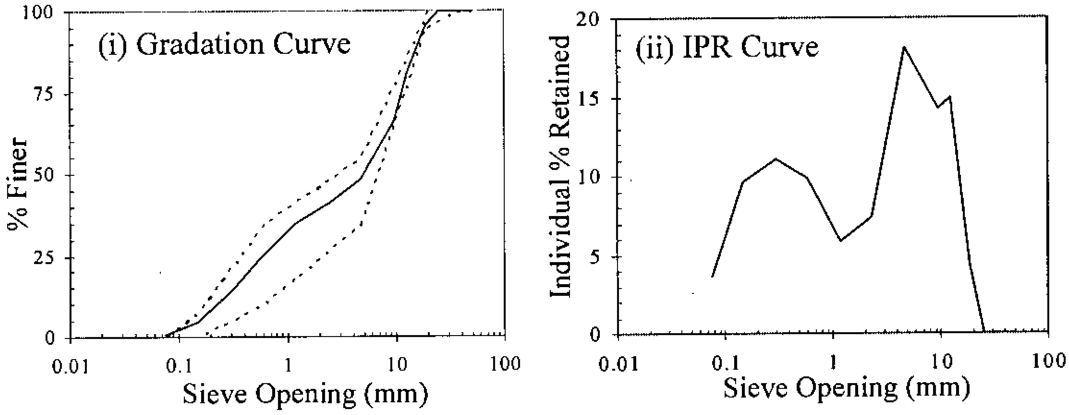
Table 4.9: Aggregate Gradation Methods for Different Mixes

Gradation ID	Method of Aggregate Gradation	Type of gradations
Gradation-1	Coarse and Fine aggregate gradation conforms ASTM C33 limit and combined as per ACI mix design method.	Fine and coarse aggregate
Gradation- 2	20mm All-in-Aggregate gradation as specified in BS 882:1992	Combined gradation
Gradation- 3	20mm, 10mm and fine aggregate as per BS882:1992	Fine and coarse aggregate
Gradation- 4	"10-15" Band Gradation	Combined gradation (band gradation)
Gradation- 5	"8-18" Band Gradation	
Gradation- 6	"6-22" Band Gradation	
Gradation- 7	"5-10-14-18" Band Gradation	
Gradation- 8	"5-10-18-22" Band Gradation	

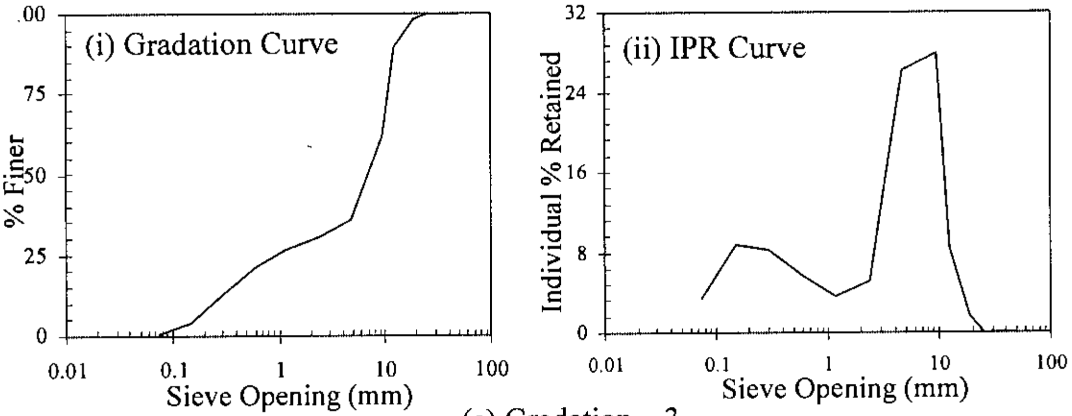
Figure 4.11 illustrates the grain size distribution for the selected aggregate gradations via gradation curves and IPR curves. Also, different parameters of these samples are presented in table 4.10.



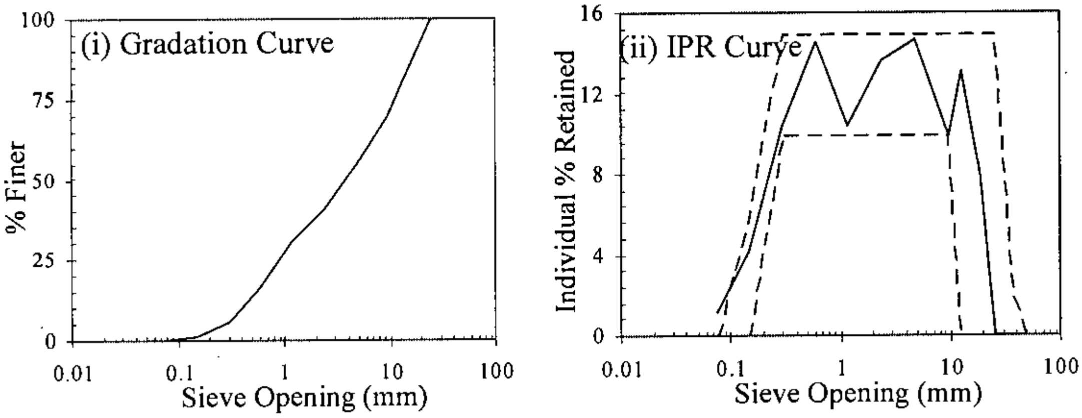
(a) Gradation – 1



(b) Gradation – 2

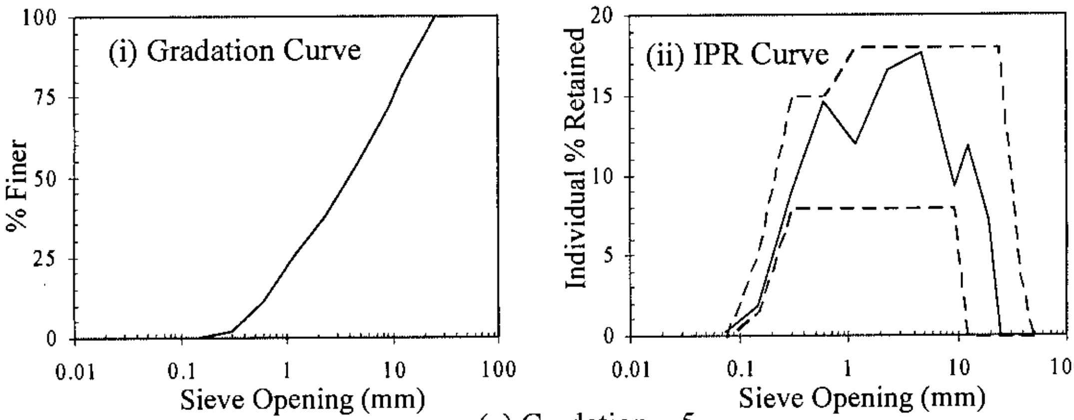


(c) Gradation – 3

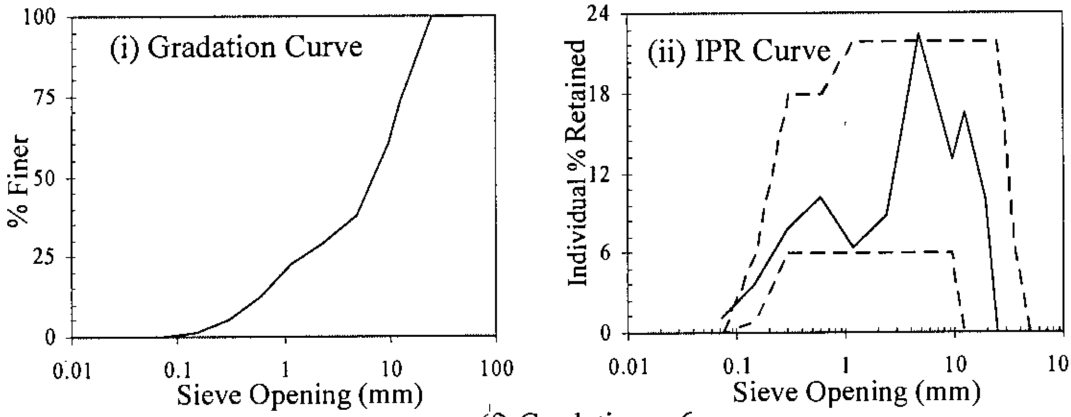


(d) Gradation – 4

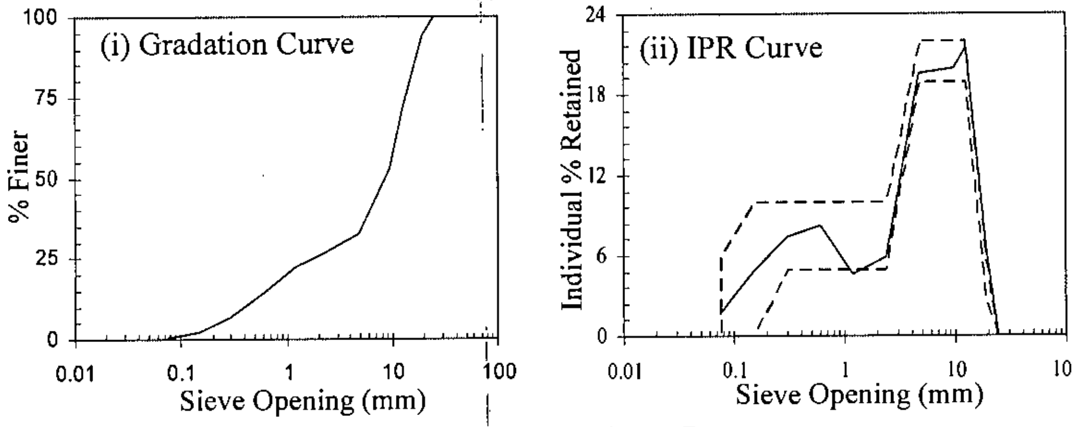
Figure 4.11: Gradation Curves for Selected Aggregates (contd.)



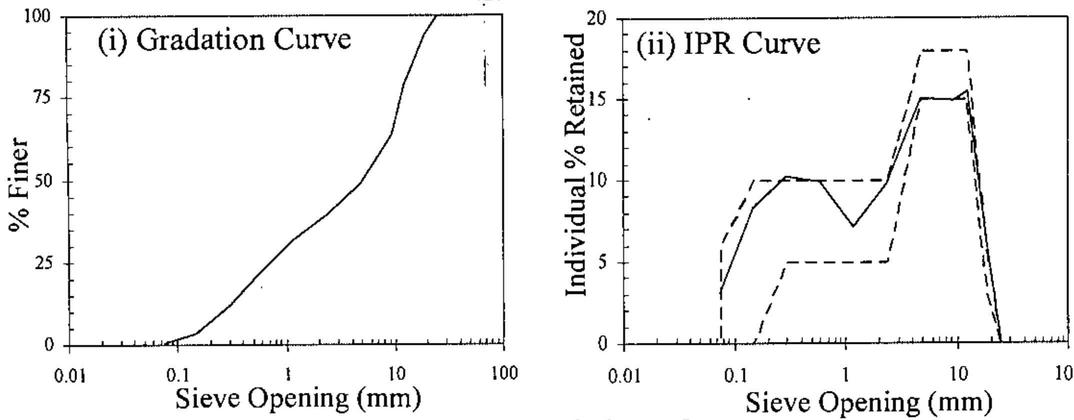
(e) Gradation – 5



(f) Gradation – 6



(g) Gradation – 7



(h) Gradation – 8

Figure 4.11: Gradation Curves for Selected Aggregates (contd.)

Table 4.10: Combined Aggregate Properties for Different Mixes

Gradation ID	FA/TA	Combined FM	FM	CF	WF	Aggregate Density (kg/m^3)	% Void Content
Gradation-1	0.47	5.48	2.82	0.71	0.42	1664	36
Gradation- 2	0.48	5.18	2.57	0.57	0.40	1647	37
Gradation- 3	0.35	5.44	2.37	0.55	0.30	1701	35
Gradation- 4	0.54	5.44	3.28	0.52	0.41	1682	35
Gradation- 5	0.54	5.58	3.59	0.45	0.38	1664	36
Gradation- 6	0.38	5.78	3.15	0.56	0.29	1663	36
Gradation- 7	0.33	5.81	2.83	0.65	0.27	1666	36
Gradation- 8	0.49	5.32	2.81	0.59	0.39	1656	36

4.3.2 Concrete Trial Mix Results

Table 4.11 represents the test results of different trial concrete mixes.

Table 4.11: Concrete Properties for Different Mixes

Mix ID	Aggregate gradation type	Fresh Concrete Density (kg/m^3)	Slump (mm)	Yield (ft^3)	Compressive Strength (MPa)		
					7 Days	14 Days	28 Days
Mix-1	Gradation-1	2302	31.75	0.78	18	26	30
Mix-2	Gradation- 2	2256	65	0.79	21	29	31
Mix-3	Gradation- 3	2204	0	0.80	38	39	46
Mix-4	Gradation- 4	2258	0	0.77	38	45	47
Mix-5	Gradation- 5	2284	6.35	0.77	35	42	51
Mix-6	Gradation- 6	2292	3	0.77	25	28	30
Mix-7	Gradation- 7	2290	25.4	0.77	28	33	37
Mix-8	Gradation- 8	2266	31.75	0.78	29	31	40

4.4 Discussions

4.4.1 Slump Variation

At particular water content (180 kg/m^3), the slumps for different trial mixes have been found to be varied in a wide range (0 to 65 mm). This may be due to the fact that, although the total water content has been remained same for all mixes but some other workability influencing important aggregate parameters such as fine aggregate to total aggregate (fa/ta) ratios as well as the particle size distributions (i.e. aggregate gradation) have been remained variable for different mixes.

4.4.2 Combined-Fineness Modulus vs Fine Aggregate-Fineness Modulus

From Figure 4.12, it seems that there might be a specific relationship between concrete compressive strength with FM of fine aggregate which was first noted by Abrams (1924). But when compressive strength is plotted against combined aggregate FM, no distinct pattern of variation can be observed. Similar result is found when slump is plotted against fineness modulus. Slumps seem to vary in a more specific trend with the FM of fine aggregate than the FM of combined aggregate (Figure 4.13). Since workability and strength are two main criteria of concrete mix design, and Combined FM does not seem to have any specific relation with these two parameter, FM of fine aggregate is therefore found to be a better parameter for mix design of concrete than the combine aggregate FM.

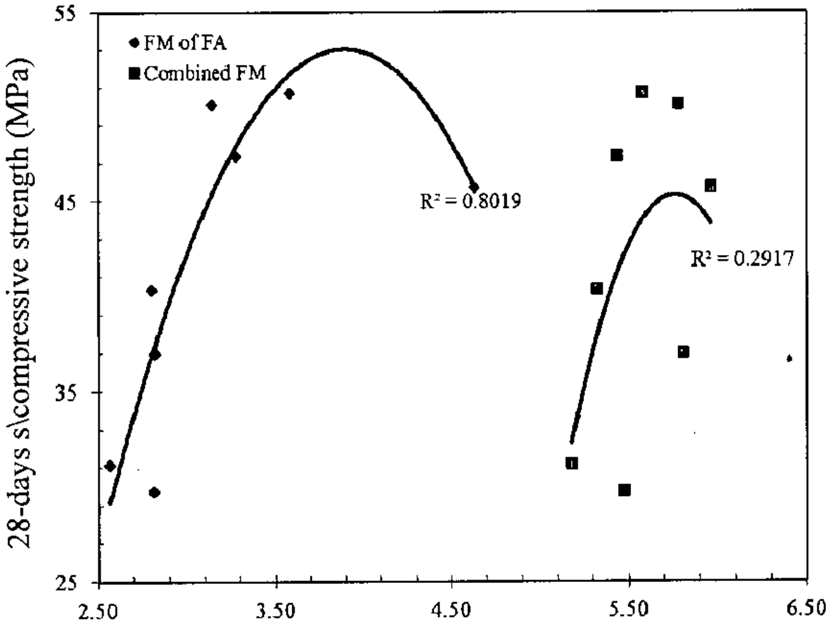


Figure 4.12: Variation of 28-days Compressive Strength (MPa) with Fineness Modulus

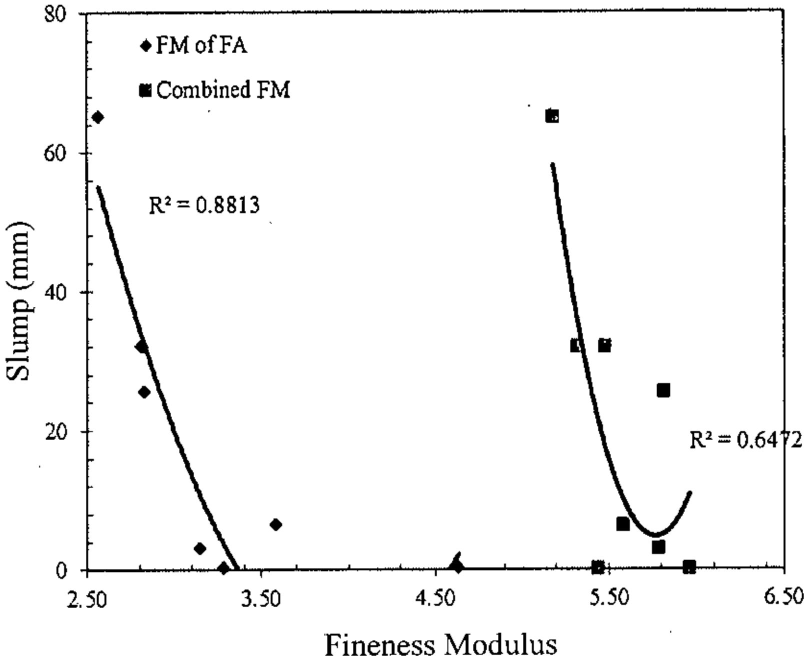


Figure 4.13: Variation of Slump (mm) with Fineness Modulus

4.4.3 Variation of 28 days Compressive Strength

The order of mixes for higher Compressive strength are-

(i) 8-18 band,

(ii) 6-22 band,

(iii) 10-15 band,

(iv) BS method of mix design using fine and coarse aggregate proportion,

(v) Aggregate Gradation as per proposed "5-10-18-22",

(vi) Aggregate Gradation as per proposed "5-10-14-18",

(vii) BS method of mix design using 20 mm all-in aggregate gradation,

(viii) ACI method of mix design using aggregates as per ASTM C33.

Figure 4.14 shows the variation of compressive strength (MPa) with time for various trial concrete mixes.

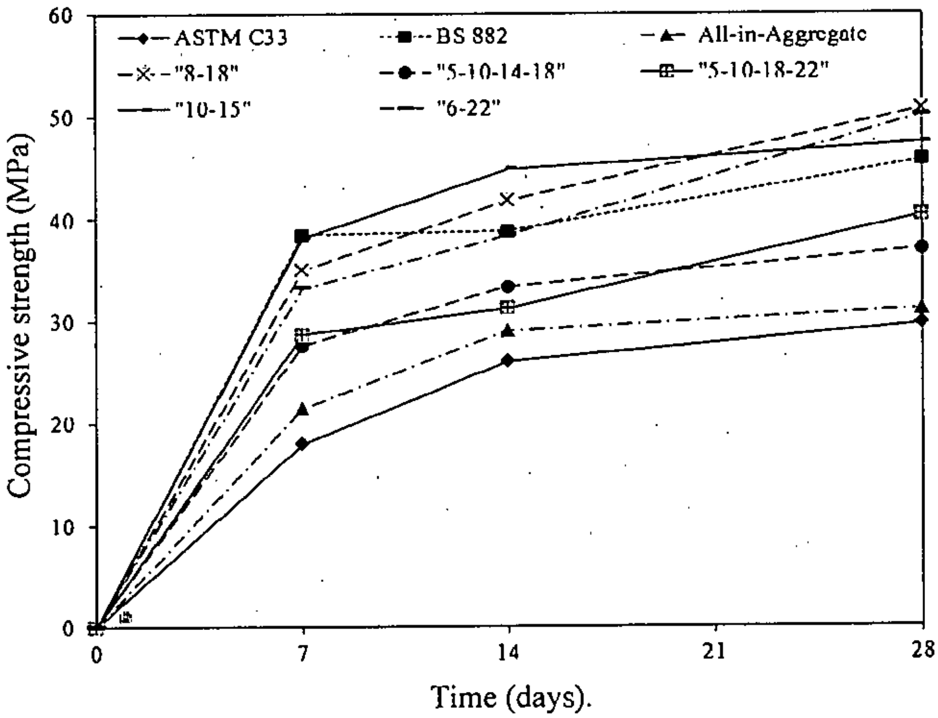


Figure 4.14: Variation of Compressive Strength (MPa) with Time (days).

4.4.4 Strength and Slump Comparison

Maximum 28 days cylinder strength has been found for 8-18 band gradation, but the corresponding workability of that mix found to be very low (6.35 mm). Figure 4.15 shows the comparison of slump (mm) and 28-days compressive strength (MPa) for different trial mixes. From Figure 4.16 it is clearly visible that for any mix with particular w/c ratio and without admixture if the strength is higher, the slump is lower and vice-versa. But to be an optimum mix, workability and strength both are the primary requirements. In that figure it has been observed that mix-7 and mix-8 give both strength and workability in sufficient amount. Aggregate gradation for both mix-7 and mix-8 have been maintained in a way, that FM of fine aggregate and Fa/ta ratios remained within a workable range. Considering the minimum 28 days strength to be the base, percentage of increase in strengths for these two mixes have been determined and presented in Table 4.12 along with other concrete and aggregate properties.

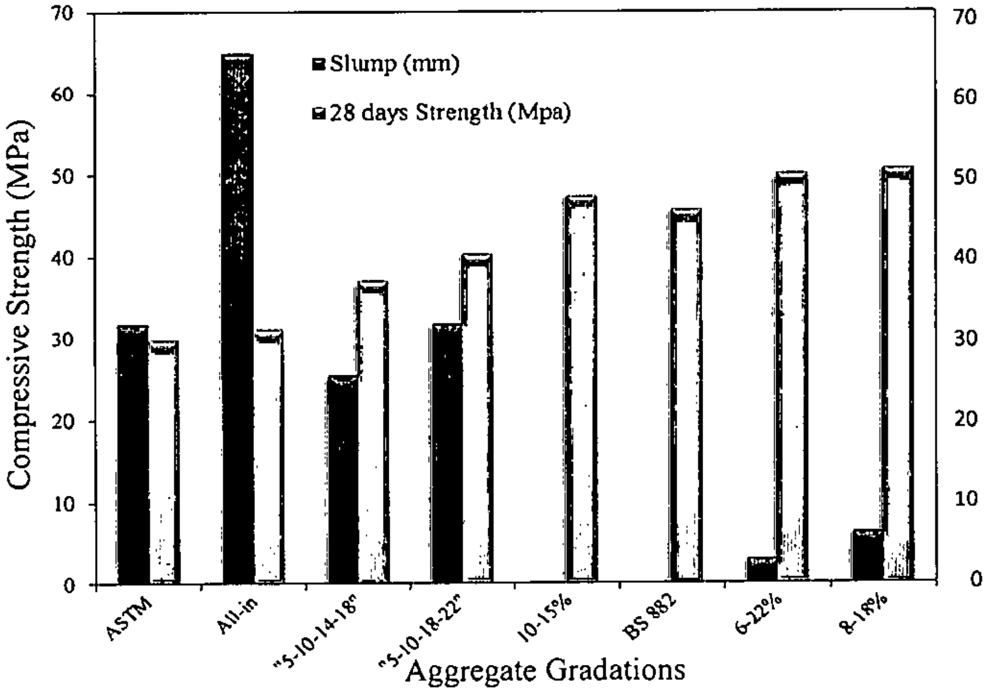


Figure 4.15: Variation of Compressive Strength and Slump for Various Mixes

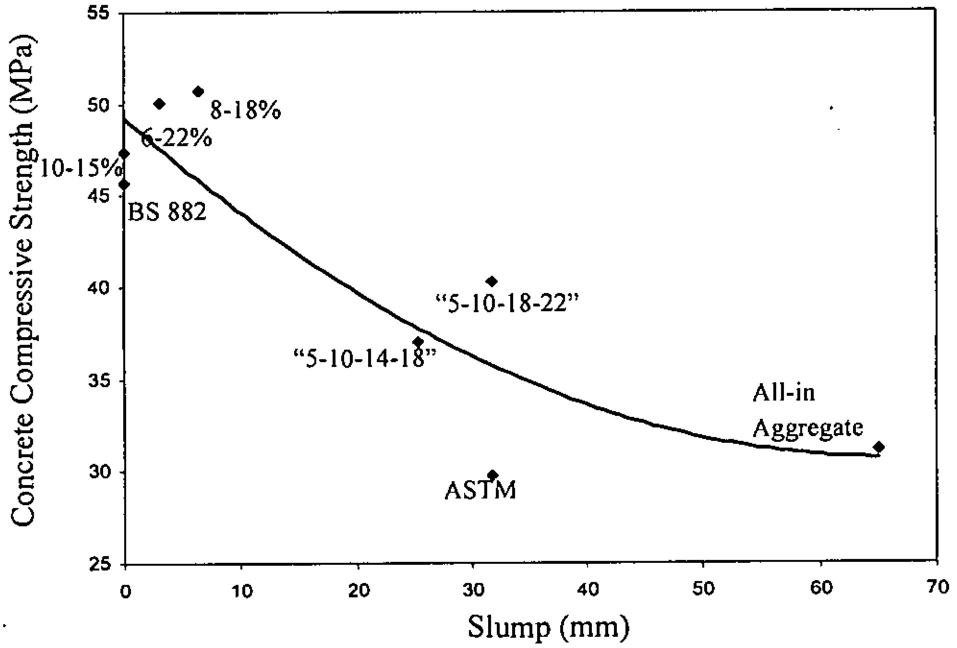


Figure 4.16: Compressive Strength (MPa) and Slump (mm) for Different Trial Mixes.

Table 4.12: Trial mixes providing both sufficient workability and increase in strength

Mix ID	FA/TA	FM of Fine Aggregate	Slump (mm)	28days Strength (MPa)	% Strength Increased
Mix-7	0.33	2.83	25.4	40	24.4
Mix-8	0.49	2.81	31.75	37	35.6

4.4.5 Variation of Concrete Properties with Coarseness Factor

Figure 4.17 shows that the compressive strength of concrete mix decreases with the increase of coarseness factor and vice-versa. This is because an increase in coarseness factor implies a decrease in intermediate size particles. Thus more the coarseness factor the mix tends to be more gap-graded and gives a lower compressive strength. Thus from Table-6, mix-1 (ACI mix design) can be consider as the most gap-graded mix and mix-5 (8-18) as the densest mix with sufficient intermediate particles.

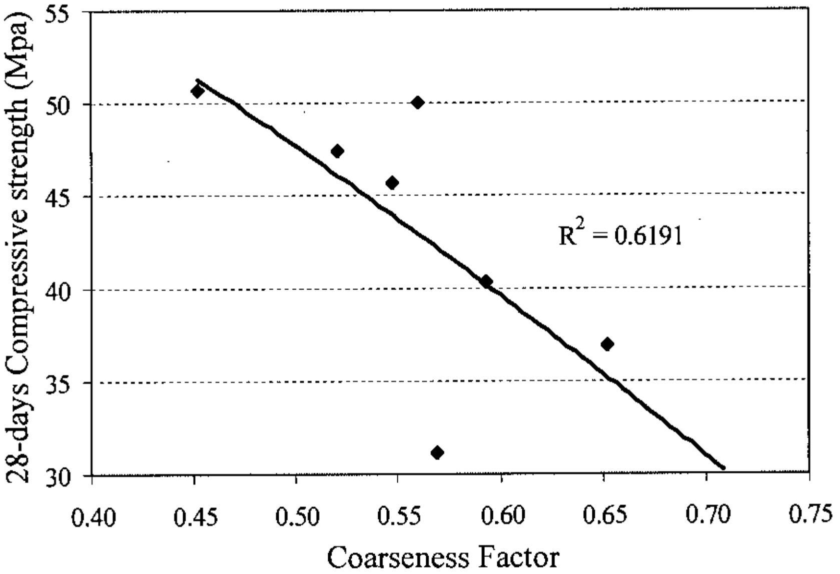


Figure 4.17: 28-Days Compressive Strength (MPa) vs. Coarseness Factor.

Table 4.10 also signifies that, considering only the aggregate density mix-3 found to be the densest mix whereas mix-6 turned out as the most gap-graded. Thus, it can be interpreted that, although mix – 3 have the maximum density but it may not have sufficient amount of intermediate particles, since its CF has been found to be higher than that of mix-5. Accordingly, considering the phenomenon of coarseness factor, it can be explained that being prepared with same mix proportions, why 28-days compressive strength of mix-5 has found to be the highest and lowest for mix-1. Another important note from Table 4.10 is that, the density of both mix-5 and mix-1 measured to be the same (1664 kg/m^3). But mix-5 which CF was 0.45 resulted in higher 28-days compressive strength than that of mix 1 which CF was 0.71. Thus, analyzing the experimental results it has been noticed that the presence of intermediate particles highly affects the compressive strengths.

4.4.6 Variation of Concrete Properties with Workability Factor

From Figure 4.18, it seems that compressive strength of concrete increases with the increase of workability up to a certain limit, after that strength starts decreasing with the increase of workability factor. That is because by definition WF is the % of aggregates passing # 8 sieves. Thus after a certain range, the mix will become more sandy with the increase of WF. From Figure 4.18 it seems that the suitable range of WF to get a higher strength is 0.30 to 0.37.From Figure 4.19 no specific relationship has been observed between workability factor and slump of the mix.

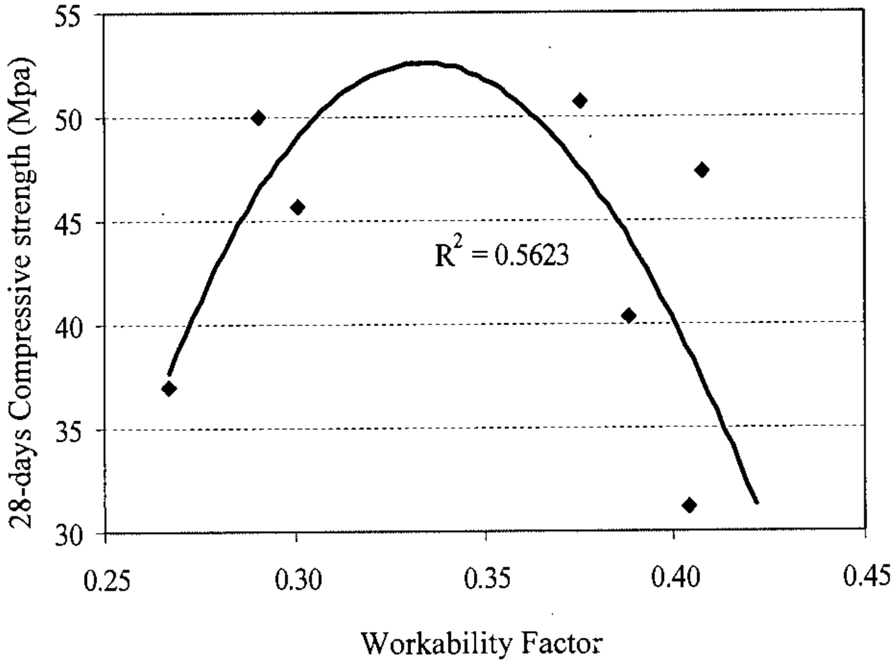


Figure 4.18: 28 – Days Compressive Strength (MPa) vs. Workability Factor.

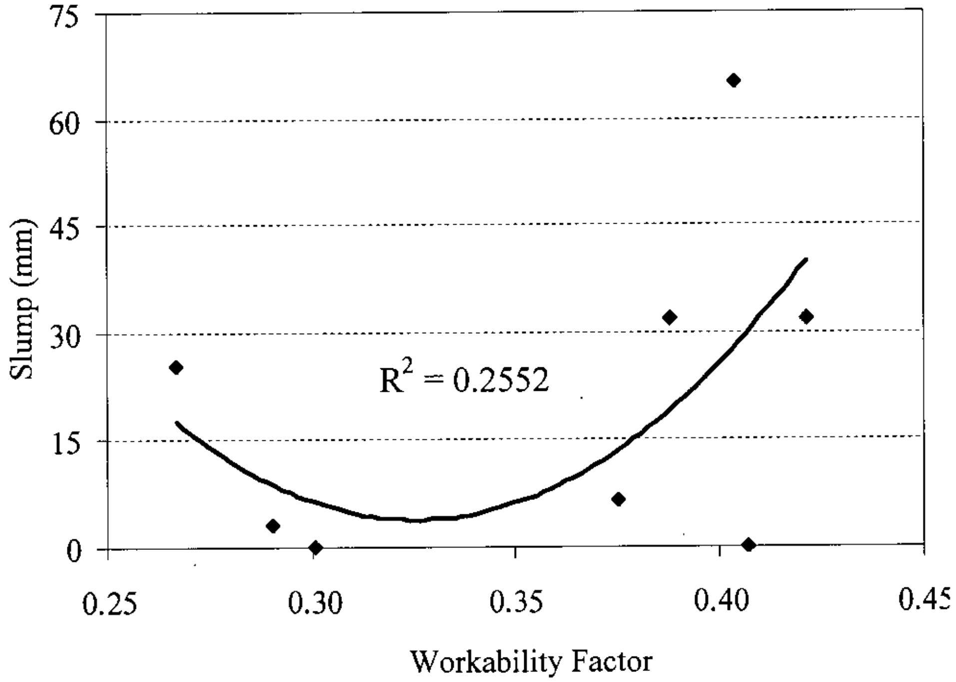


Figure 4.19: Variation of Slump (mm) with Workability factor.

4.4.7 Test Results of Conventional Mix Design Methods

As mentioned earlier, the w/c ratio for all the trial concrete mixes have been maintained to 0.44. For this mix proportion, as per ACI mix design method slump should be 1 to 2 inch and 28-days compressive strength should be higher than 40 MPa if OPC cement used for the mixes. Similarly as per British method of mix design the slump should be 20 to 50 mm and 28-days compressive strength should be higher than 40 MPa. Since the mixes have been prepared with CEM II/B-M cements, the slump can be expected to be little higher than these values whereas the strength supposed to be a little lower than 40 MPa. But from the trial mixes, it has been seen that, mix-1 and mix-3 have been failed to meet the slump requirement and mix-1 and mix-2 failed the strength requirement, although the aggregate gradations have followed the codes requirements.

Table 4.14: Concrete Properties for the Mixes Prepared Following the Conventional Codes

Mix ID	FA/TA	Combined FM	FM	CF	WF	Aggregate Density (kg/m^3)	Fresh Concrete Density (kg/m^3)	Slump (mm)	28 Days compressive strength (MPa)
Mix-1 (ASTM C 33)	0.47	5.48	2.82	0.71	0.42	1664	2302	31.75	30
Mix-2 (BS 882, all-in aggregate)	0.48	5.18	2.57	0.57	0.40	1647	2256	65	31
Mix-3 (BS 882)	0.35	5.96	2.37	0.55	0.30	1701	2204	0	46

There may be several reasons behind this deviation. Some important reasons are discussed below-

- *Coarseness factor*

For mix-1, both of the aggregate density and CF have to be high, which represents that possibly, this mix has a lacking in some range of intermediate particles. Thus, the mix can be inferred as gap-graded and which resulted in lower compressive strength than expected. For mix-2, the CF was 0.57 which represents that this mix may have sufficient portion of intermediate particles (from CF chart) but the total aggregate density has been found to be very low, which may be one of the reason of lower compressive strength.

For mix-3, both coarseness factor and aggregate density have been found to be adequate. Accordingly, the mix resulted in 46 MPa as the 28-days compressive strength which well fits the expected strength (40 MPa).

- *Workability factor*

It has been discussed earlier that the possible suitable range of WF for higher strength concrete mix is in between 0.3 to 0.37. From Table, the WF for mix-1 and mix-2 observed to be outside of this range, whereas the WF for mix-3 (0.30) is within the range and consequently, only mix-3 satisfied the 28-days strength requirement.

4.5 Concluding Remarks

This chapter presented a comprehensive experimental study on available aggregate gradation methodologies along with two newly proposed gradations. Comparison of different aggregate gradations in terms of 28 days compressive strength and workability of concrete mixes prepared with same mix proportion has been the prime objective of the research. From this comparison, the newly developed "5-10-14-18" and "5-10-18-22" band gradations have been found to provide a balanced mix with sufficient workability and compressive strength. Thus, these two band gradations have been selected for further experimental investigation in next stages of the research.

Chapter 5

SUITABILITY OF "5 – 10 – 14 – 18" AND "5 – 10 – 18 – 22" BAND GRADATIONS

General

From the previous stage of the research, it has been found that 5-10-14-18 and 5-10-18-22 band gradations can be considered as more apposite than other existing aggregate gradations in terms of concrete compressive strength and workability. In this chapter parametric analysis of these two selected band gradations have been featured based on some trial concrete mix results. In this phase of the research, the possible extreme cases of aggregate gradations have been selected for concrete mixes.

5.1 Background

5-10-14-18 and 5-10-18-22 band gradations are developed in a way that any aggregate gradation which satisfies the Individual Percent Retained (IPR) requirements for all sieve sizes of these gradation bands will have some of their parameters (i.e. FM and fa/ta ratio) within a particular narrow range. The primary objective of next stage research has been selected as the identification of the maximum possible variation in concrete properties that are achievable with same mix proportions but different aggregate gradations within any of the selected band gradations. In order to check the variability of concrete properties within an aggregate gradation band, boundary cases of these bands have been selected. Then using these selected aggregate gradations, concrete mixes have been so designed that water content and w/c ratio remained constant for all of the trial mixes. Accordingly, maximum ranges of possible variations of concrete properties within any of the proposed band at a particular water content and w/c ratio have been obtained through this experimental study.

5.2 Boundary Values

Since ranges for two parameters (FM and fa/ta) have been fixed, total four boundary conditions are possible for each gradation band. Table 5.1 shows the boundary cases based on the definitions of respective band gradations. Attaining the boundary case gradations is mostly dependent on the available fine aggregate (# 4 passing aggregates) gradations. Table

5.2 shows the possible boundary case gradation using locally available aggregates in Dhaka.

Table 5.1: Boundary Cases for 5-10-18-22 and 5-10-14-18 Bands

5-10-18-22		**5-10-14-18**	
Fa/ta	**FM**	**Fa/ta**	**FM**
0.43	2.00	0.4	2.00
0.43	3.50	0.4	3.50
0.25	2.00	0.55	2.00
0.25	3.50	0.55	3.50

Table 5.2: Practical Boundary Cases for 5-10-18-22 and 5-10-14-18 Bands

5-10-18-22		**5-10-14-18**	
Fa/ta	**FM**	**Fa/ta**	**FM**
0.29	2.31	0.4	2.75
0.43	2.62	0.5	2.88
0.42	1.95	0.5	2.19
0.29	2.18	0.4	1.98

5.3 Aggregate Gradations

Figure 5.1 shows the relative positions of the selected aggregate gradations in FM vs. fa/ta chart. Continuing for previous chapter here these selected aggregate gradations have been named as gradation – 8, gradation - 9 up to gradation – 16 (Figure 5.1). Proportions of source aggregate required to obtain the gradation – 9 has been shown in Table 5.3, similar information for gradation - 10 to gradation - 16 can be found in Appendix I.

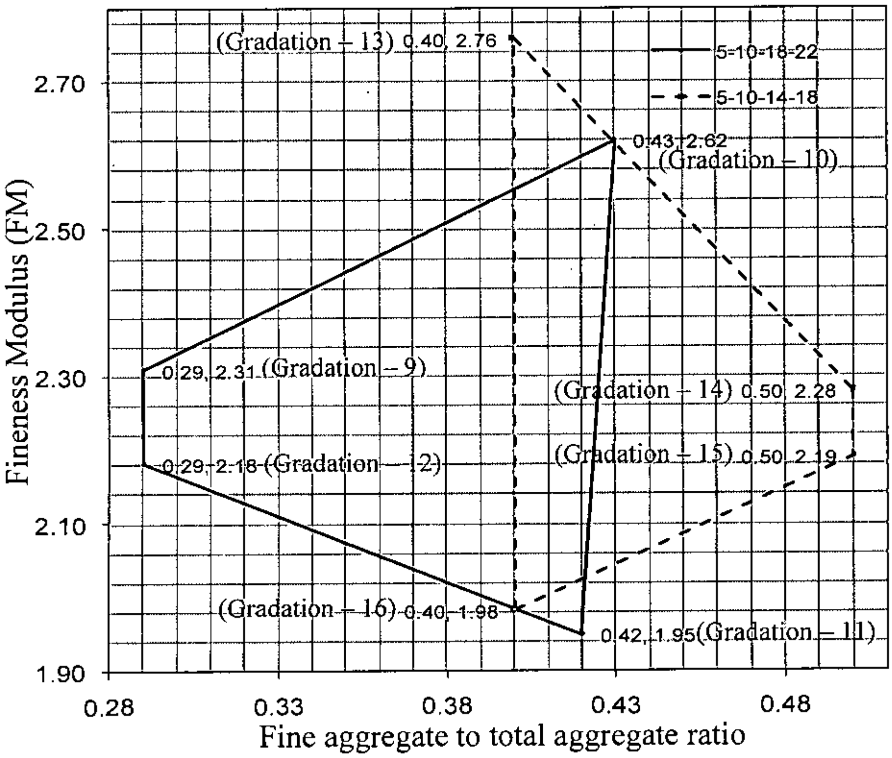
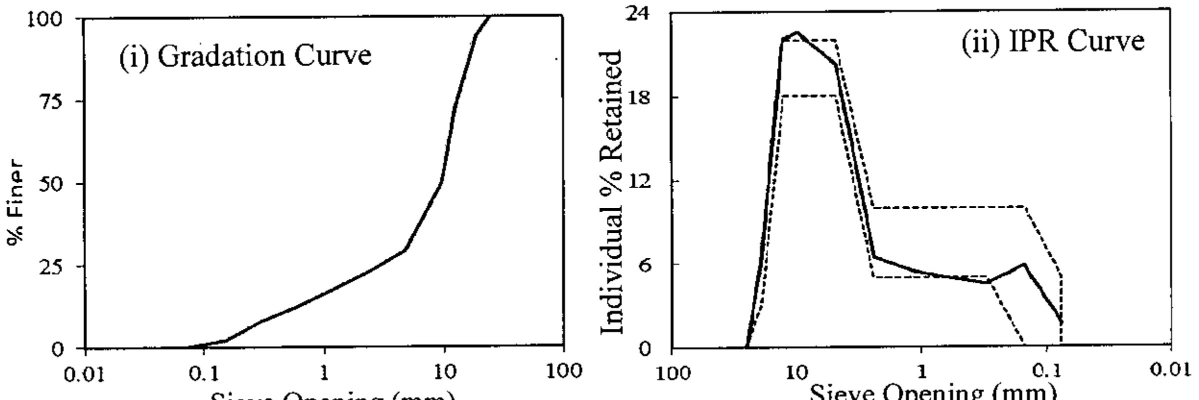


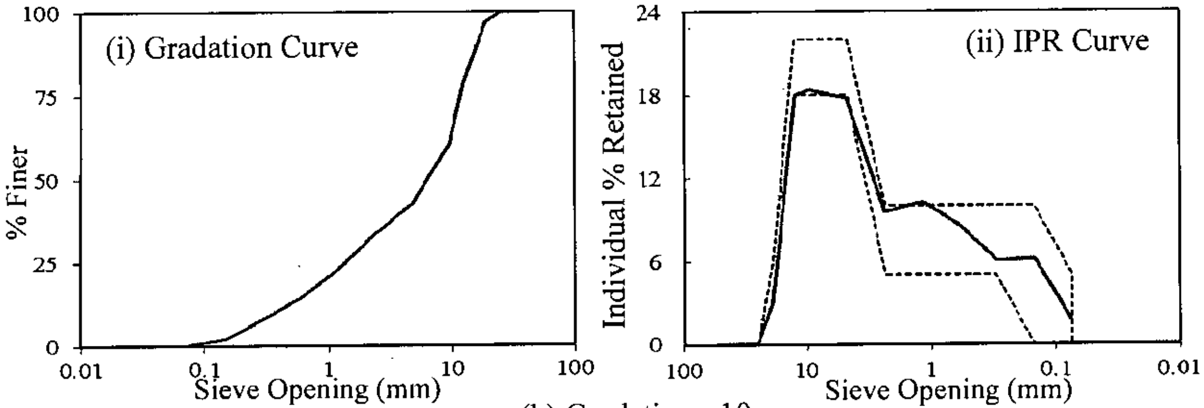
Figure 5.1: Positions of Selected Aggregate Gradations in FM vs. Fa/Ta Chart

Table 5.3: Proportion of Source Aggregates Required for Gradation – 9

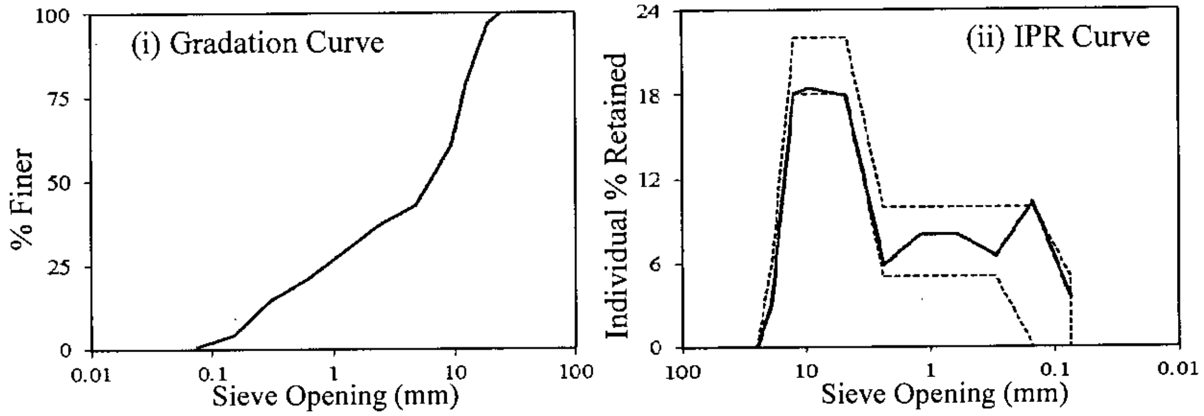
		Combined aggregate gradation	**Fine Portion**	**Coarse Portion**
Proportions of Source aggregates	Filler	0	-	-
	Local sand	9.5	42 %	-
	Sylhet Sand	13	58 %	-
	¼ inch down grade	1.5	-	1.9 %
	½ inch down grade	26	-	33.5 %
	3/8 inch	22	-	28.4 %
	½ inch	22	-	28.4 %
	3/4 inch	6	-	7.7 %
Other Properties	Overall FM	5.94	-	-
	FM	2.31	-	-
	Particles passing #4	29.00	-	-
	Particles retained #4	70.75	-	-



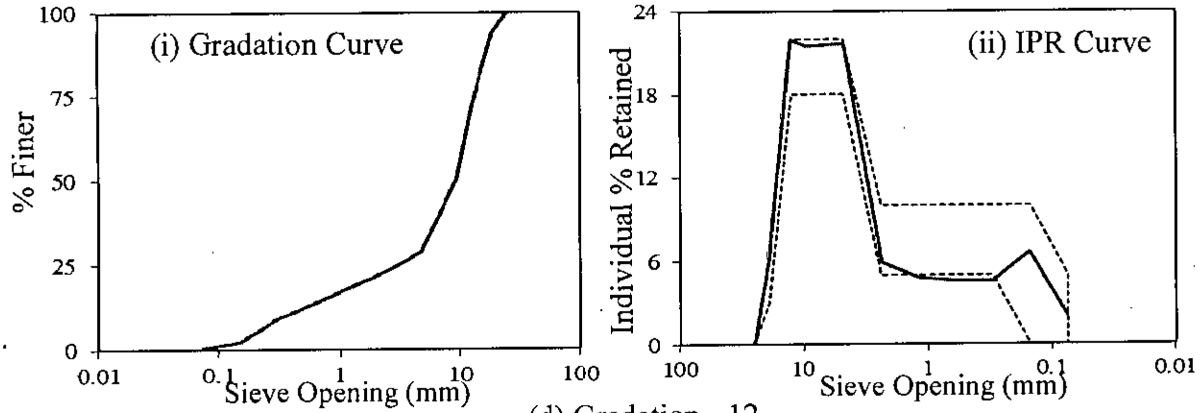
(a) Gradation - 9



(b) Gradation - 10

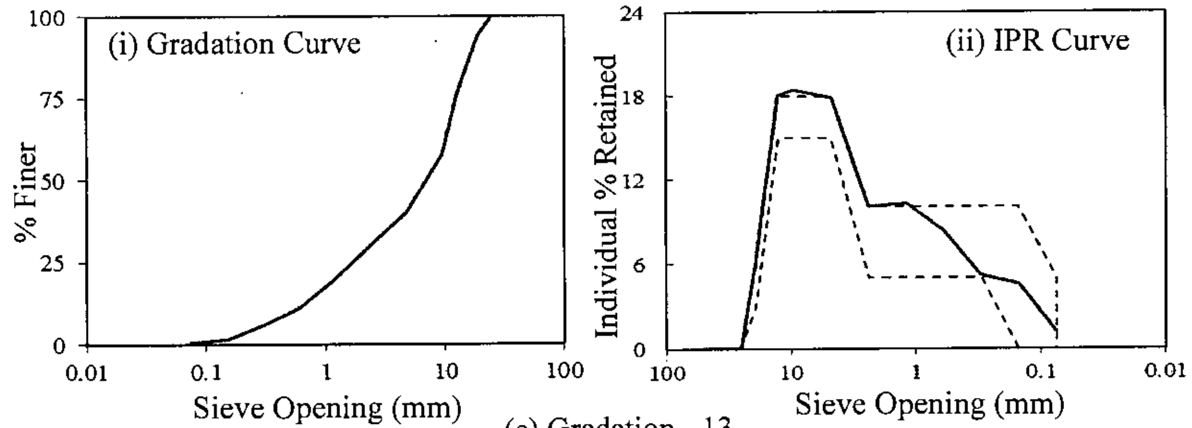


(c) Gradation - 11

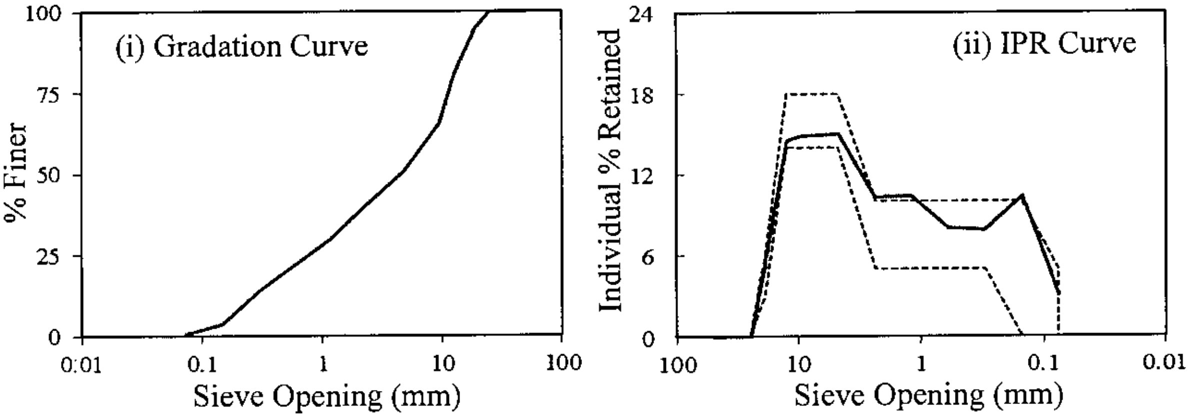


(d) Gradation - 12

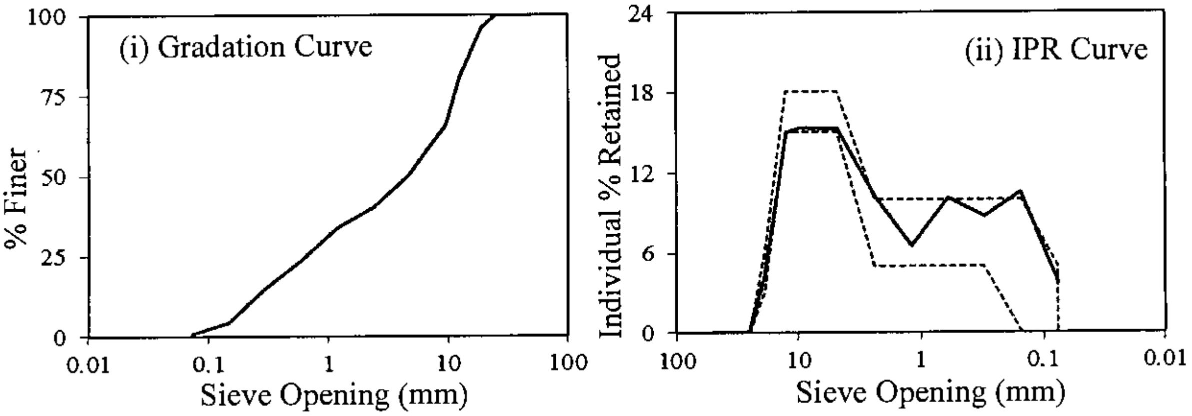
Figure 5.2: Grain Size Distributions for Selected Aggregate Gradations (Contd.)



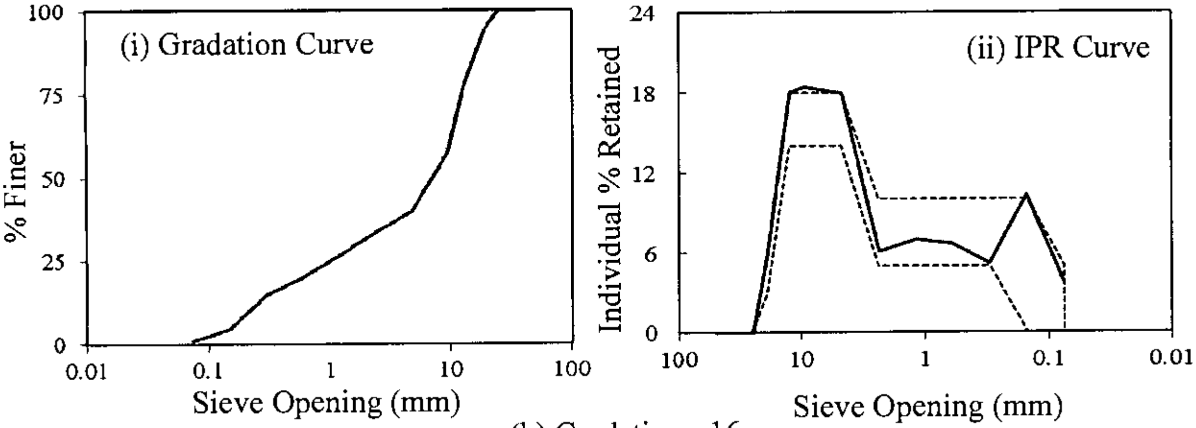
(e) Gradation - 13



(f) Gradation - 14



(g) Gradation - 15



(h) Gradation - 16

Figure 5.2: Grain Size Distributions for Selected Aggregate Gradations (Contd.)

5.4 Results

For the selected aggregate gradations, different combined aggregate properties and test results of trial concrete mixes are shown in Table 5.4 and Table 5.5 respectively.

Table 5.4: Properties of Different Selected Aggregate Gradations

	Aggregate gradation ID	Concrete trial mix ID	Combined FM	FM	Fa/ta	CF	WF
5-10-18-22	Gradation – 9	Mix – 9	5.94	2.90	0.29	65	23
	Gradation – 10	Mix – 10	5.61	3.14	0.43	59	33
	Gradation – 11	Mix – 11	5.37	2.58	0.42	62	36
	Gradation – 12	Mix – 12	5.89	2.74	0.29	64	23
5-10-14-18	Gradation – 13	Mix – 13	5.81	3.32	0.40	60	30
	Gradation – 14	Mix – 14	5.29	2.86	0.50	58	40
	Gradation – 15	Mix – 15	5.20	2.72	0.50	58	40
	Gradation – 16	Mix – 16	5.48	2.54	0.40	64	33

Table 5.5: Test Results for Concrete Trial Mixes

Aggregate Gradation type	Mix ID	Fresh Concrete Density (kg/m^3)	Slump (mm)	Yield (ft^3)	Relative Yield	Strength (MPa)		
						7 Days	14 Days	28 Days
5-10-18-22	Mix – 9	2316	19	2.31	1.05	10	16	22
	Mix – 10	2282	19	2.35	1.06	12	21	32
	Mix – 11	2284	13	2.34	1.06	10	17	26
	Mix – 12	2312	25	2.32	1.05	10	15	26
5-10-14-18	Mix – 13	2316	13	2.31	1.05	10	17	21
	Mix – 14	2280	38	2.35	1.06	10	14	23
	Mix – 15	2280	32	2.35	1.06	10	16	23
	Mix – 16	2282	13	2.35	1.06	12	17	28

Figure 5.3 and 5.4 represent the gain of compressive strength of concrete with time (days) for "5-10-18-22" and "5-10-14-18" band gradations respectively.

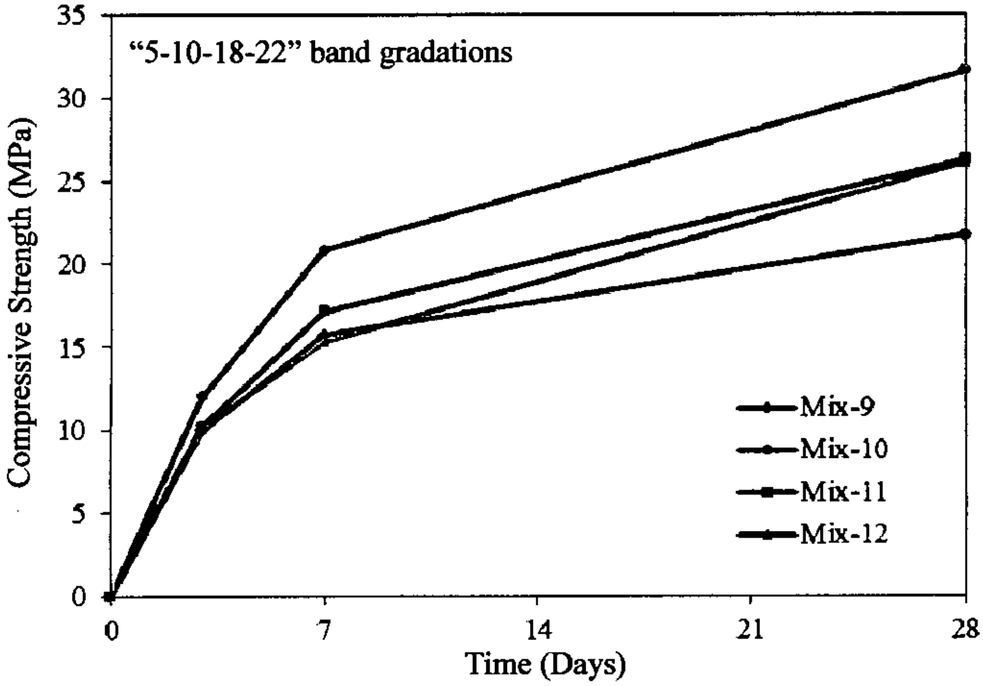


Figure 5.3: Variation of Compressive Strength (MPa) with Time for 5-10-18-22 Band Gradations.

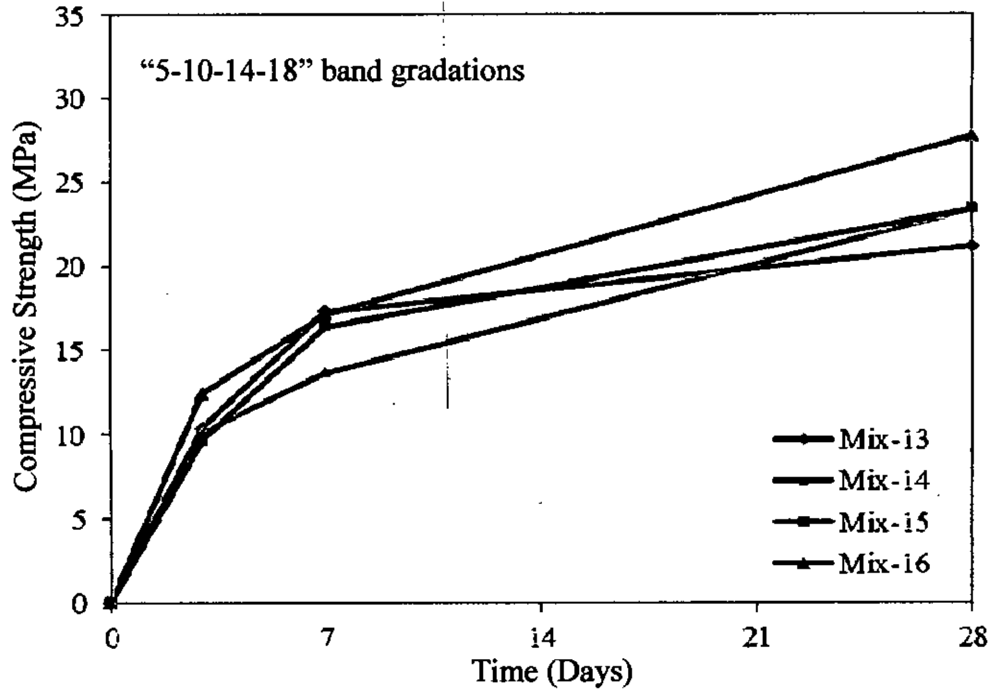


Figure 5.4: Variation of Compressive Strength (MPa) with Time for 5-10-14-18 Band Gradations.

5.5 Comparative Analysis of "5-10-14-18" and "5-10-18-22" Bands

5.5.1 Fresh Concrete Density

From Table 5.4, it can be observed that, for all of the eight trial concrete mixes, fresh concrete density ranges from 2280 kg/m^3 to 2316 kg/m^3. The standard deviation of the data set is 17 kg/m^3 which is only about 0.8% of the minimum density. Thus, from these experimental results, it can be inferred that for a particular mix proportions, the position of the aggregate gradation within any of 5-10-14-18 and 5-10-18-22 band gradations have insignificant impacts on fresh concrete density. Therefore some other important parameters of concrete mixtures, such as void content, air content, yield and relative yield are also independent of the position of the mix within any of the gradation bands.

5.5.2 Compressive Strength

3 days, 7 days and 28 days concrete compressive strengths (MPa) for various mix positions shown in Figure 5.5 to Figure 5.7 respectively. From Figure 5.7, it can be observed that for mixes with a particular w/c ratio but different aggregate gradations within the band 5-10-18-22 may have a maximum variation of 28 days compressive strength of about 32%. For 5-10-14-18, this variation is 24%. These variations are quite small considering that the variations from the average strength are only about 15 to 20%.

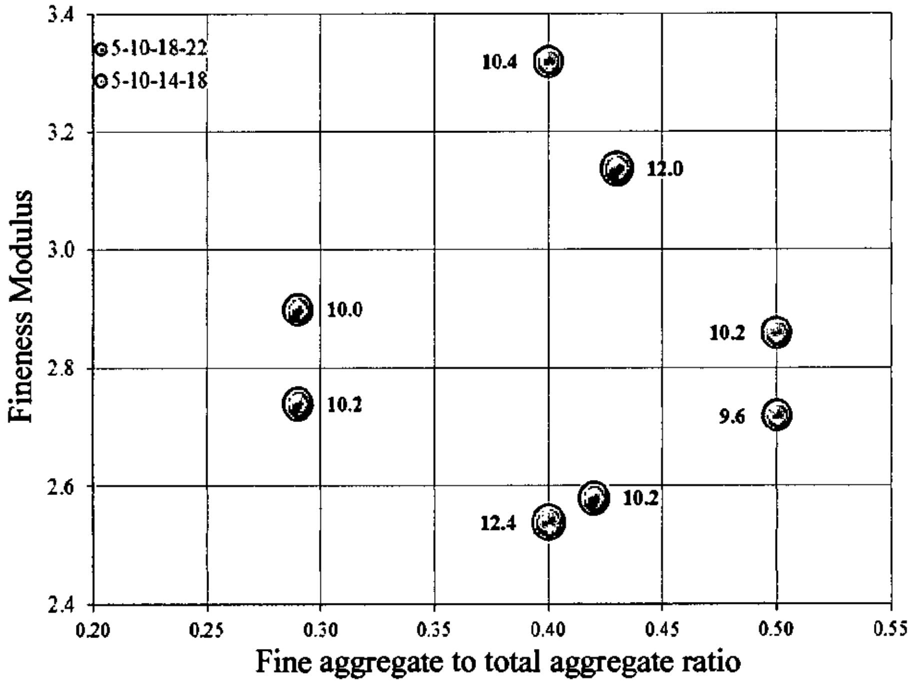


Figure 5.5: 3 Days Compressive Strength (MPa) of Concrete Mixes for Various Positions in FM vs. Fa/Ta Chart

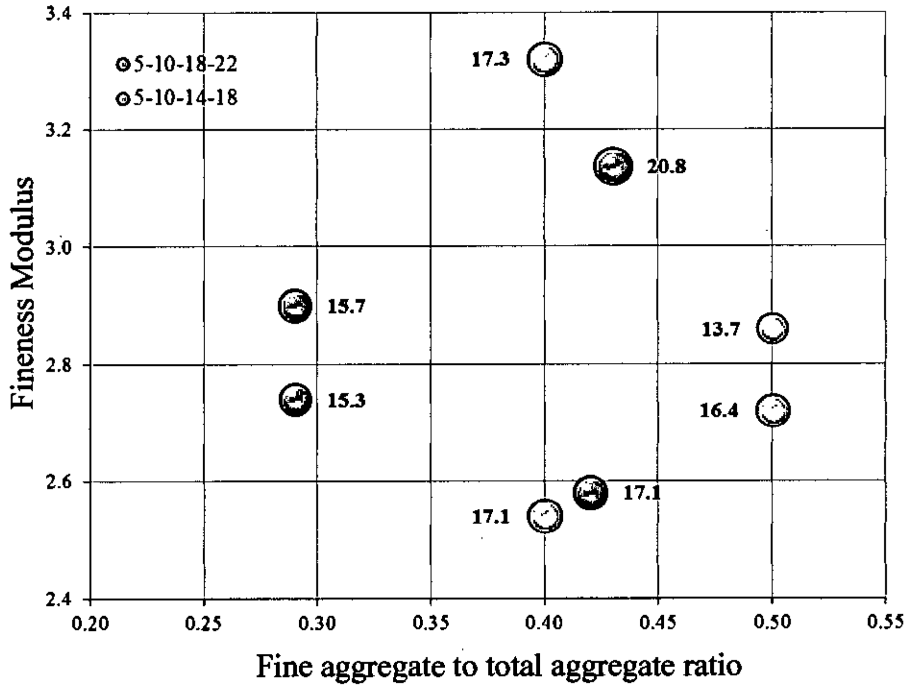


Figure 5.6: 7 Days Compressive Strength (MPa) of Concrete Mixes for Various Positions in FM vs. Fa/Ta Chart.

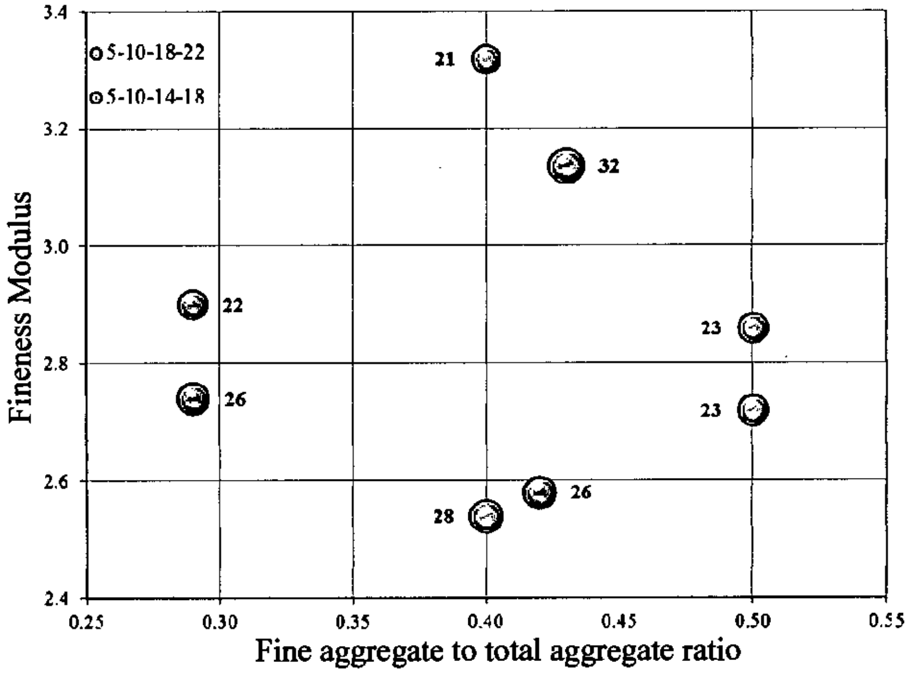


Figure 5.7: 28 Days Compressive Strength (MPa) of Concrete Mixes for Various Positions in FM vs. Fa/Ta Chart.

5.5.3 Workability

Figure 5.8 represents the slump value (mm) for different positions of mixes. This figure indicates that for specific water content and having aggregate gradation anywhere within the recommended bands may produce a variable workability. These results also ensure that with a particular maximum nominal size of aggregate, it is possible to have variation in concrete workability without changing the water content. Such as, for 5-10-18-22 band at particular water content slump can be increased by simply shifting the aggregate gradation position from right to the left of the FM vs. fa/ta chart. Similar effects can be achieved in 5-10-14-18 band by shifting the aggregate gradation positions to the right and vice-versa.

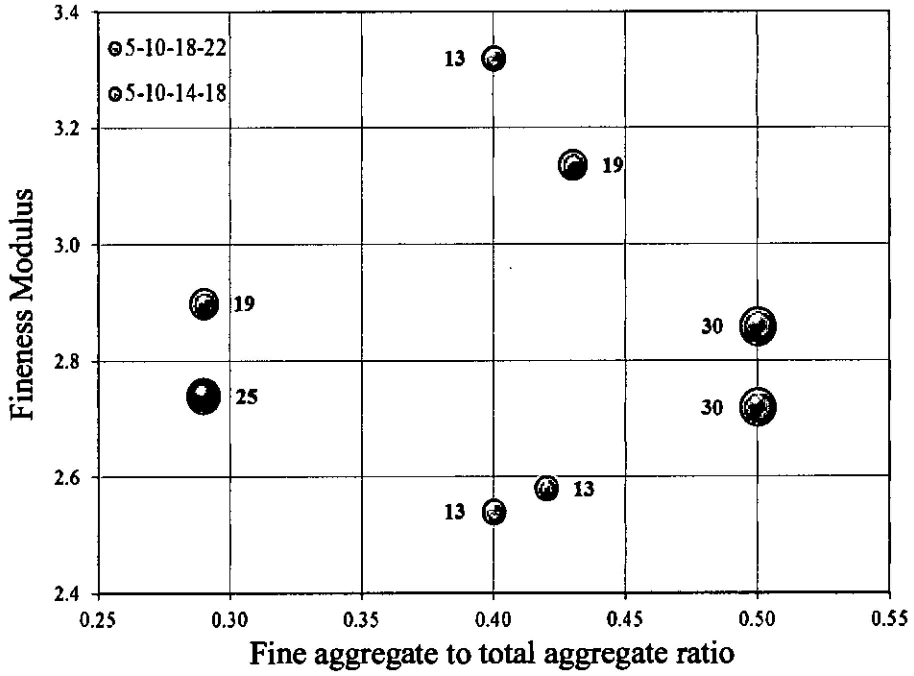


Figure 5.8: Slump Values (mm) of Concrete Mixes for Various Positions in FM vs. Fa/Ta Chart.

5.6 Correlating Aggregate Gradation Bands with Concrete Mix Design

From the experimental results, it is evident that, equal compressive strength and workability are achievable using any of these recommended aggregate gradation bands. Thus, the choice of the aggregate gradation band will mainly depend on user's perception and available aggregate sizes. It can be recommend that, for fa/ta ratio 0.40 and below, "5-10-18-22" band should be used. Similarly, for fa/ta ratio higher than 0.40, "5-10-14-18" gradation band is recommended.

The boundary cases considered in this research may not be same for any other season in the same area or any other area, because, locally available fine aggregate gradations depend on both area and seasons. But since the selected boundary cases are very close to the outmost boundaries, this little difference will may not affect the results much.

5.6.1 Variation of Compressive Strength

Although the variation of compressive strength within a band is quite negligible, still it can be utilized in concrete mix design. Such as, with a fixed w/c ratio, concrete compressive strength can be increased up to 46% simply by shifting the mix position in the chart shown in Figure 5.9. In this figure, arrow represents the direction in which any shifting of the mix will increase the compressive strength and the straight lines represent the directions along which shifting of mix possible without altering the compressive strength of the mix.

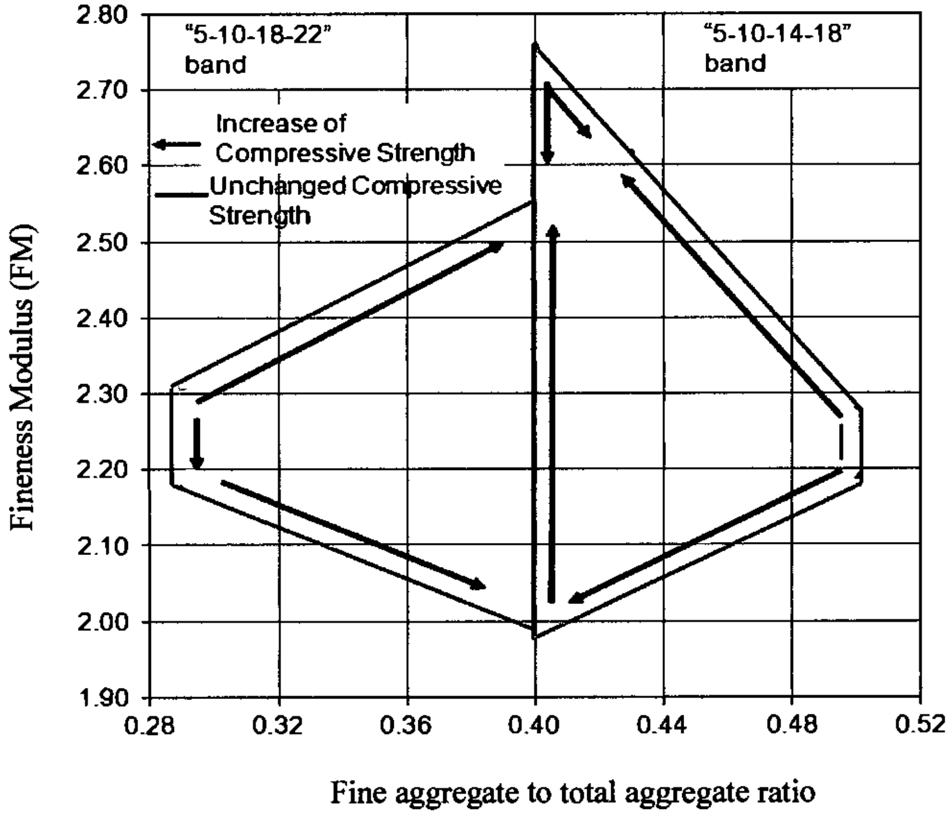


Figure 5.9: Variation of Concrete Compressive Strength within the Aggregate Gradation Bands

5.6.2 Variation of Workability

Similar to the concrete compressive strength, it is also possible to alter the workability of the mix without changing the water or aggregate contents, by changing the concrete mix position within the chart shown in Figure 5.10. In this figure, arrow represents the increase of workability and straight lines represent no change of workability in the corresponding directions.

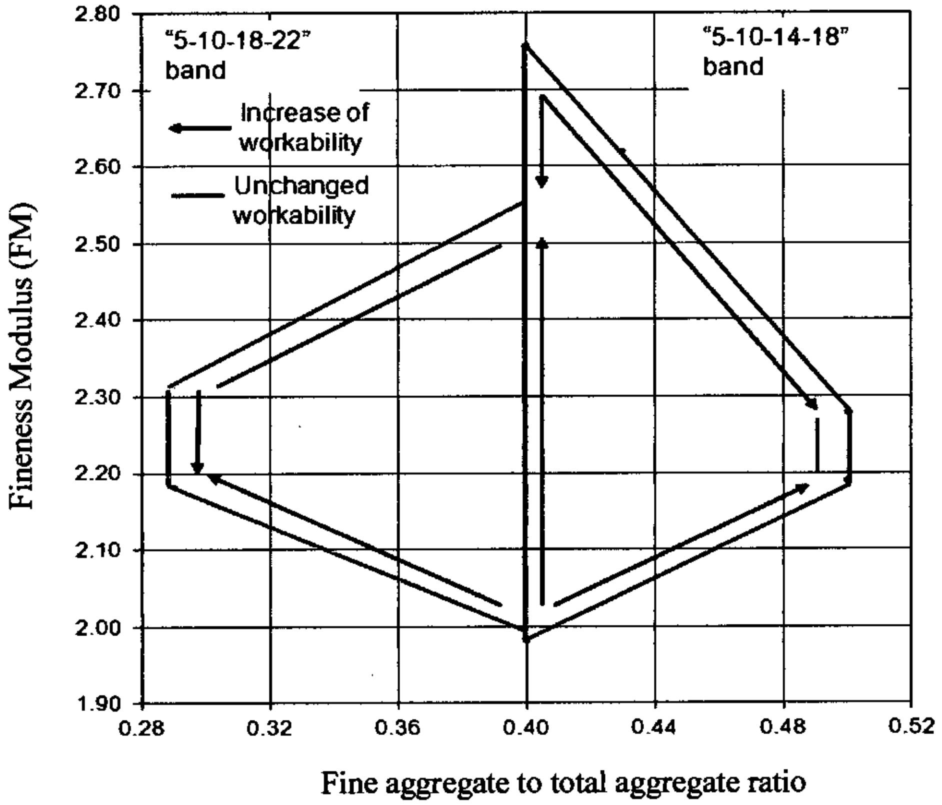


Figure 5.10: Variation of Concrete Compressive Strength within the Aggregate Gradation Band

5.6.3 Categories of Shifting

Considering both the variations in compressive strength and workability (Figure 5.9 & Figure 5.10), the shifting of the mix position can be categorized into four different ways-

A. Increase of both compressive strength and workability.

B. Increase of compressive strength and decrease of workability.

C. Increase of compressive strength with fixed workability.

D. Increase of workability with fixed compressive strength.

These shifting of mix positions are marked in Figure 5.11. From this figure, it can also be detected that, within the chart there is an optimum region in which direction both the concrete compressive strength and workability of the mix increases.

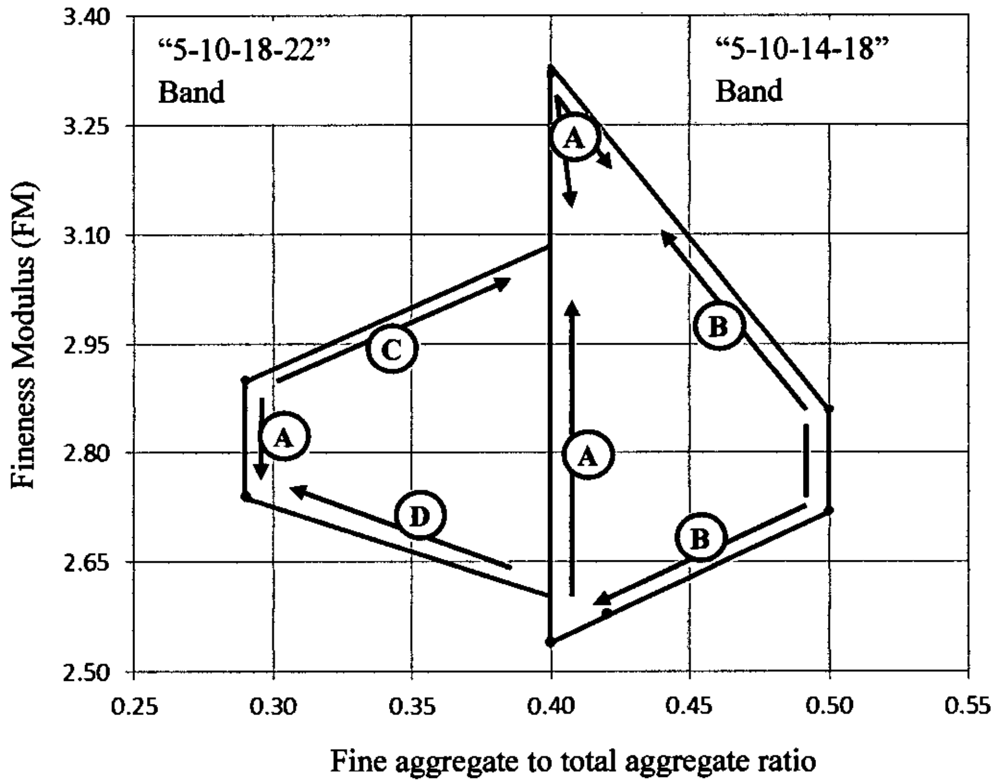


Figure 5.11: Variation of Concrete Compressive Strength and Workability within the Aggregate Gradation Band.

5.7 Practical Application

The fundamental challenge of these band gradations is to produce the aggregate gradations in field, particularly for fine aggregate (sand). But through defining 5-10-14-18 and 5-10-18-22 band gradations a wide range of fine aggregates (percent of materials retained on #100 and #200 sieves) has been allowed to make the gradations easier to obtain. Also, during these experiments, only two types of fine aggregate sources have been utilized to obtain the specified band gradations. However, computer program can be an easy solution for achieving any specified aggregate gradation. Fatmi et. al. (2011) has already developed a computer program (using MATLAB) for similar purpose. Using this program, the proportions of different source aggregate samples can be determined to achieve any specific aggregate gradation.

5.8 Concluding remarks

In this chapter, efforts have been made to assess the maximum possible variation in concrete properties within the recommended aggregate gradation band using a particular mix proportions. Moreover, from this research it has also been observed that FM vs. Fa/ta mix proportions. Moreover, from this research it has also been observed that FM vs. Fa/ta chart can be applied as a useful tool for selecting optimum aggregate gradation. Since these parameters are directly linked with the aggregate grain size distribution, any modification of the aggregate gradations according to this chart can be readily reachable.

CHAPTER 6

IDENTIFICATION OF CONCRETE MIX DESIGN STEPS

General

This chapter consists of the graphical presentation of concrete properties resulted from mixes prepared using "5-10-14-18" and "5-10-18-22" band gradations of aggregates and two different types of cements. This chapter also features the effects of w/c ratio, water content, cement content and aggregate content on concrete compressive strength and workability. Effect of time delay between concrete preparation and casting has also been focused here. At the end of this chapter, a new method for concrete mix proportioning has been proposed which is based on the locally available aggregates in Dhaka, Bangladesh. Also, the proposed mix design method has been compared with conventional methods (i.e. ACI, DOE method) with respect to their key features.

6.1 Experiments

CEM-II/B-M (42.5 N) and CEM-I (OPC or PC Type-I) cements have been used for this research purpose. In this stage of the research the aggregates have been graded to follow the requirements of "5-10-14-18" and "5-10-18-22" band gradations. The total concrete mixes can be considered in four different categories based on the materials used for concrete production. These categories are described in table 6.1.

Table 6.1: Different Categories of the Concrete Trial Mixes

Categories of concrete mixes	Cement used	Aggregate gradation band
Category – A	CEM - II/B-M	5-10-18-22
Category – B		5-10-14-18
Category – C	CEM – I	5-10-18-22
Category – D		5-10-14-18

6.1.1 Concrete Workability

Total sixteen trial concrete mixes have been prepared within the category – A. As in initial

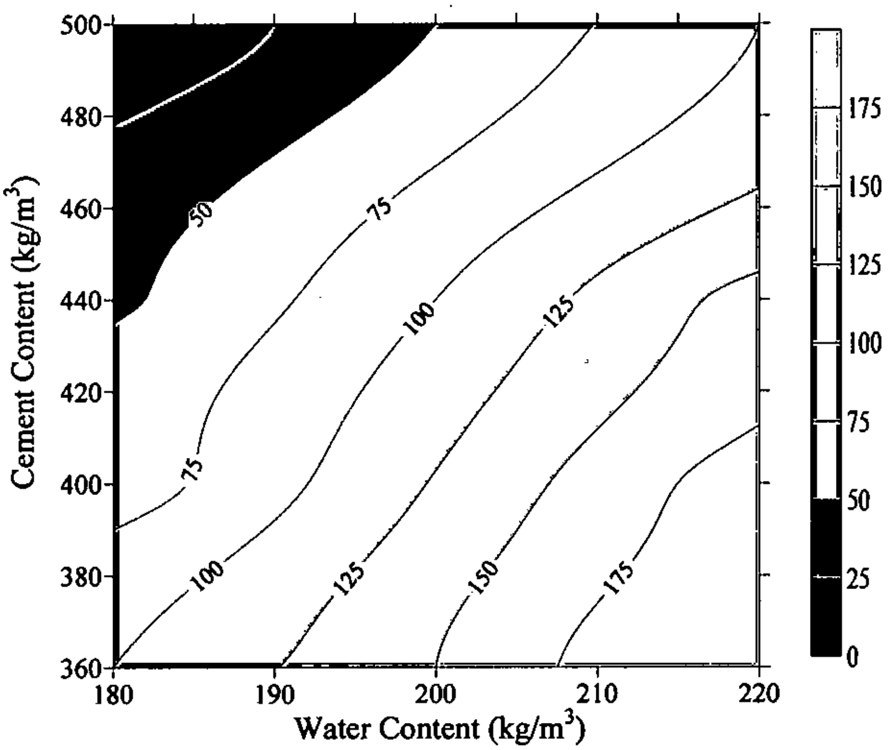


Figure 6.3: Variation of Slump for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-14-18 Band Gradation (Category – B).

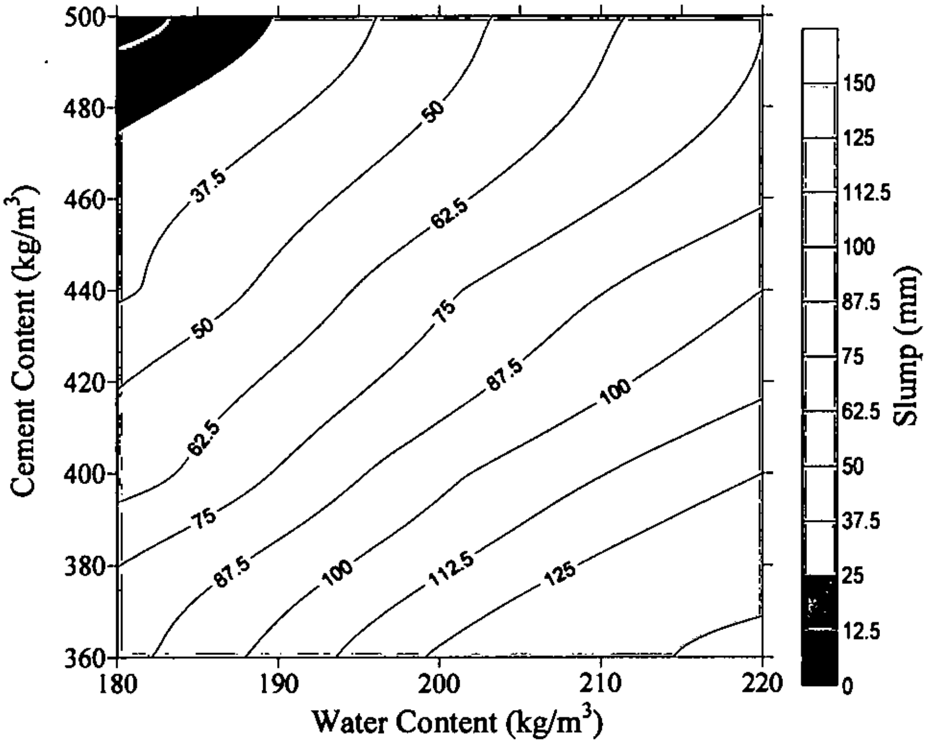


Figure 6.4: Variation of Slump for Concrete Mixes Prepared with CEM I Cement and 5-10-18 – 22 Band Gradations (Category – C).

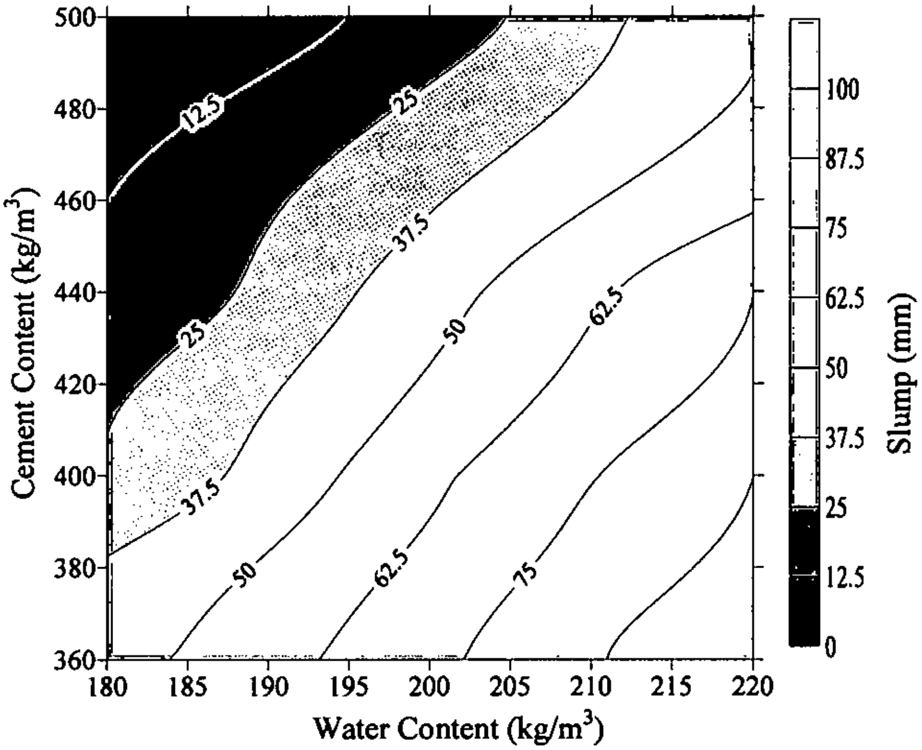


Figure 6.5: Variation of Slump for Concrete Mixes Prepared with CEM I Cements and 5-10-14-18 Band Gradation (Category – D).

6.1.2 Concrete Compressive Strength

Variations of concrete compressive strength (MPa) with mix proportions for different categories of concrete mixes have been shown in figure 6.6 to 6.17

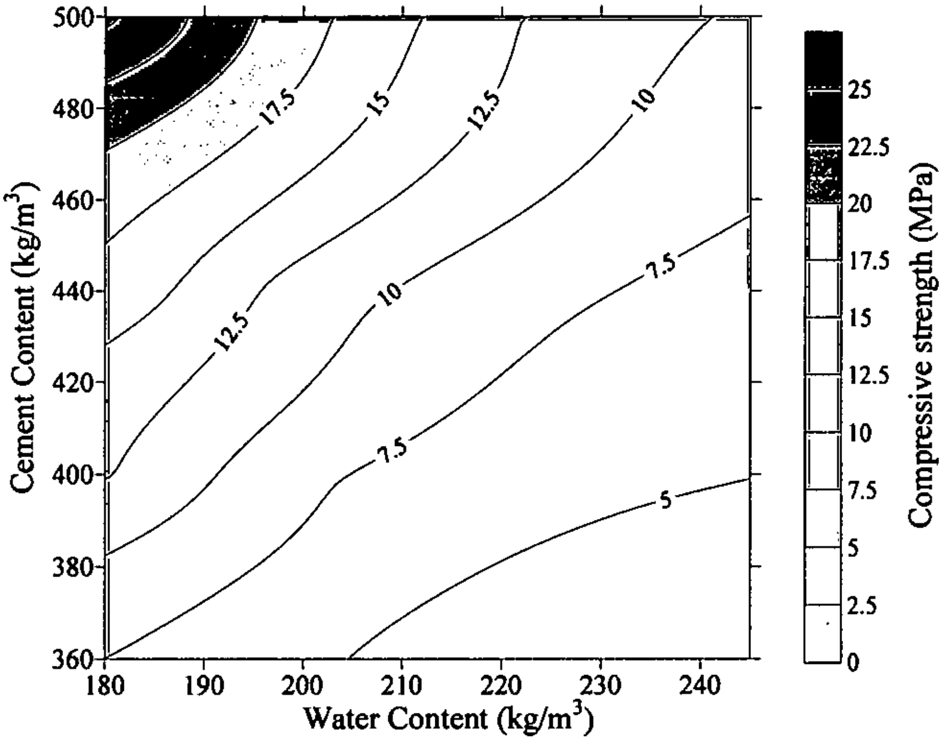


Figure 6.6: Variation of 3 Days Compressive Strength (MPa) For Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-18-22 Band Gradation (Category – A)

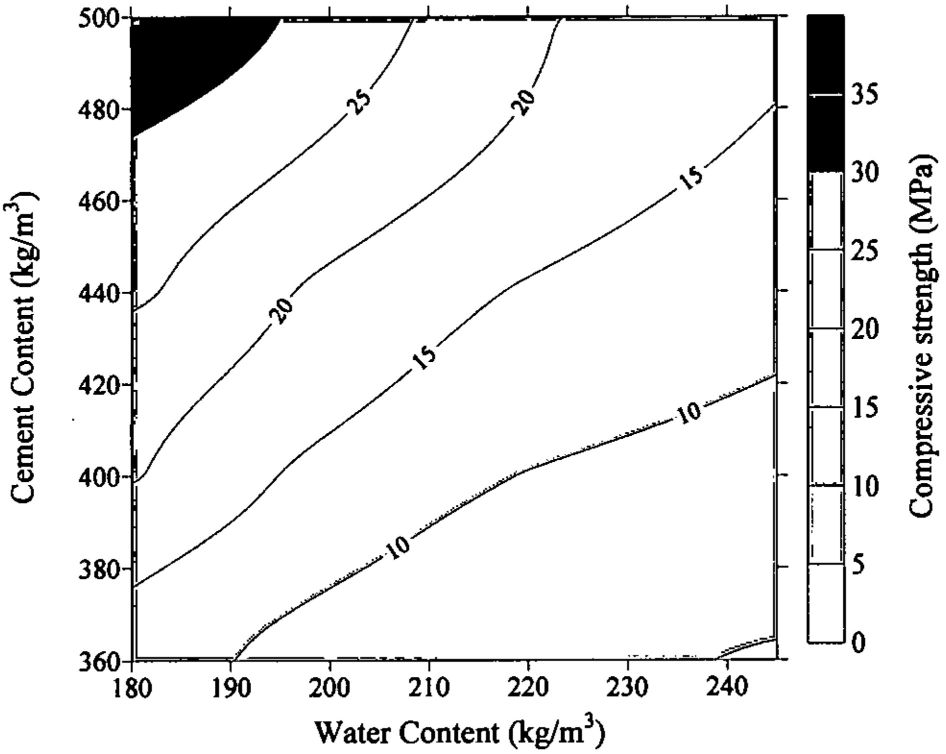


Figure 6.7: Variation of 7 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-18-22 Band Gradation (Category – A)

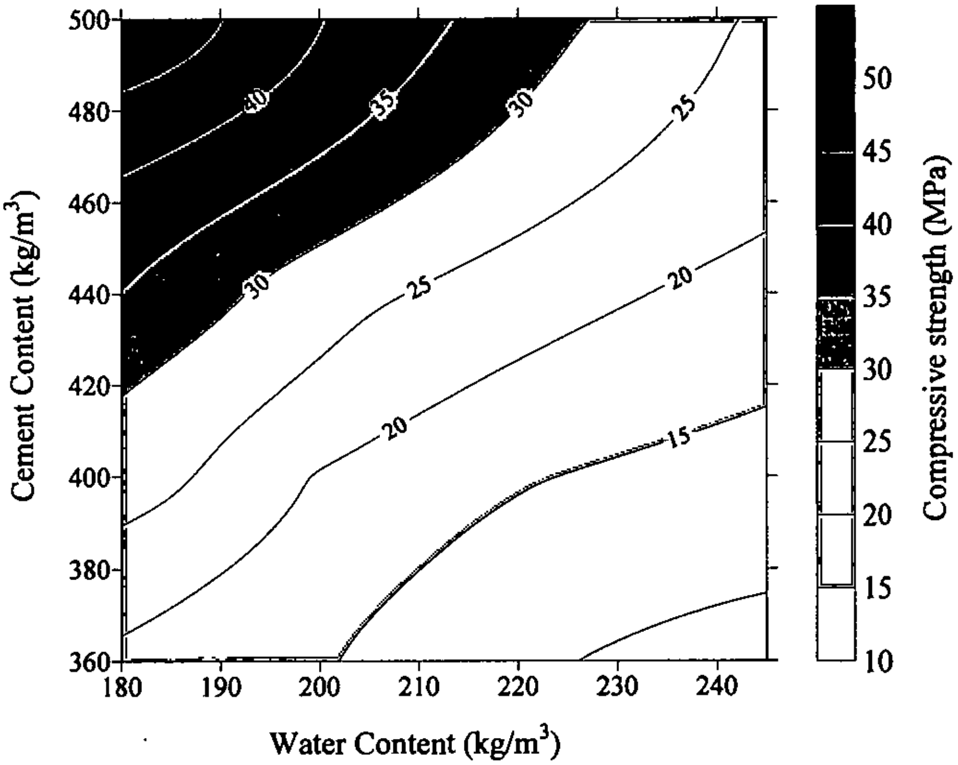


Figure 6.8: Variation of 28 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-18-22 Band Gradation (Category – A)

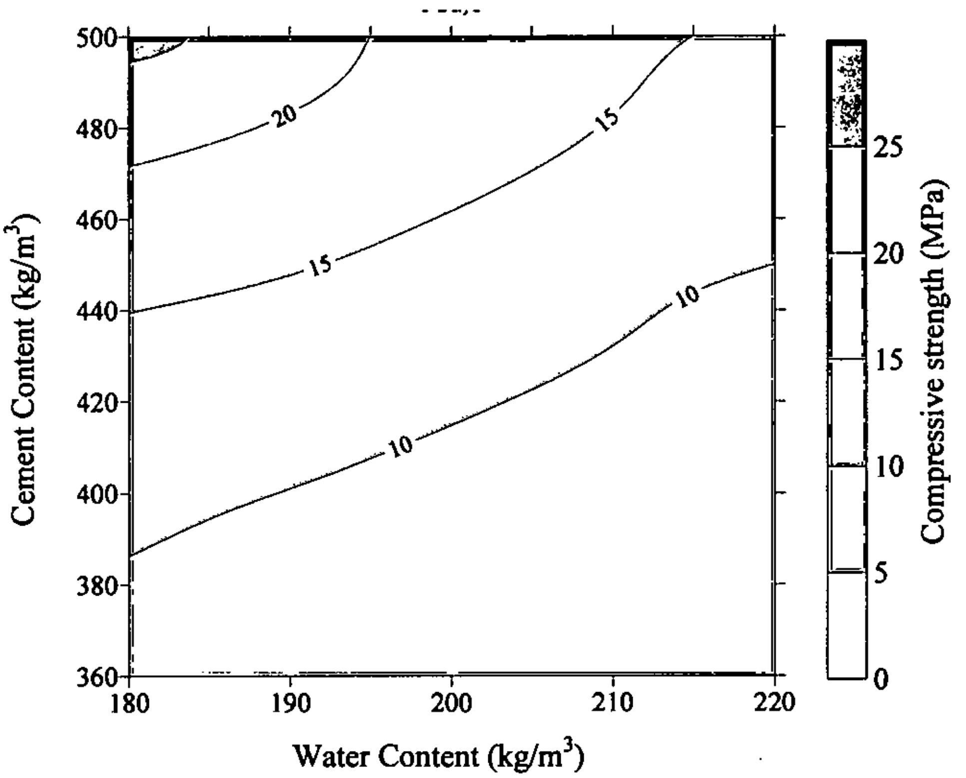


Figure 6.9: Variation of 3 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-14-18 Band Gradation (Category – B)

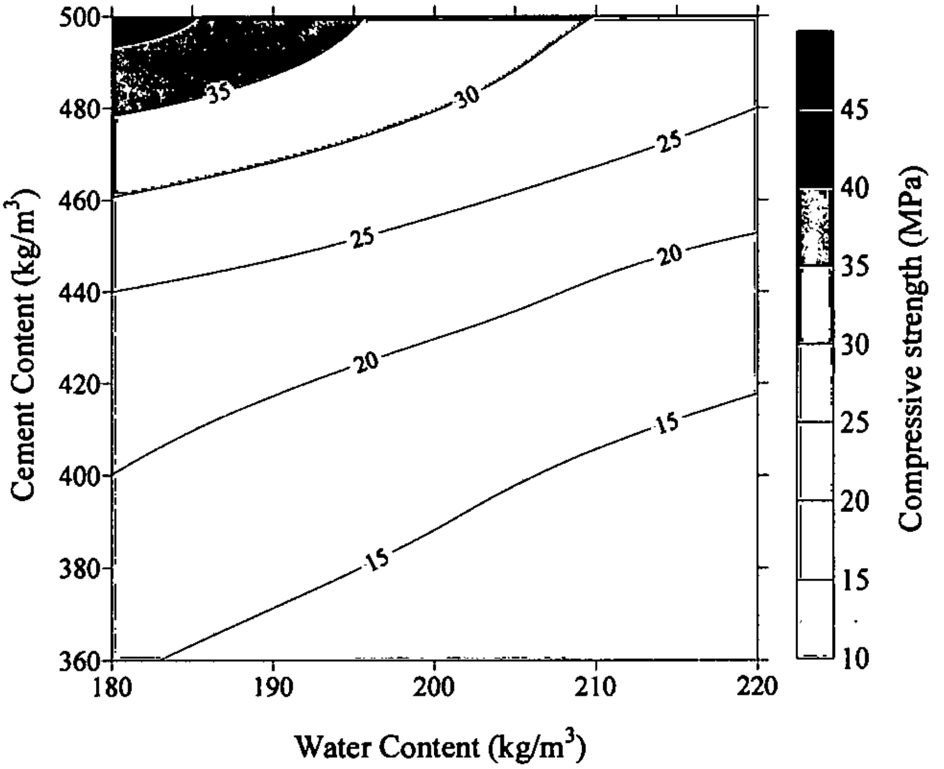


Figure 6.10: Variation of 7 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-14-18 Band Gradation (Category – B)

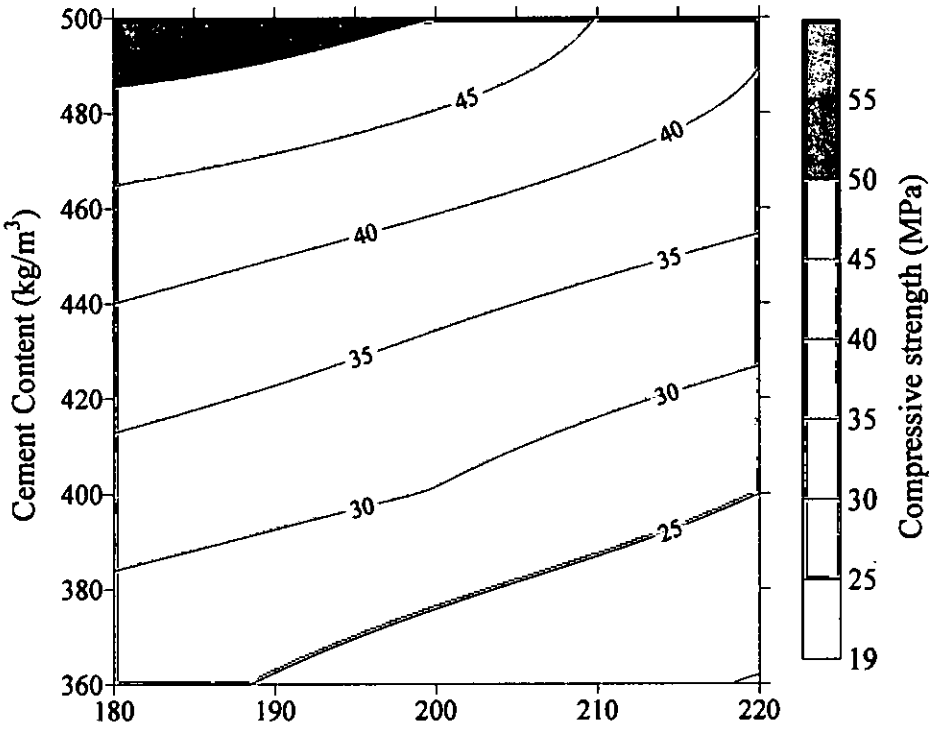


Figure 6.11: Variation of 28 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-14-18 Band Gradation (Category-B)

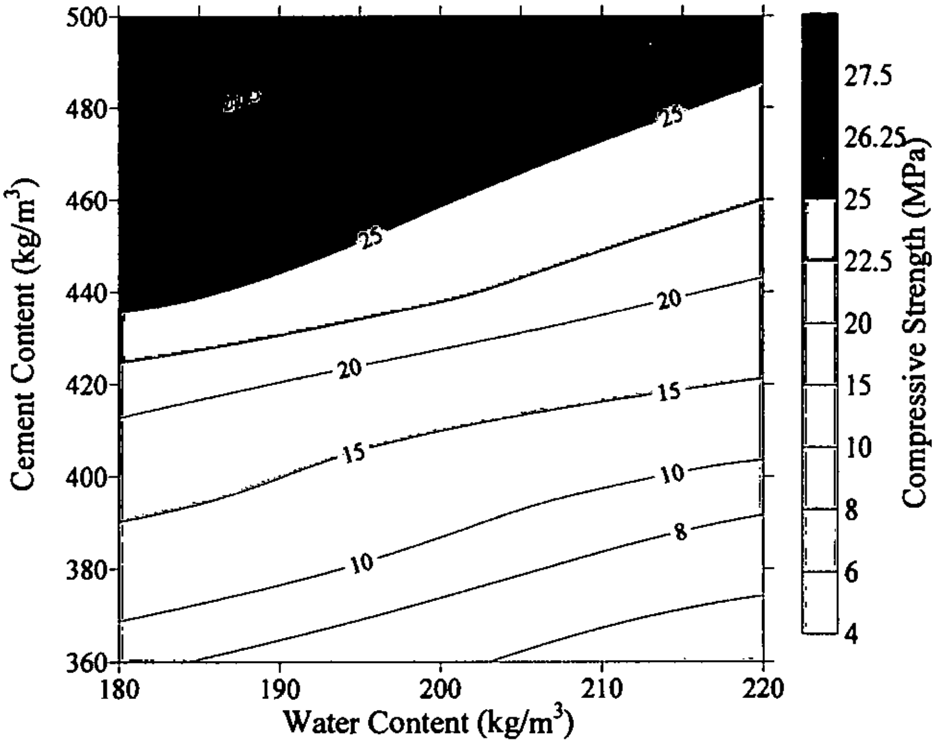


Figure 6.12: Variation of 3-Days Compressive Strength for Concrete Mixes Prepared with CEM I Cements and 5-10-18-22 Band Gradation (Category – C)

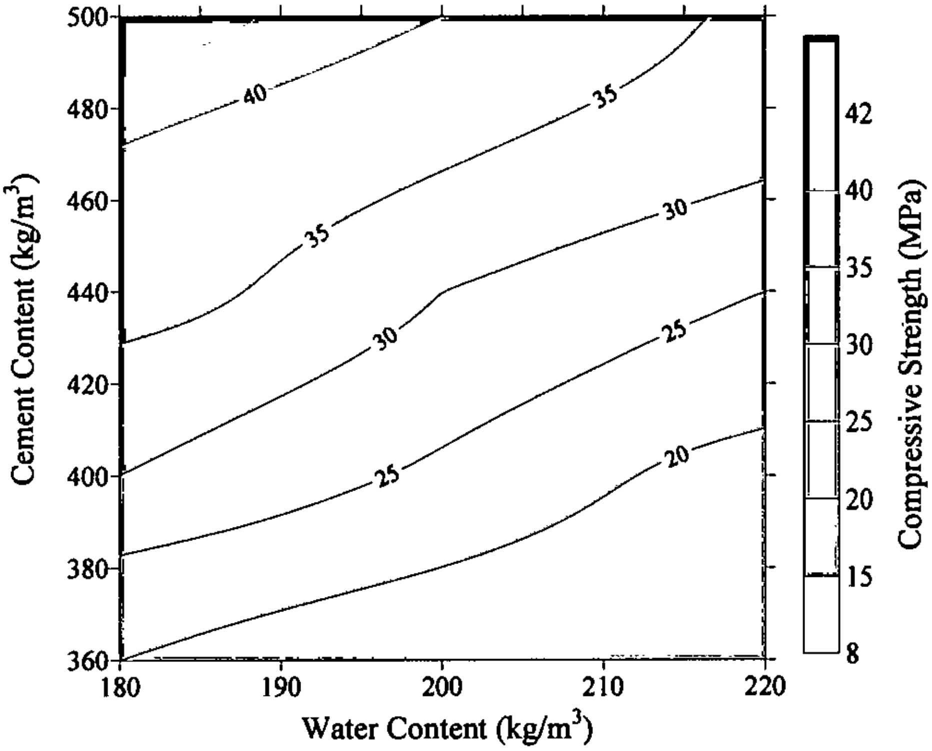


Figure 6.13: Variation of 7-Days Compressive Strength for Concrete Mixes Prepared with CEM I Cements and 5-10-18-22 Band Gradation (Category – C)

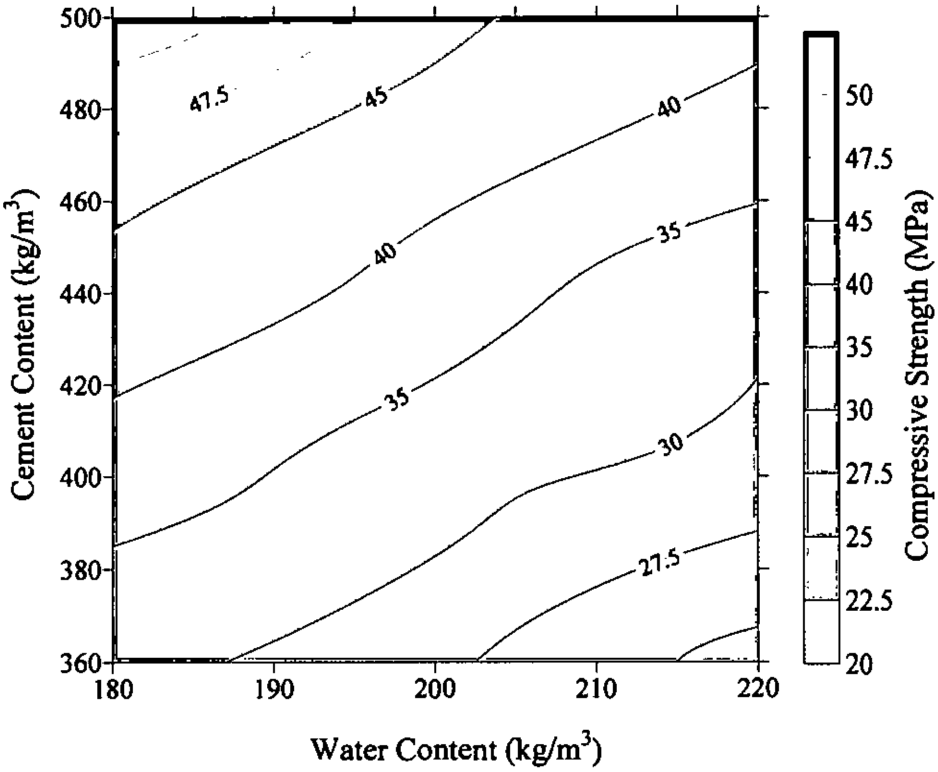


Figure 6.14: Variation of 28-Days Compressive Strength for Concrete Mixes Prepared with CEM I Cements and 5-10-18-22 Band Gradation (Category – C)

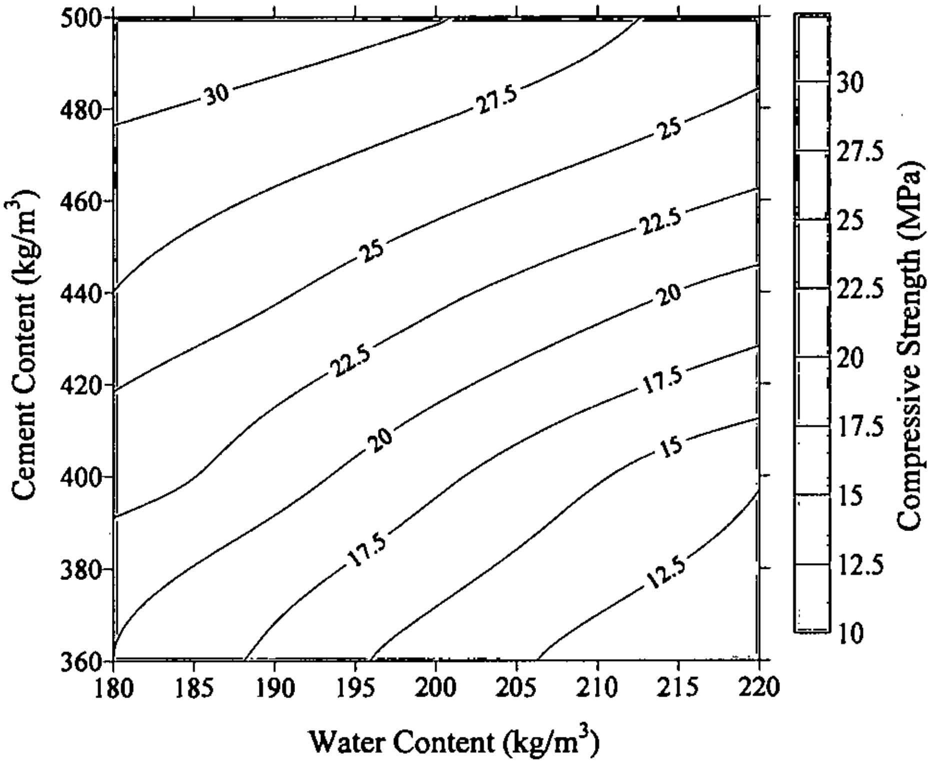


Figure 6.15: Variation of 3 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM I Cements and 5-10-14-18 Band Gradation (Category – D)

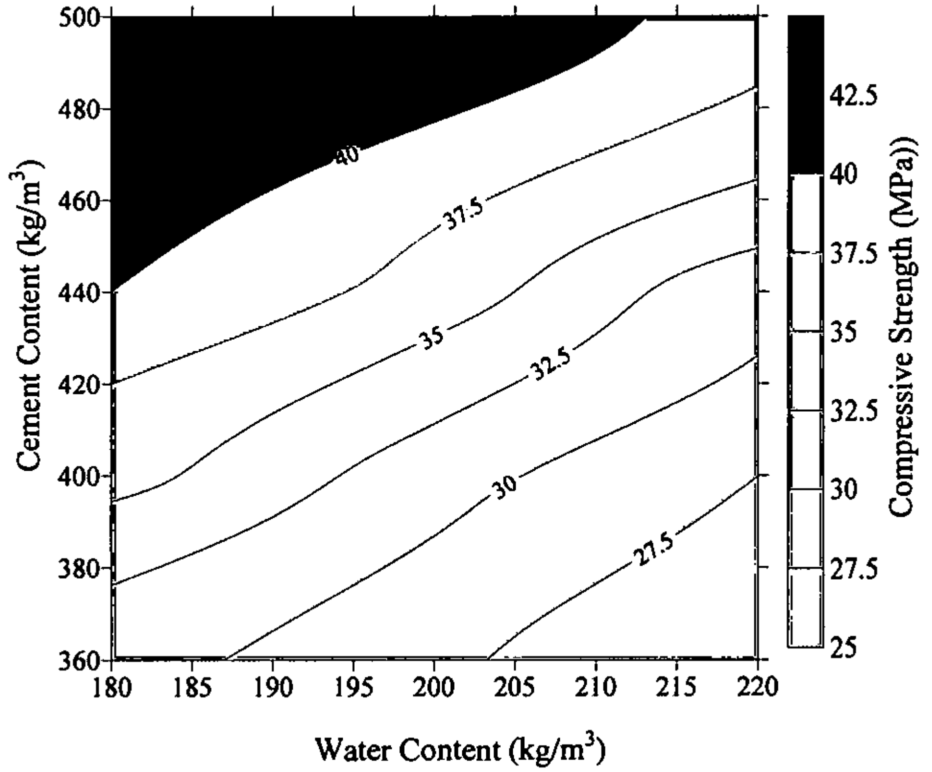


Figure 6.16: Variation of 7 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM I Cements and 5-10-14-18 Band Gradation (Category – D)

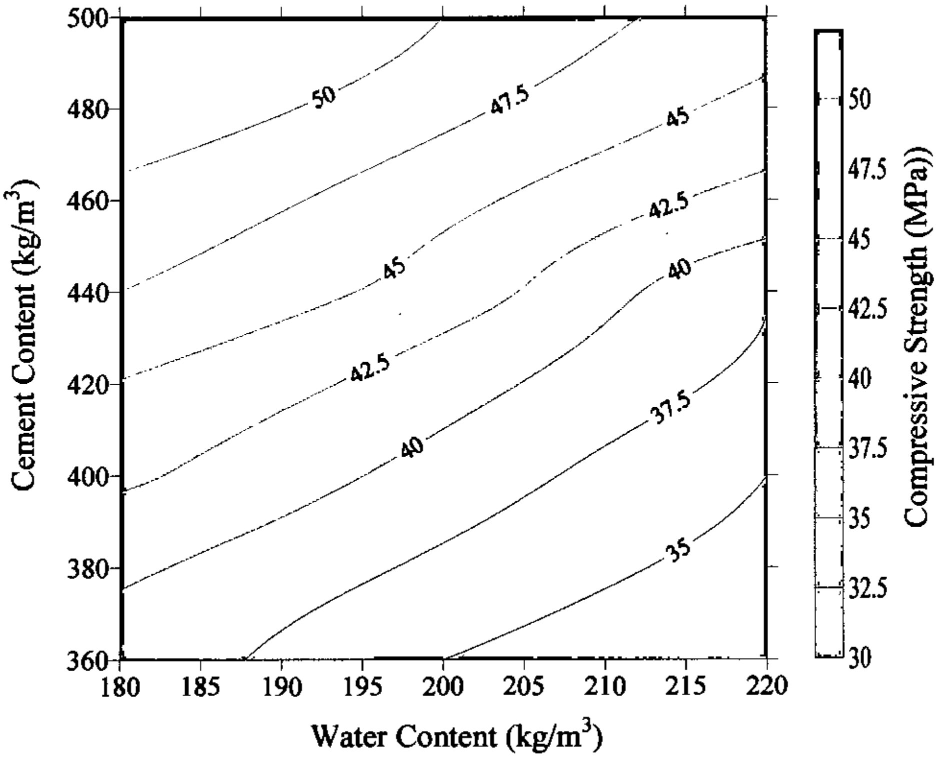


Figure 6.17: Variation of 28 Days Compressive Strength (MPa) for Concrete Mixes Prepared with CEM I Cements and 5-10-14-18 Band Gradation (Category - D)

6.1.3 Variation of Concrete Compressive Strength with w/c Ratios and time (days).

Test results have also been plotted to observe the effects of w/c ratio on concrete compressive strength, rate of gain of strength for different types of cements at various cement contents and variation of slump with water content for different types of mixes. Details of these figures have shown in Appendix-B, C and D, respectively. Figure 6.18 and 6.19 represent the variation compressive with w/c ratios and variations of slump with water contents, respectively, for concrete mixes prepared with CEM II/B-M and 5-10-18-22 band gradation shown in figure.

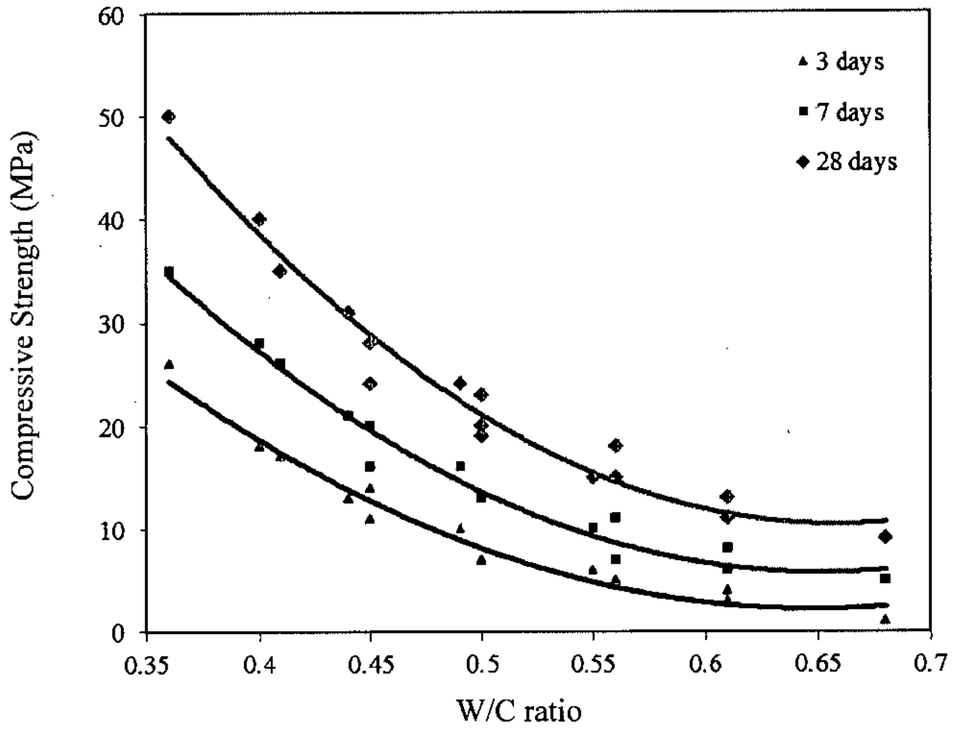


Figure 6.18: Variation of Strength with w/c Ratio for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-18-22 Band Gradation.

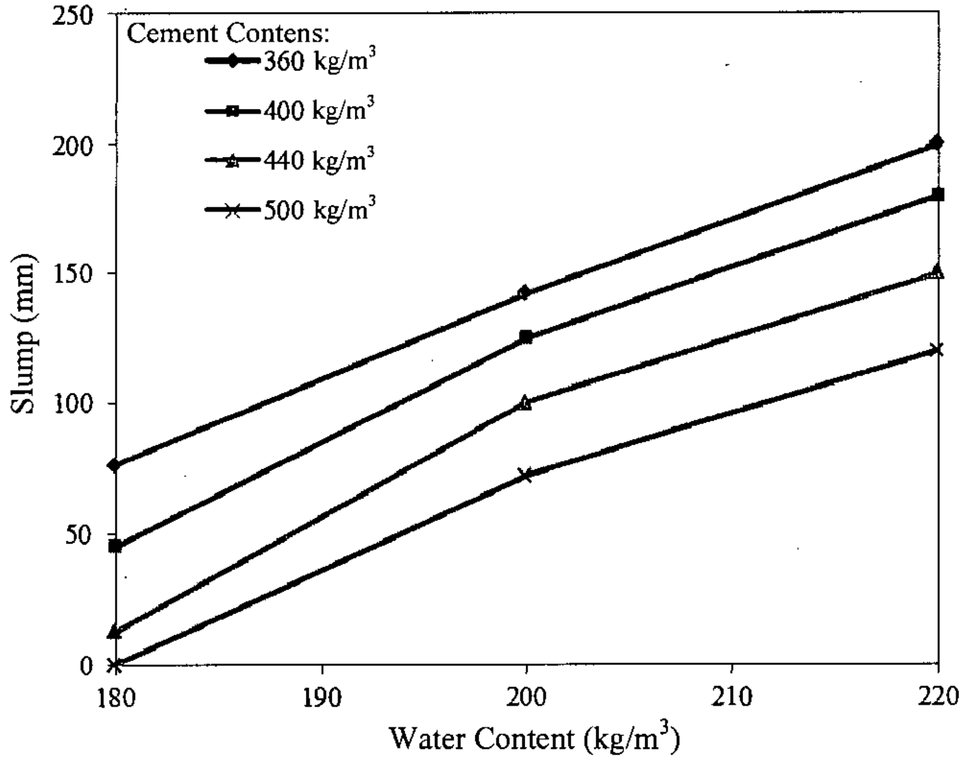


Figure 6.19: Variation of Slump with Water Content for Concrete Mixes Prepared with CEM II/B-M Cements and 5-10-14-18 Band Gradation.

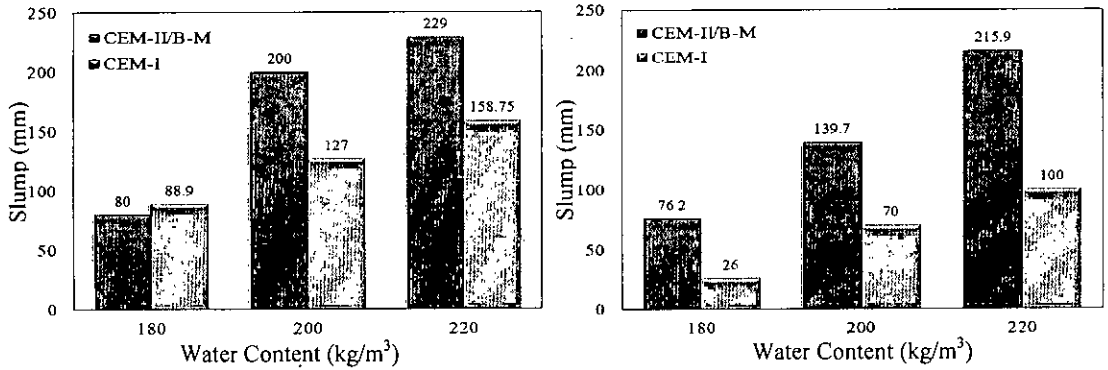
6.2 Effects of Cement Type on Slump

Within the scope of the research, large set of concrete mixes have been prepared with various cement contents, water contents and two specific cement types. Utilizing the test results of these mixes efforts has been made to quantify the change in concrete slump value for different types of cements at variable cement contents. Figure 6.20 graphically represents the concrete slumps (mm) for mixes prepared with CEM I and CEM II/B-M cements at different water and cement contents. Table 6.2 represents the percentage of difference of concrete slump for concrete mixes prepared with these two cements.

Table 6.2: Variation of Slump Values for Different Cement Types

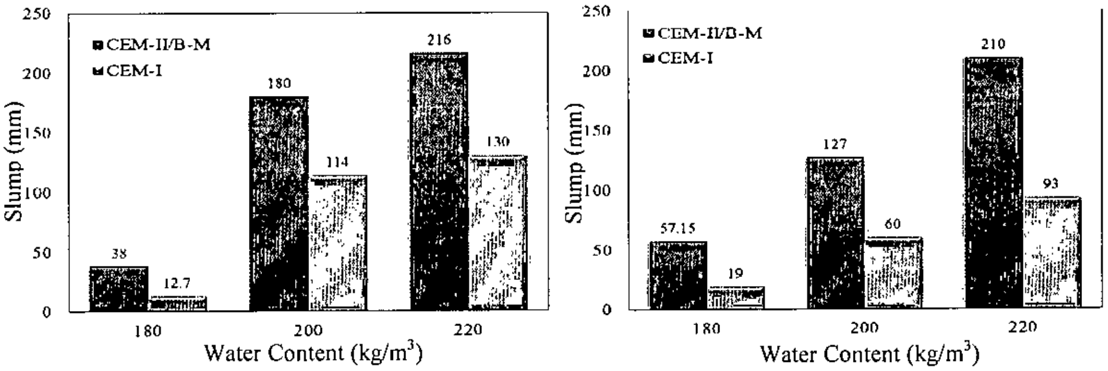
Cement Content kg/m^3	**Water Content kg/m^3**	**"5 – 10 – 18 – 22" gradation**				**"5 – 10 – 14 – 18" gradation**			
		PCC	**OPC**	**% of Difference**	**Avg[1].**	**PCC**	**OPC**	**% of Difference**	**Avg[1].**
360	180	80	89	-11	19	76	26	66	56
	200	200	127	37		140	70	50	
	220	229	159	31		216	100	54	
400	180	38	13	67	48	57	19	67	58
	200	180	114	37		127	60	53	
	220	216	130	40		210	93	56	
440	180	20	13	37	50	13	0	100	67
	200	165	40	76		100	50	50	
	220	203	127	37		180	89	51	
500	180	0	6	-	73	0	0	0	41
	200	102	13	88		61	12	80	
	220	184	76	59		89	51	43	

[1] Avg. - represents the average value of slump difference with respect to PCC cements.



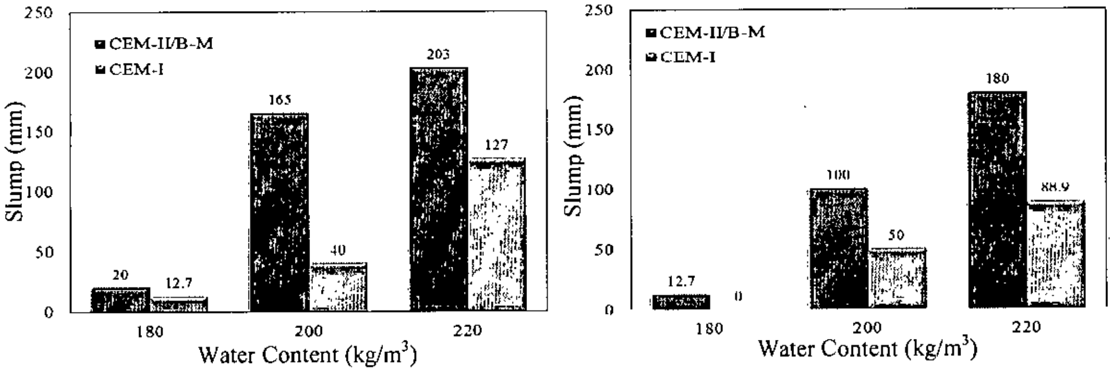
(i) 5-10-18-22 Band Gradation (ii) 5-10-14-18 Band Gradation

(a) Cement Content = 360 kg/m^3



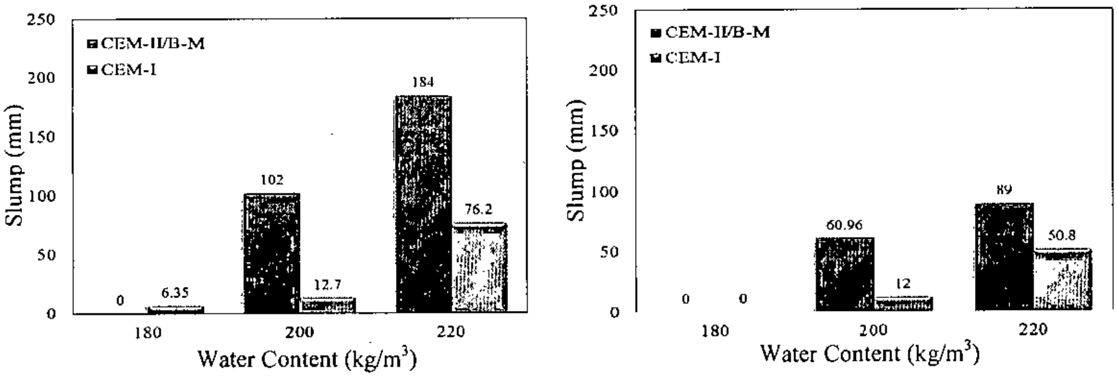
(i) 5-10-18-22 Band Gradation (ii) 5-10-14-18 Band Gradation

(b) Cement Content = 400 kg/m^3



(i) 5-10-18-22 Band Gradation (ii) 5-10-14-18 Band Gradation

(c) Cement Content = 440 kg/m^3



(i) 5-10-18-22 Band Gradation (ii) 5-10-14-18 Band Gradation

(e) Cement Content = 500 kg/m^3

Figure 6.20: Comparison of Slumps (mm) For PCC and OPC Cement Types

From figure 6.20 it can be observed that, keeping the water content, cement content and aggregate gradation type same, PCC provides different slump value than that of OPC cements. Most of the cases CEM-II/B-M cement results in higher slump than CEM-I cement. From the trial mix results it has been observed that, this difference between slump values for different cement types, depends on number of factors.

(i) Water content – the percentage of difference decreases with the increase of water content.

(ii) Cement Content – since this variation of slump is caused because of the cement type variation, it is very likely that the difference will increase with increase of cement content.

(iii) Aggregate Gradation – from table it can be observed that the percentage of variations for "5-10-14-18" gradation is much higher than that of "5-10-18-22" band gradation. Thus, although unclear but it is apparent that aggregate gradation type may have effects on the difference between slump values initiated by cement type.

6.3 Information Required for Concrete Mix Design

1) Required compressive strength.

This gives the characteristic strength requirements of concrete. Depending upon the level of quality control available at the site, the concrete mix has to be designed for a target mean strength which is higher than the characteristic strength.

2) Workability required.

The choice of a suitable workability of the concrete at the time of placement depends on the difficulty of the structure to be executed: minimum section of the structure and its shape, amount of reinforcements, quality of the man-power, and organization on the job site in terms of available effective compaction systems. Table 6.3 represents the concrete workability usually required for different types of concrete works based on previous researches as well as practical experiences.

Table 6.3: Recommended workability of concrete at the time of concrete placement.

Type of concrete work	Degree of workability	Slump (mm)
Blinding concrete; Shallow sections; Pavements using pavers	Very low	< 25
Mass concrete; Lightly reinforced sections in slabs, beams, walls, columns; Floors; Hand placed pavements; Strip footings	Low	25-75
Heavily reinforced sections in slabs, beams, walls, columns; Canal lining;	Medium	75-100
Trench fill; In-situ piling	High	100 – 150
Decks Floors	Very high	> 150

3) Exposure condition of concrete member

Exposure condition of concrete is important for ensuring the durability of concrete structure. The possible exposure conditions in the context of Bangladesh have been shown in table 6.4.

4) Aggregate gradation band

As it is discussed in earlier chapters, two types of aggregate gradation bands have been proposed through this research work (i.e. 5-10-14-18 and 5-10-18-22 bands). For practical application 5-10-14-18 band gradation are more desirable because –

(i) The range of fine aggregate to total aggregate ratio maintained in 5-10-14-18 band is 0.4 to 0.5. This range can be considered as an optimum range based on previous researches as well as practical experiences.

(ii) From the data set obtained in this research work, it has been observed that the rate of variation in test results for 5-10-18-22 is higher than that of 5-10-14-18.

Thus considering these issues, 5-10-14-18 band is more recommended than 5-10-18-22 unless otherwise any practical constraint dominates the purpose.

5) Type of cement

As in preliminary stage, this mix design method has been proposed only for CEM I and

CEM II/B-M cements, thus the user need to know the type of cement before starting the mix design procedure.

6) Maximum possible water/cement ratio.

The Bangladesh National Building Code (BNBC) has limited the maximum w/c ratio for reinforced concrete at different exposure conditions (Table 6.4) for particularly concrete works at Bangladesh. In these concrete mix design same limiting maximum w/c ratio will be followed.

Table 6.4: Limiting w/c Ratio Based on Exposure Conditions

Exposure Type	Maximum w/c Ratio*
Exposed to normal water	0.5
Exposed to brackish water, sea water or spray form these	0.4
Moderate Sulphate exposure (150 – 1500 ppm)	0.5

*Source: Bangladesh National Building Code (1993), Article: 5.5: Durability of Concrete

7) Degree of supervision.

Degree of supervision represents the quality of the concrete construction, thus it is significant to estimate the probable deviation of actual strength from the design strength.

8) Time delay between concrete mixing and concrete placing.

The time delays between concrete mixing and concrete placing cause loss concrete workability. Thus the time delay is required to know to modify the concrete proportion properly so as to get the required workability at the time of concrete placement.

6.4 Concrete Mix Design Steps

Step-1: Determination of target strength

The required target average compressive strength can be calculated using design compressive strength as per the following equation.

$$f_t = f'_c + sk$$

Where,

f'_c = characteristic compressive strength (MPa) at 28 days,

s = standard deviation of compressive strength described in table 6.5.

k = a statistical factor, depending upon the accepted proportion of low results and the number of tests, in general comes from Himsworth constant (1954) (table 6.6)

Table 6.5: Typical values of the standard deviation for different conditions of placing and mixing of concrete

Degree of quality control	**Degree of supervision**	**Description**	**Standard Deviation, s (MPa)**
Excellent / Laboratory precision	Continual supervision	Completely accurate aggregate gradation, exact water/cement ratio, controlled temperature environment.	≤ 3
Very good	Continual supervision	Weigh batching of all materials, combination of different aggregate sizes to achieve the recommended aggregate gradation, strict control of aggregate grading, control of water added to allow for moisture content of aggregates.	3 - 4
Good	Frequent supervision	Weigh-batching of all materials, control of aggregate grading, control of water added, periodic check of workability.	4 - 6
Fair	Occasional supervision	Volume batching of all aggregates allowing for bulking of sand, slight deviation of aggregate gradation allowed, water content controlled by inspection of mix.	6 - 8
Poor / uncontrolled	Little or no supervision	Volume batching of all materials.	8 - 10

Table 6.6: Values for the Factor "k"

Percentage of results allowed to fail below the minimum	Value of "k"
16	1.0
10	1.28
5	1.64
2.5	1.96
1.0	2.33
0.6	2.50
0.1	3.09

Step-2 Determination of required workability

Workability of concrete mixture during the time of mixing and during the time of placing may not be always same. After the mixing, the cement starts hydration process and thus concrete starts losing its workability. If there is any considerable time delay between concrete mixing and concrete placing procedure, then this time delay may result significant difference in concrete workability at these two stages.

Workability at the time of concrete mixing will be higher than that of the time of concrete placing and the difference between these two workabilites can be named as "workability loss".

Therefore,

$Workability_{loss} = Workability_{mixing} - Workability_{casting}$

Here,

$Workability_{loss}$ = Loss of workability due to time delay between concrete mixing and placing

$Workability_{mixing}$ = Required workability at the time concrete mixing

$Workability_{casting}$ = Required workability at the time concrete Placing

Workability loss depends on number of factors, these are –

- Time delay between concrete mixing and concrete placing – as the time delay increases the workability loss will also increase.

- Temperature – hydration process is faster in higher temperature, thus workability loss will also be higher for higher temperature.
- Type of chemical admixture – water reducers and superplasticzers reduce the w/c ratio at a given workability and thus increases workability loss. Again for accelerator the workability loss will be higher and for retarder this loss will be lower.

Table 6.7 shows the workability loss (mm) for variable time delays that have been found in this research.

Table 6.7: Workability (mm) Losses for Time Delay between Mixing and Placing of Concrete.

Time delay (minute)	**Workability loss [a](mm)**
10 to 20	up to 35 mm
25 to 40	25 to 50 mm
40 to 60	30 to 70 mm
60 to 80	up to 110 mm

[a] workability loss measured at the temperature range 20°C to 30°C.

Here important to note that, the workability of concrete mixture presented in table 6.8 is recommended for using at the time of concrete placing. The workability loss being taken into account, the required workability *(Workability $_{mixing}$)* for concrete mix design at the time of concrete mixing can be calculated as below-

$$Workability_{mixing} = Workability_{loss} + Workability_{casting}$$

Step-3: Selection of water/cement ratio

Contours shown in figure 6.21 represents both variation of 28 days compressive strength (MPa) and slump (mm) with water and cement content for concrete mixes prepared with CEM II/B-M cement and 5-10-18-22 band aggregate gradation. In this figure the solid thick line represents the slump ranges (mm) and gradually filled contours represent range of 28 days compressive strength in MPa. Similar types of figures for other cement type and aggregate gradating have been shown in figure 6.22 to figure 6.24. Now, if the target concrete compressive strength at 28 days and required workability are known, mix proportions such as water and cement content can be determined directly from these figures. Accordingly using this selected water and cement content, w/c ratio need to be calculated and checked with the minimum requirements as mentioned in table 6.4.

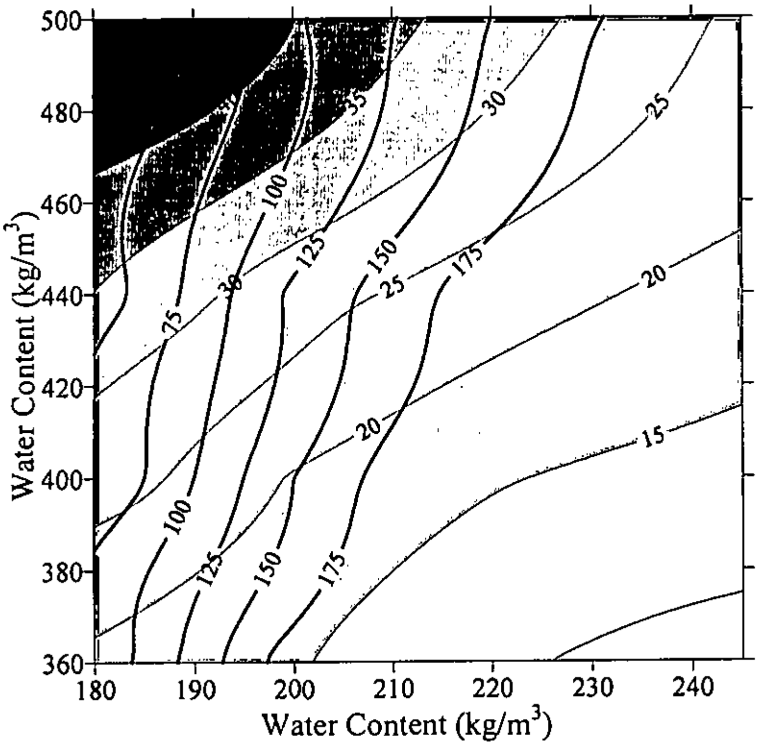


Figure 6.21: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for CEM II/B-M Cements and 5-10-18-22 Band Gradation (Category – A).

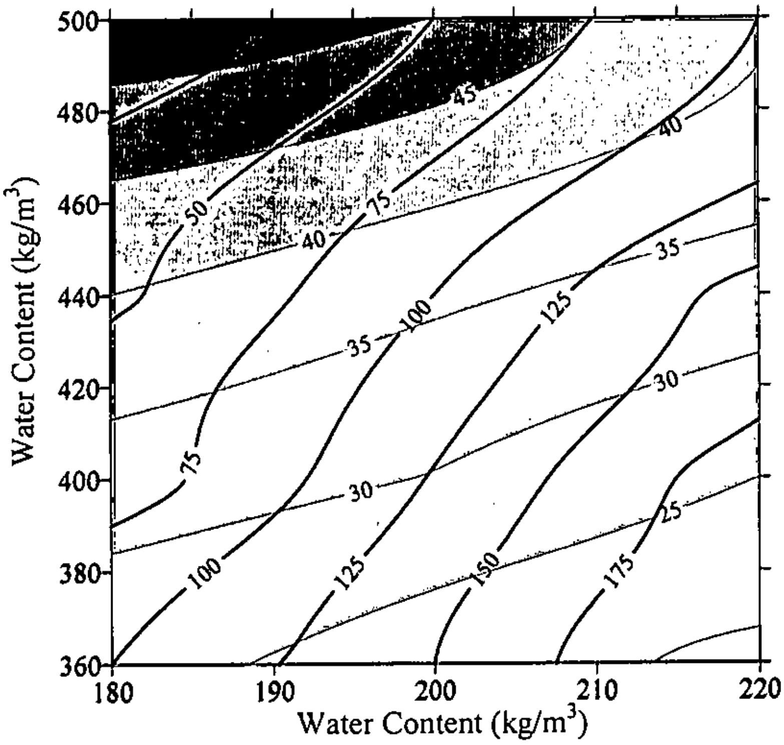


Figure 6.22: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for CEM II/B-M Cements and 5-10-14-18 Band Gradation (Category – B).

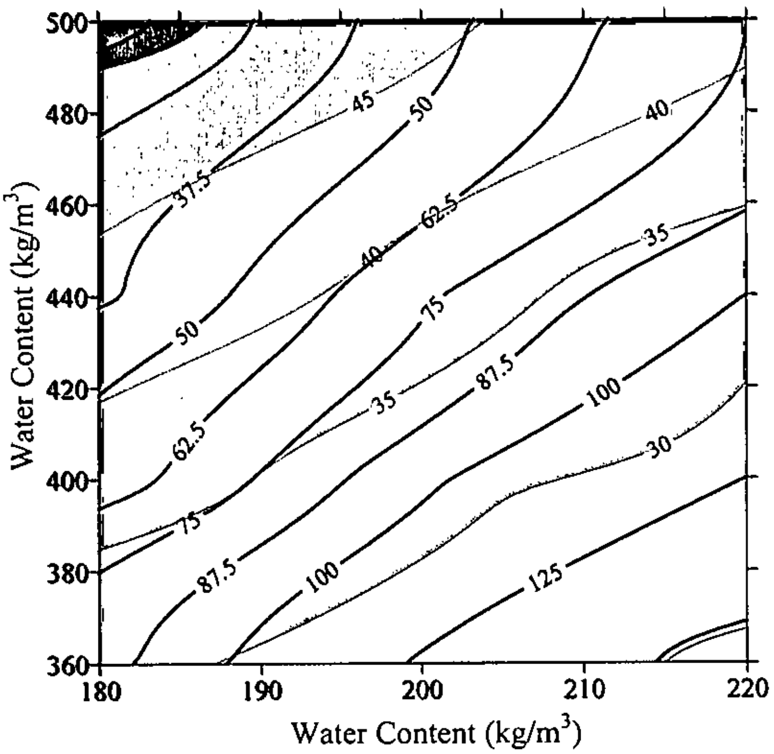


Figure 6.23: 28 Days Compressive Strength and Slump with Various Mix Proportions for with CEM I Cements and 5-10-18-22 Band Gradation (Category – C).

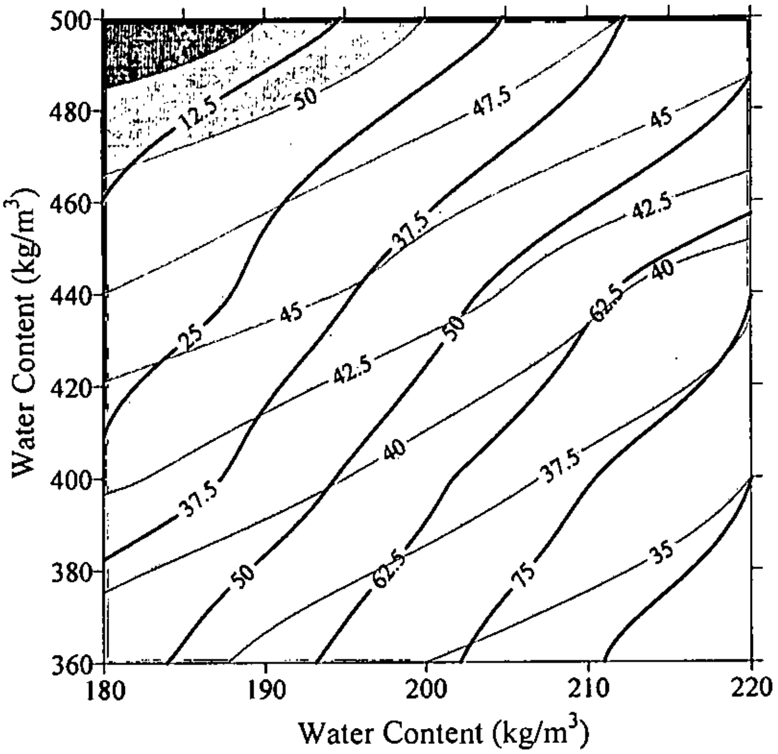


Figure 6.24: 28 Days Compressive Strength and Slump with Various Mix Proportions for with CEM I Cements and 5-10-14-18 Band Gradation (Category – D).

Step-4 Modification for compressive strength and workability

The contours presented in figure 6.21 to 6.24 are based on a particular FM and fa/ta ratio. For all the concrete mixes prepared with 5-10-14-18 band gradation, FM and fa/ta-ratio are 2.26 and 0.45, respectively. For, 5-10-18-22 band these values are 2.33 and 0.34. Thus for any FM and fa/ta other than these values, concrete properties need to be modified accordingly. Figure 6.25 and 6.24 show the variation in concrete properties due to the change in FM and fa/ta. This figure are plotted from the test results of phase 2 of the research where concrete mixes have been prepared with same mix proportions but different FM and fa/ta ratio within the band. Total eight (8) concrete mix results are employed to draw these figures. The dark lines show the possible boundary of the aggregate samples using locally available aggregates. Also these figures are expected to be independent of the cement type since only the percentages of variations have been shown here.

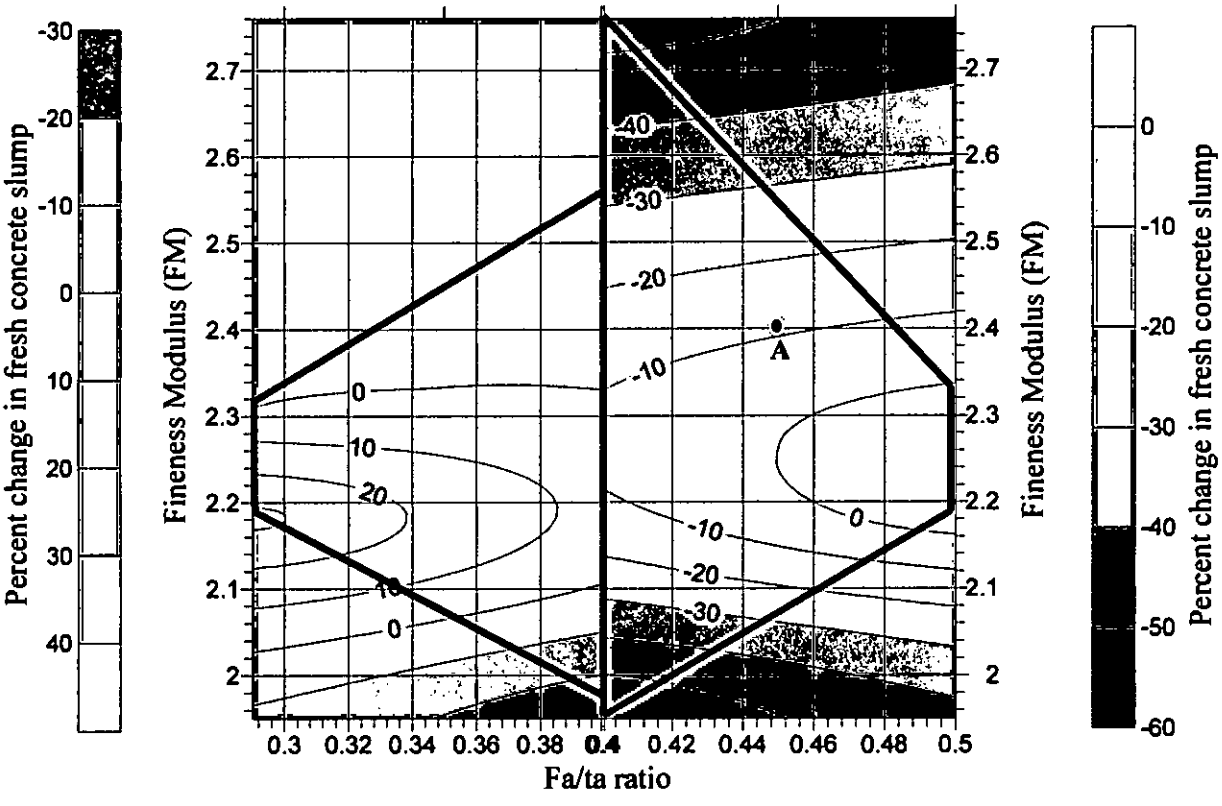


Figure 6.25: Variation in Concrete Workability for Different FM and Fa/Ta Values.

For example, let required compressive strength is 30 MPa and required slump is 75 mm. using the contours presented in figure 6.21 to 6.24, w/c ratio can be calculated based on cement type and aggregate gradation bands (say, w/c = 0.5). Now considering the locally available aggregate sizes assume that the user is able to achieve a particular aggregate gradation band only with FM = 2.4 and fa/ta ratio = 0.45. Whereas the contours for 5-10-

14-18 band are based on FM = 2.26 and fa/ta ratio = 0.45. Thus, due to this change in aggregate properties concrete properties need to modify accordingly. The available FM and fa/ta represented as the point A on the figures. From figure-1, it can be summarize that, using the available aggregate and mix proportion from the contour the concrete workability will be 11% less than the expected. Thus the modified slump ($S_{modified}$) will be = 75*(1-0.11) =66.75mm. Similarly from figure 2, due to the change in aggregate properties concrete compressive strength will be reduced by 13 percent. Thus, the modified concrete strength ($f'_{c\ modified}$) = 30* (1-0.13) = 26.1 MPa.

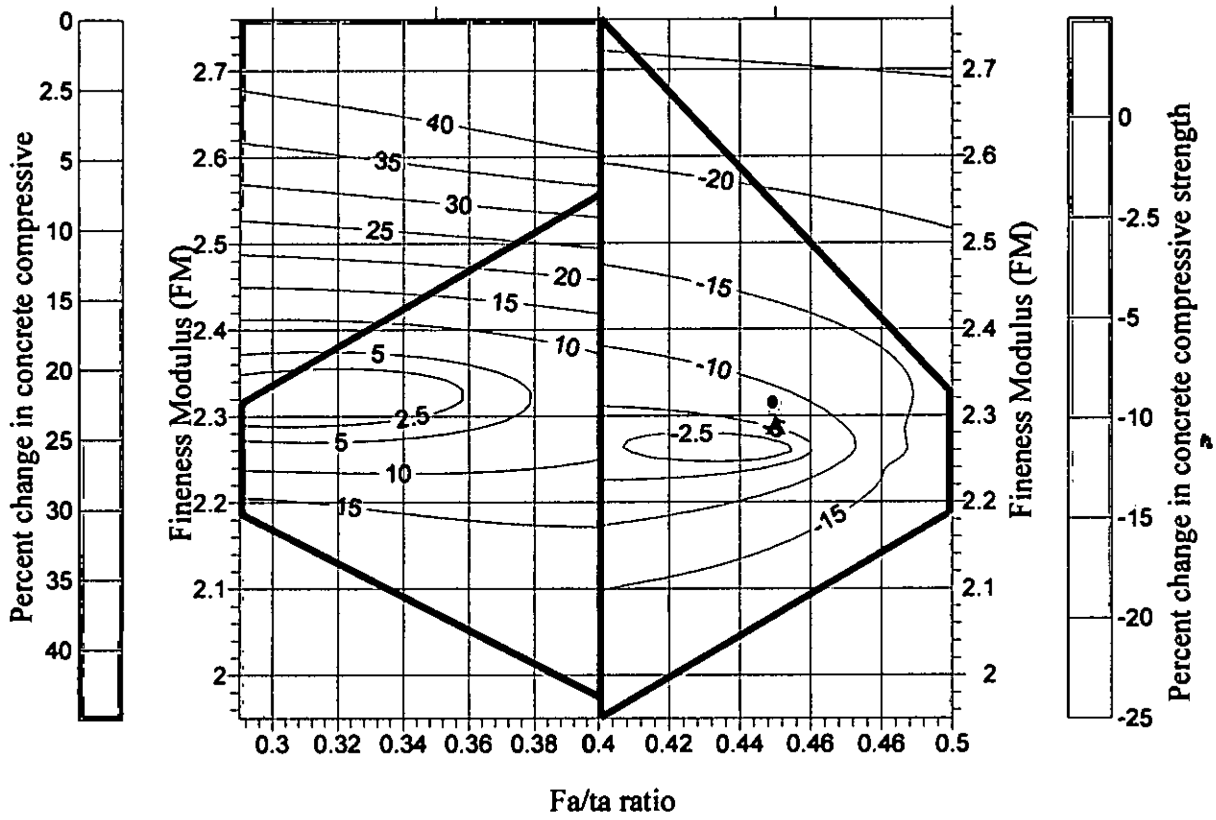


Figure 6.26: Variation in Concrete Compressive Strength for Different FM and Fa/Ta Values.

Step – 5: Modified W/C Ratio

Figure 6.27 shows the variation concrete compressive strength with w/c ratio. These set of curves are prepared from all type mix results of this research. It describes the effects of w/c ratio on concrete compressive strength irrespective of all other influencing factors (i.e. cement type, aggregate type, curing time etc.). Thus these generalised curves can be used to modify w/c ratio as per requirement.

Let, the w/c ratio from step – 3 and modified compressive strength from step - 4 represents the point A on the figure. Through this point (A) draw a line (BAC) parallel to the nearest given curves. Now, these resulted BAC line will be the characteristic compressive strength vs. w/c ratio curve for the required concrete. Using this curve, required w/c ratio can be found for any target strength.

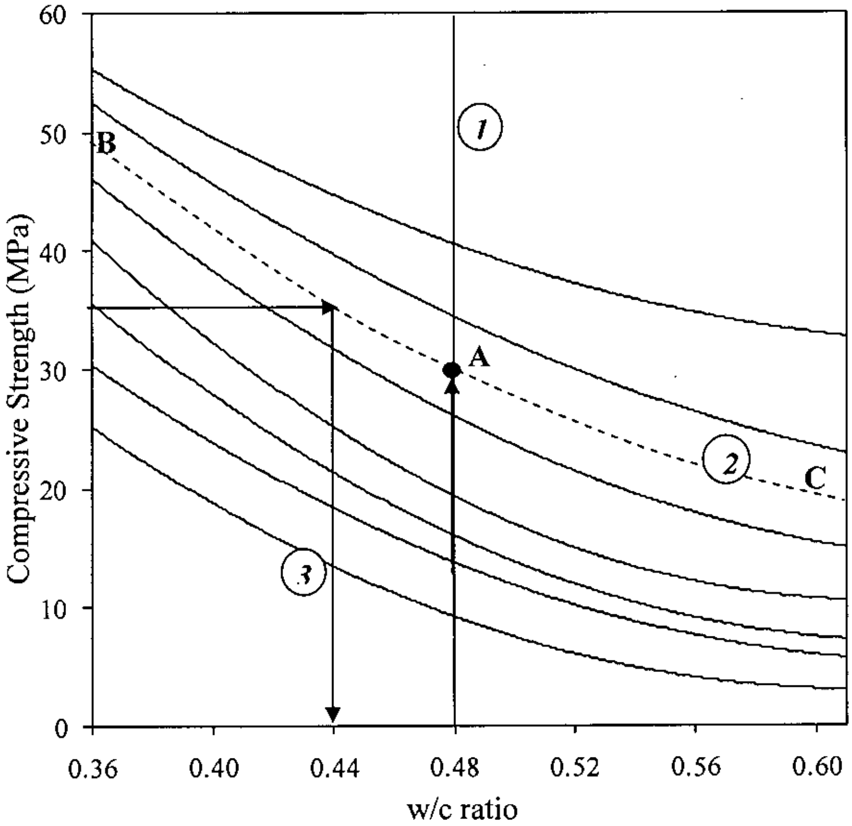


Figure 6.27: Concrete Compressive Strength vs. w/c Ratio Different Types of Concrete Mixes.

For example, let the target compressive strength from step – 1 is 35 MPa and from step – 3 the required w/c ratio found to be 0.48. But, because of the aggregate properties the modified compressive strength at the end of step – 4 is found to be 32MPa. Now, (1) first, this will result in point A on the graph. (2) Using the point A draw a line (BAC) parallel to nearest given curve. (3) Using this line (BCA) the modified w/c ratio for 35MPa is 0.44

Step – 6: Modified Water Content

Figure 6.28 shows the generalised curves for the variations of slump with water content. The water content from step - 3 and modified slump from step – 6 can be used to determine the modified water content from this figure similar to the step – 5.

If the modified slump and water content from step-3 represents the point A on the figure, then similar to the step -5, draw a line through A parallel to the nearest given curves. Then, these BAC line will be slump vs water content characteristics line for the required concrete. Using this line, water content for any required slump can be found.

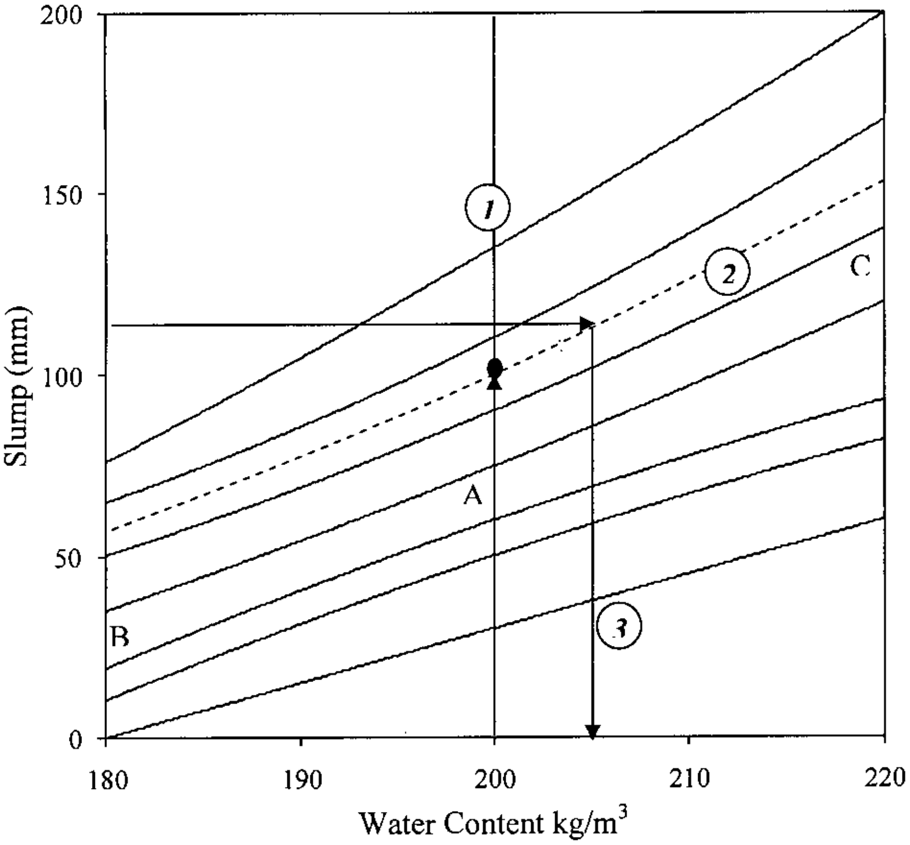


Figure 6.28: Concrete Compressive Strength vs. w/c Ratio Different Types of Concrete Mixes.

For example, let using 200 kg/m^3 water content the modified slump ($S_{modified}$) at the end of step-4 is found to be 100 mm. where as the required slump is 125 mm. now, (1) using these modified slump (100 mm) and water content (200 kg/m^3) plot the point A on the figure. (2) Through the point A draw a line (BAC) parallel to the nearest given curves. (3) Using the line BCA, find the water content (205 kg/m^3) required for 125mm slump.

<u>Step – 7:</u> Calculation of cement content

After knowing both of w/c ratio and water content, required cement content can be calculated using following equation-

$$\text{Cement Content } (kg/m^3) = \text{Water content } (kg/m^3) / \text{w/c ratio}$$

<u>Step – 8:</u> Calculation of total aggregate content

Knowing the cement content and water content, aggregate content can be determined by absolute volume method. That is, for unit volume of concrete, determine the portion fulfilled by cement and water, and then the rest of the volume must occupied by the aggregates.

For unit volume of concrete, ($1m^3$),

- *Cement volume,* m^3 *= Cement Content (kg) / (sp. Gravity of cement x unit weight of water (kg/*m^3*)*
- *Water volume,* m^3 *= Water Content (kg) / unit weight of water (kg/*m^3*)*
- *Aggregate Volume,* m^3*= 1 - Cement volume,* m^3 *- Water volume, m*

6.5 Proposed Concrete Mix Design Examples

Example - 1: Design the concrete mix for target compressive strength at 28 days is 25 MPa (3500 psi) and 120 mm (4.5 inch) slump at the time of concrete mixing. Available Cement type CEM II/B-M. Based on the locally available aggregate, FM and fa/ta ratio required to achieve 5-10-14-18 band are 2.47 and 0.41, respectively.

Solution: since already the target 28 days compressive strength and required slump at the time of concrete mixing have been given, no need to consider standard deviation and workability loss. Concrete mix design steps given from step – 3 of previous article.

1) **Selection of water/cement ratio**

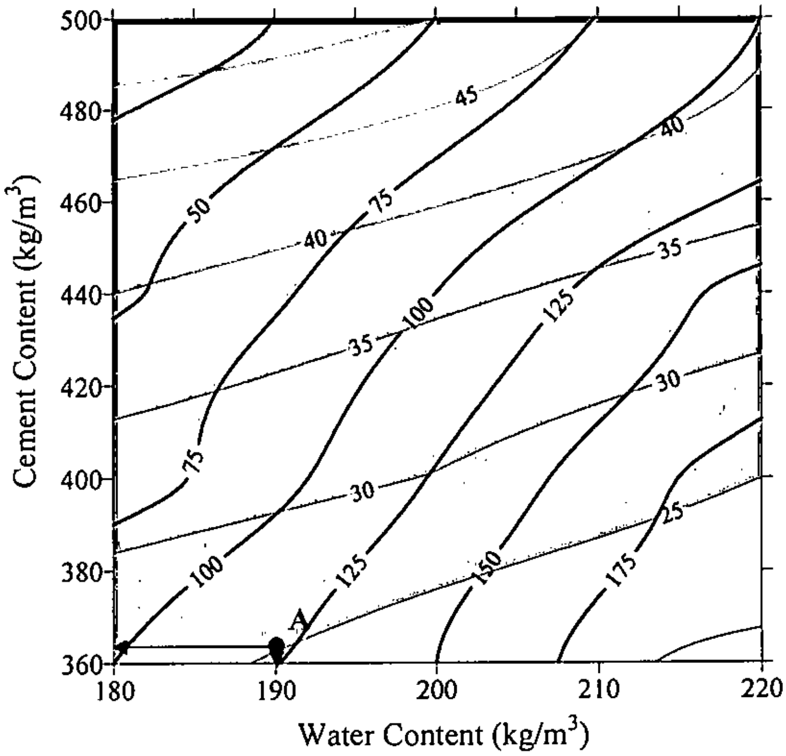


Figure 6.29: 28 Days Compressive Strength and Slump with Various Mix Proportions for Mixes Prepared with CEM II/B-M Cements and 5-10-14-18 Band Gradation (Example).

For required 28 days compressive strength 25 MPa and 120 mm slump, let select the point A on the figure 6.29.

Thus, from preliminary selection,

Water content = 190 kg/m^3 and Cement content = 362 kg/m^3

w/c ratio = 190/362 = 0.525.

2) Modification for compressive strength and workability

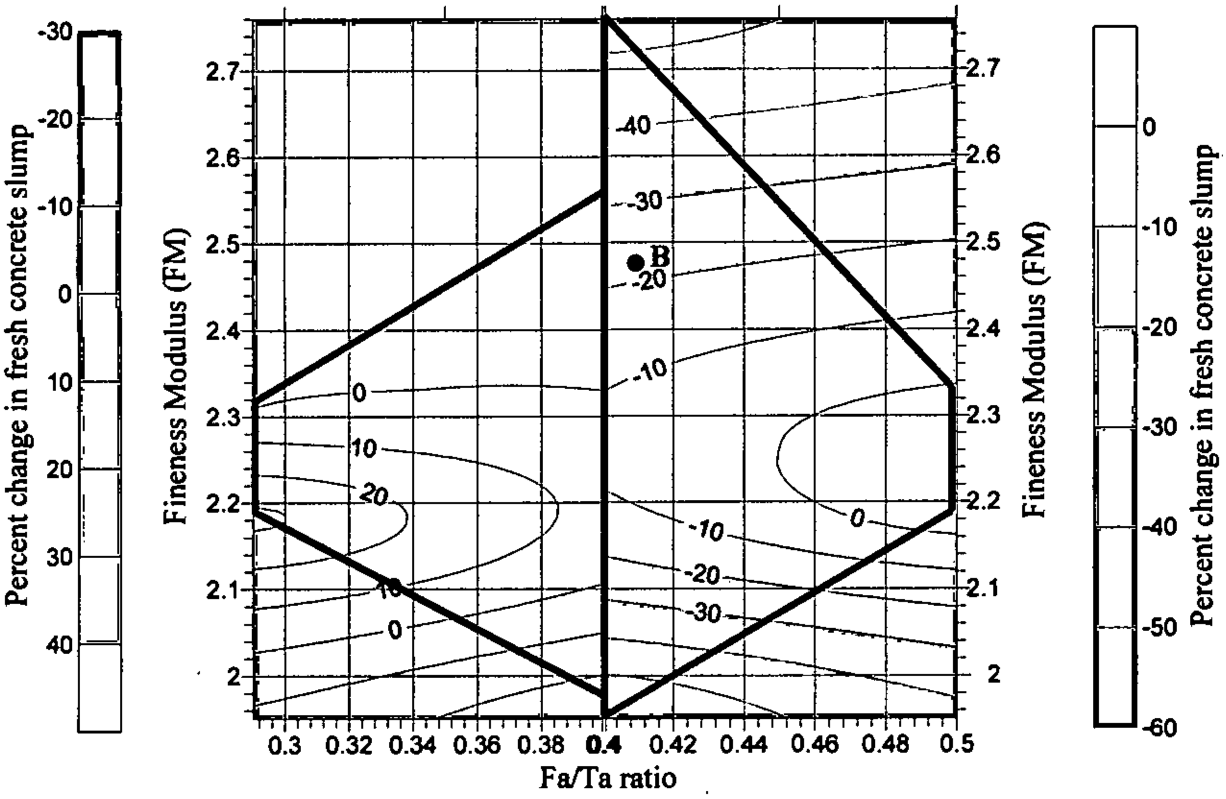


Figure 6.30: Variation in Concrete Workability for Different FM and Fa/Ta Values (Example)

The available aggregate properties (FM = 2.20 and fa/ta = 0.42) represent the point B on figure 6.30. Thus it signifies that due to the change in aggregate properties, fresh concrete workability will be lower by 22%. So, the modified slump($S_{modified}$) = 120* (1-0.22) = 93.6 mm

Similarly, due to the available aggregate properties which represent the point c on figure 6.3, the 28 days compressive strength will be lower by 15%. Thus, the modified 28 days compressive strength ($f'_{c\ modified}$) = 25* (1-0.15) = 21.25 MPa

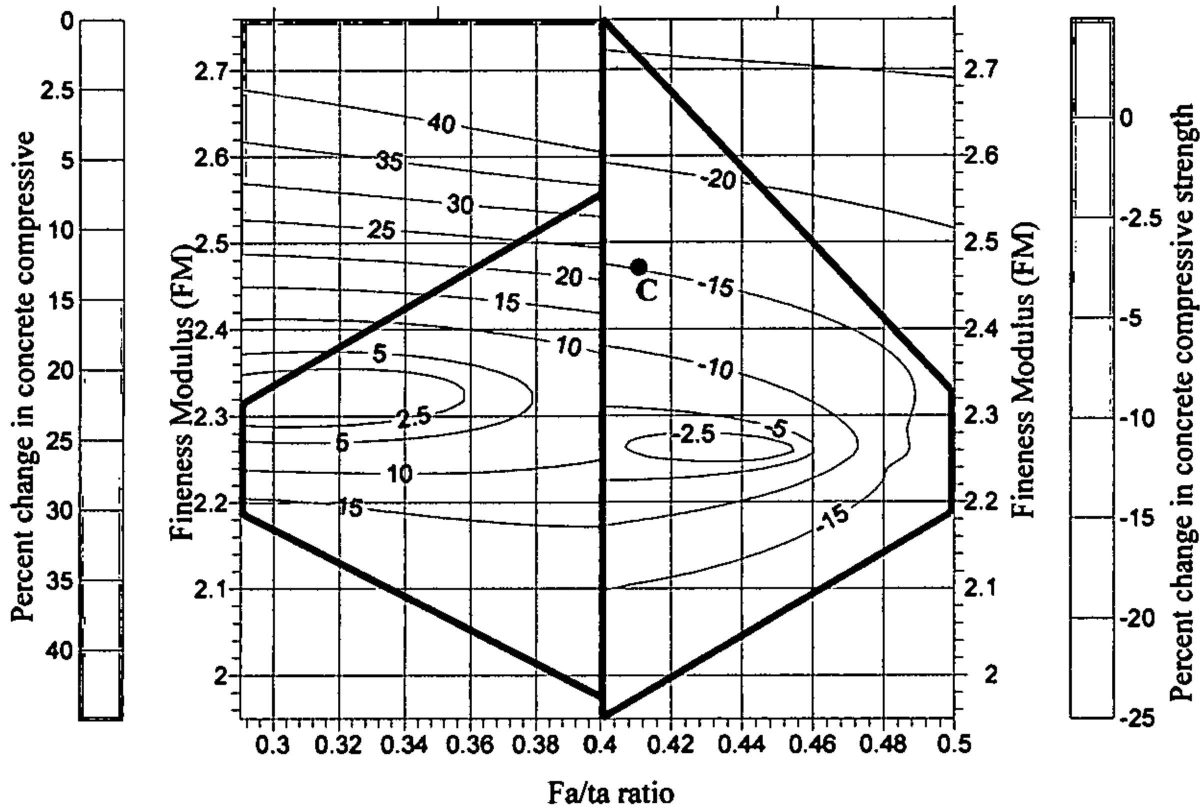


Figure 6.31: Variation in Concrete Compressive Strength for Different FM and Fa/Ta Values (Example).

3) Final W/C Ratio

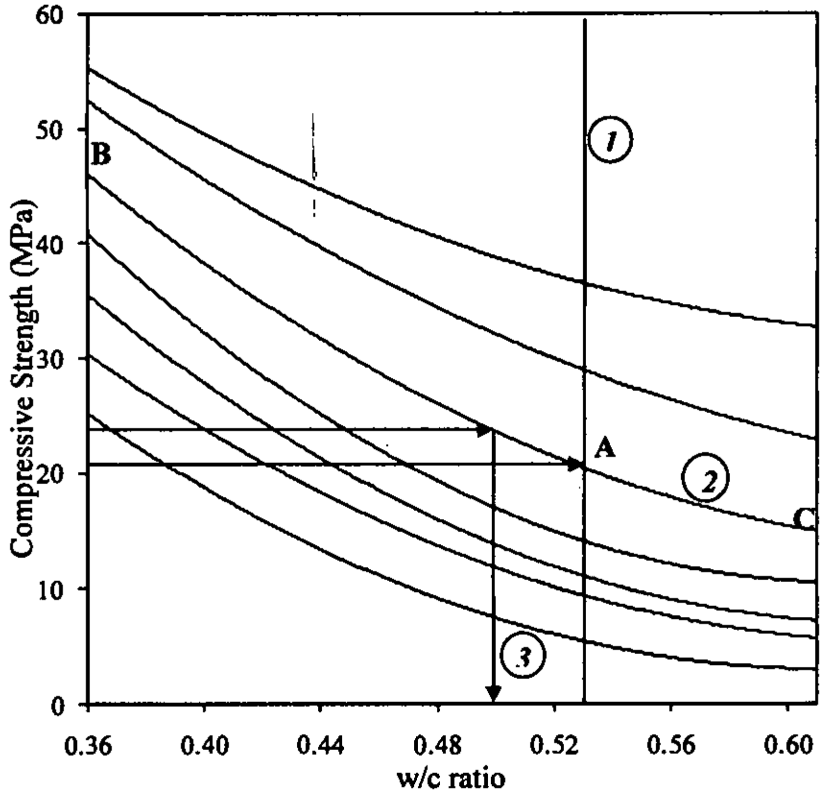


Figure 6.32: Concrete Compressive Strength vs. w/c Ratio Different Types of Concrete Mixes.

Using the modified compressive strength (21.25 MPa) and w/c ratio from step – 1, determine the final w/c ratio from figure 6.32. From this figure, the final w/c ratio found to be 0.50 (figure 6.32).

4) Modified Water Content

From step -2 the modified slump is 110.4 mm at water content 190 kg/m^3. Using these values, determine the required water content for slump = 120 mm. from figure the final water content is 194 kg/m^3(figure 6.33).

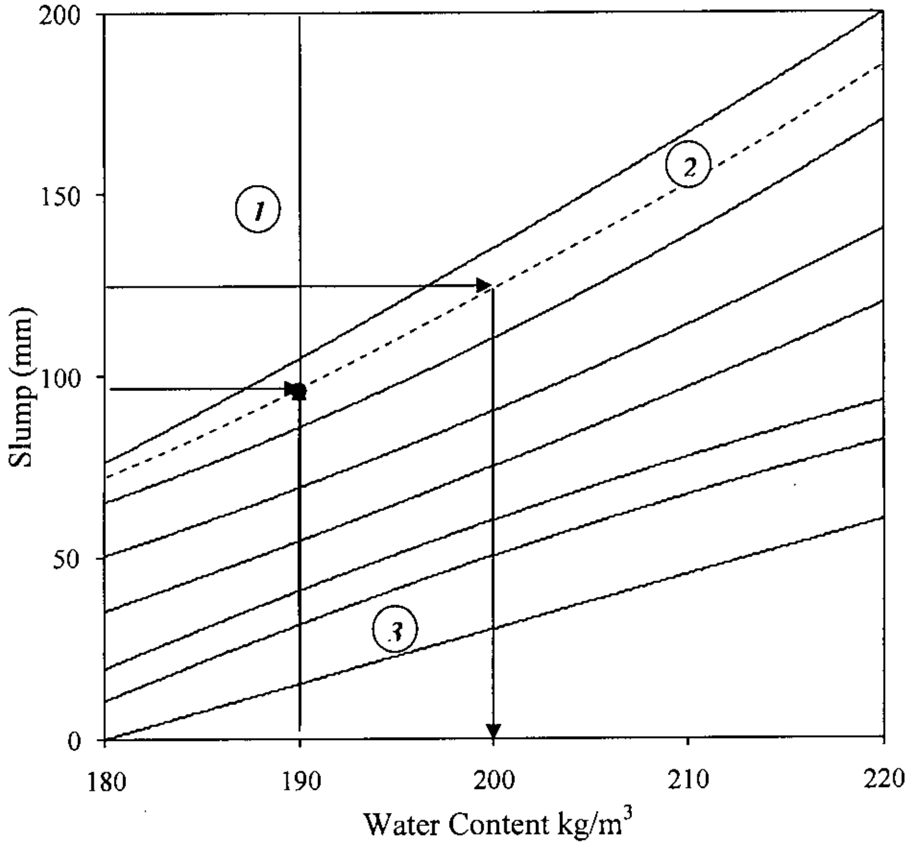


Figure 6.33: Concrete Compressive Strength vs. w/c Ratio Different Types of Concrete Mixes (Example).

5) Calculation of cement content

Required cement content = 200/0.5 = 400 kg/m^3

6) Calculation of total aggregate content

From absolute volume of concrete,

Total aggregate content = [1 – 200/1000 – 400/(3.15*1000)]*2.7*1000

= 1817 kg/m^3.

Fine aggregate content = = 0.41*1817 = 745 kg/m^3

Coarse aggregate content = 1817 – 745 = 1072 kg/m^3

Mix proportions:

Water content = 200 kg/m^3

Cement Content = 400 kg/m^3

w/c ratio = 0.50

Fine aggregate = 745 kg/m^3

Coarse aggregate = 1072 kg/m^3

6.6 Comparison with Other Concrete Mix Design Methods

6.6.1 Selection of W/C Ratio

DOE Method: in this method w/c need to be selected from a generalised set of compressive strength vs. w/c ratio curves. In this set of curves, a wide range of strength variation has been addressed (figure 6.34 and table 6.8).

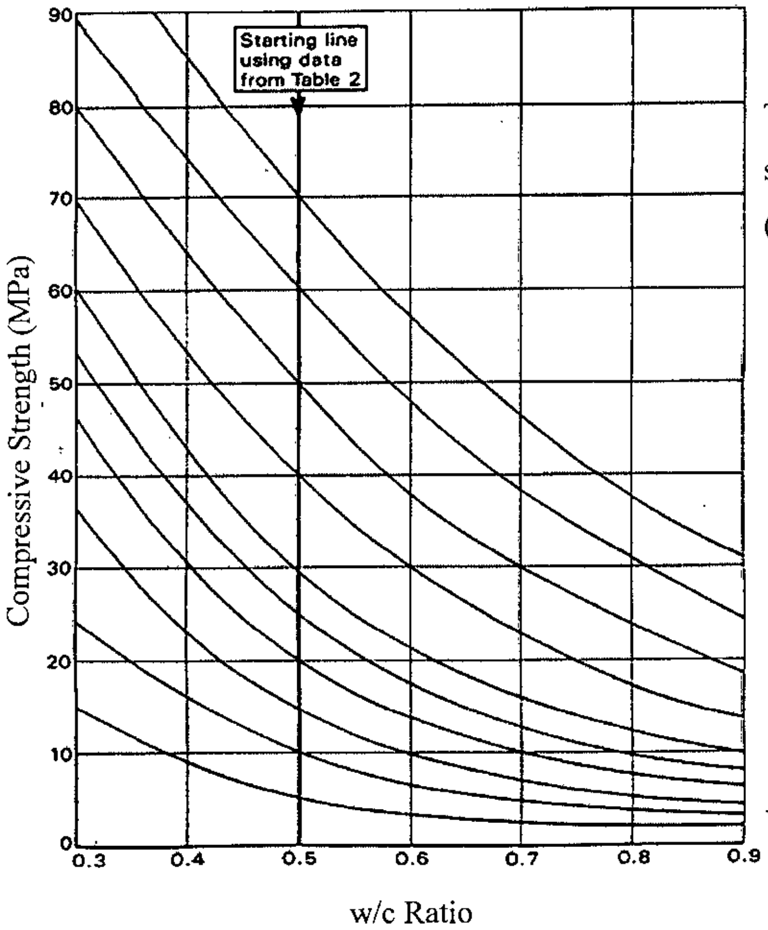


Table 6.8: Concrete Compressive strength (MPa) at w/c ratio 0.5 (Source: BS 812)

Type of Cement	Type of Coarse aggregate	28 days	91 days
Ordinary Portland or Sulfate Resisting Portland	Uncrushed	42	49
	Crushed	49	56
Rapid Hardening Portland	Uncrushed	48	54
	Crushed	55	61

Figure 6.34: Determination of w/c ratio using BS 812 standard

ACI Method: In ACI method of concrete mix design the w/c ratio is selected based on the target strength and the type of concrete (i.e. air entrained or non air entrained) from a given table (table – 6.9). Also in this method data is given only upto 6000psi.

Table 6.9: Concrete compressive strength for various w/c ratios (Source: ACI 211)

Required strength (psi)	water/cement ratio (non-air)
6000	0.41
5000	0.48
4000	0.57
3000	0.68
2000	0.82

Proposed method: In the proposed method of concrete mix design, preliminary the w/c ratio selected from a contour which represents the variation of compressive strength for different mix proportions. Example of such a contour is shown in figure 6.35. Also, from this figure it can be observed that for a single w/c ratio there are multiple compressive strength of concretes are achievable. Thus this method addresses the effects of cement-water volume on concrete.

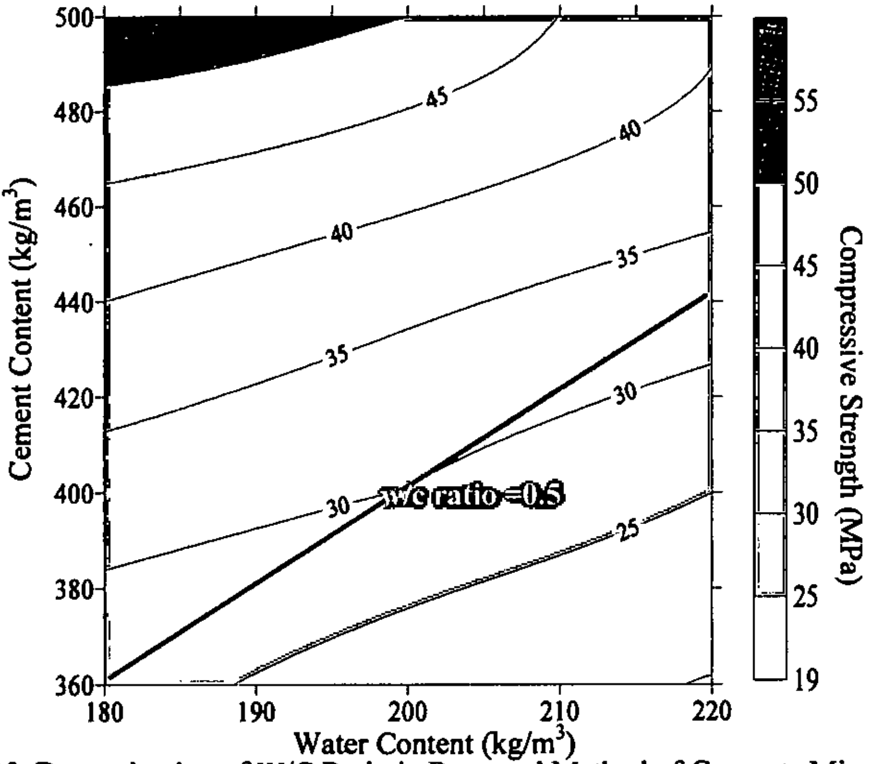


Figure 6.35: Determination of W/C Ratio in Proposed Method of Concrete Mix Design

6.6.2 Selection of Water Content

DOE Method: It is assumed that the workability of a concrete mix depends primarily on: the free water content and the fine aggregate type and, to a lesser degree, the coarse aggregate type. On the basis of tests the DOE Method provides a Table from which on can estimate the free water content, which will provide a given workability for concrete made from given fine and coarse aggregate types and a given maximum size of coarse aggregate (table 6.11).

Table 6.11: Determination of Water Content for Required Slump (Source: BS 812)

Maximum Size of Aggregate (mm)	Type of Aggregate	Slump (mm)			
		0-10	10-30	30-60	60-80
10	Uncrushed	135	160	185	200
	Crushed	160	185	210	225
20	Uncrushed	120	140	160	175
	Crushed	150	170	190	200
40	Uncrushed	100	125	145	160
	Crushed	140	155	170	185

ACI Method: Water content, is determined based on the nominal maximum size of aggregate, type of concrete (air-entrained or non-air entrained), and specified slump as shown in table 6.10.

Table 6.10: Determination of Water Content (lb/yd^3) for Required Slump (Source: ACI 211)

Slump (inch)	Maximum Size of Aggregate (inch)						
	3/8	1/2	3/4	1	1-1/2	2	3
1 to 2	350	335	315	300	275	260	220
3 to 4	385	365	340	325	300	285	245
6 to 7	410	385	360	340	315	300	270

Proposed method: In this method, water content determined preliminary based on required slump, aggregate gradation, cement and water content. Then, this water content further modified based on aggregate properties (i.e. fine aggregate proportion, FM of fine aggregate) (figure 6.36)

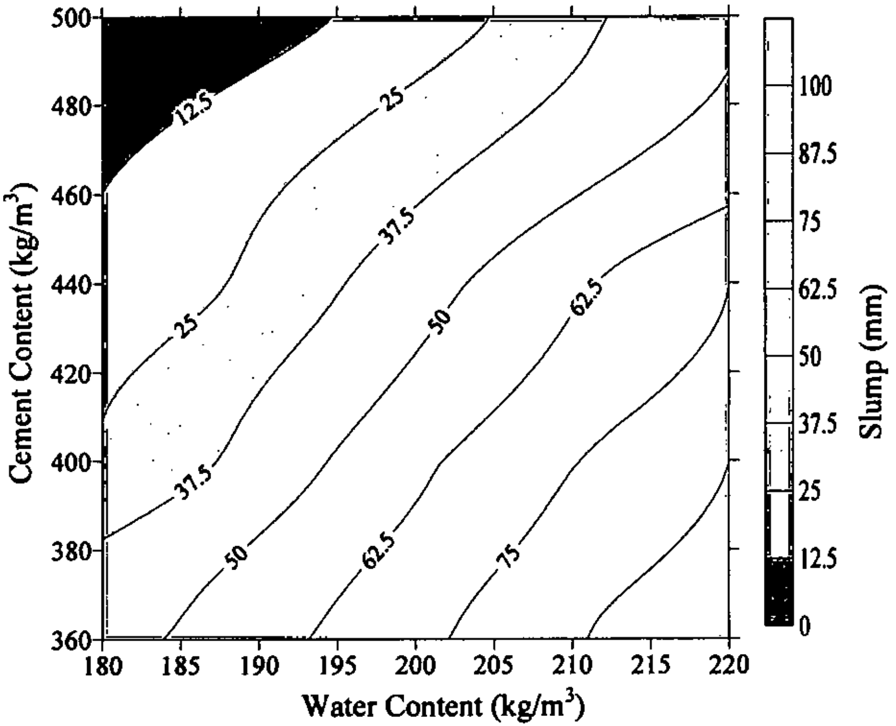


Figure 6.36: Determination of Water Content in Proposed Method of Concrete Mix Design

6.6.3. Proportions of Fine Aggregate and Coarse Aggregate

DOE method: proportion of fine aggregates determined based on workability, nominal maximum aggregate size and aggregate gradation.

ACI method: Coarse aggregates content, as dry rodded bulk (percentage) of concrete unit volume, is determined based on the nominal maximum size of aggregate, and the fineness modulus of sand.

Proposed method: the proportion of fine aggregate completely depends on the locally available aggregate gradation so as to get the optimum gradation band.

6.6.4 Examples to Compare Different Concrete Mix Design Methods

Example 1: Table 6.12 shows the concrete mix proportions as determined using ACI 211, BS 812 and proposed method for target strength 35 MPa and slump 75 mm using CEM I cement. Also it has been mentioned that the FM of locally available sand is 2.4.

Table 6.12: Concrete Mix Proportions for Target Strength 35 MPa and 75 mm slump.

Concrete Mix design method	ACI	DOE	Proposed
W/C ratio	0.48	0.58	0.53
Water Content (kg/m^3)	202	200	208
Cement Content (kg/m^3)	420	345	390
Total Aggregate Content (kg/m^3)	1757	1665	1771
Fine aggregate (kg/m^3)	700	583	Depends on locally available aggregate gradation
Coarse Aggregate (kg/m^3)	1057	1082	

Example 2: Table 6.13 shows the concrete mix proportions as determined using ACI 211, BS 812 and proposed method for target strength 45 MPa and slump 65 mm using CEM I cement. Also it has been mentioned that the FM of locally available sand is 2.4.

Table 6.13: Concrete Mix Proportions for Target Strength 45 MPa and 65 mm slump.

Concrete Mix design method	ACI	DOE	Proposed
W/C ratio	Not applicable	0.50	0.43
Water Content (kg/m^3)		190	205
Cement Content (kg/m^3)		380	480
Total Aggregate Content (kg/m^3)		1665	1700
Fine aggregate (kg/m^3)		583	Depends on locally available aggregate gradation
Coarse Aggregate (kg/m^3)		1082	

6.7 Verification of the Proposed Mix Design Method using Laboratory Experiments

To check the performance of proposed concrete mix design method three concrete mixes have been prepared in laboratory environment. For all of these mixes, 5-10-14-18 aggregate gradation band has been used for which required fa/ta ratio found to be 0.41 with FM of sand equals 2.47. Table 6.14 shows the target 28 days and compressive strengths and slump for these mixes and subsequent mix proportions determined using proposed method of concrete mix design. Table 6.15 shows the resulted compressive strength and workability of the mixes and their standard deviation in percentage from target values. Figure 6.37 illustrates the rate of strength gain of these mixes with time.

Table 6.14: Mix Proportions Determined From Proposed Mix Design Method

Mix ID	Target Slump	Target 28 days Strength	Cement	FM	Fa/ta	Water Content (kg/m^3)	Cement Content (kg/m^3)	w/c Ratio
A	120	25	CEM II/B-M	2.47	0.41	200	400	0.50
B	75	35	CEM I			211	426	0.495
C	37.5	45	CEM I			202	517	0.39

Table 6.15: 28 Days Compressive Strength and Slump Test Results

Mix ID	Slump				28-days Compressive Strength (MPa)			
	Target	Resulted	Standard Deviation, SD (%)	Avg. SD, (%)	Target	Resulted	Standard Deviation, SD (%)	Avg. SD, (%)
A	120	152.4	27	44	25	28	12.0	7.3
B	75	127	69		35	35	1.0	
C	37.5	50.8	35		45	49	9.0	

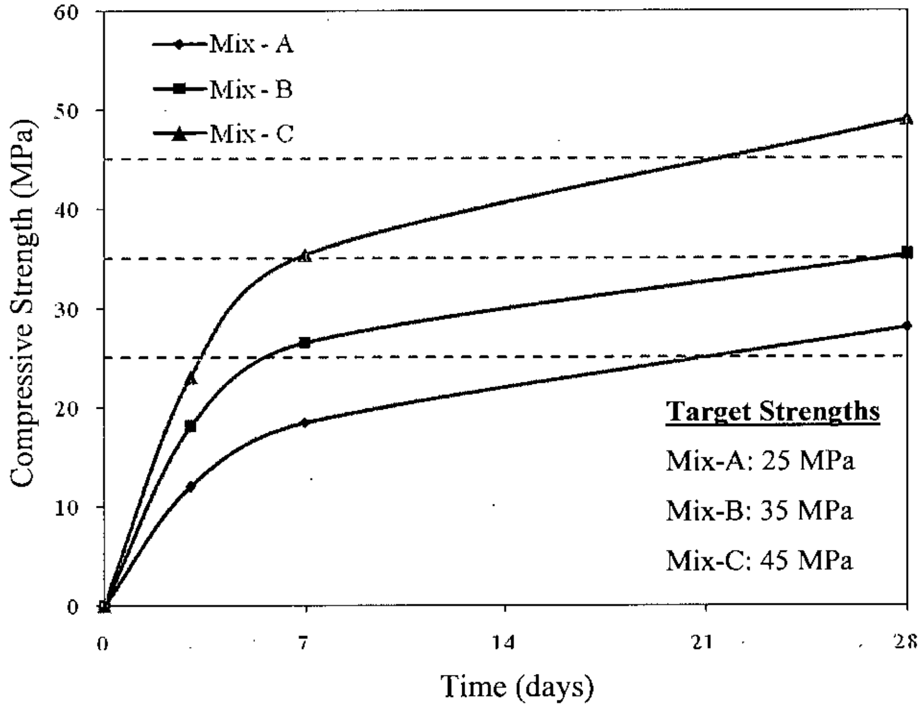


Figure 6.37: Strength Gain of Concrete Mixes with Time (days)

6.8 Concluding Remarks

This chapter presents the test results and other required information for concrete mix design. Also, in this chapter a completely new concrete mix design procedure has been described. This newly proposed method of concrete mix design can be utilized to achieve a wide range of concrete compressive strength form 2.5 MPa to 55 MPa. Mathematical examples of this mix design procedure have been shown for better understanding of the method. Laboratory mixes prepared to examine the performance of the proposed method shows an appreciable performance in case of 28 days compressive strength with very low average standard deviation and in case of slump, the average standard deviation is found to be 44% of target slump value (on higher side). But in case of concrete casting, usually slump of the first mix used to adjust the water content of the rest of the mixes. Also, the standard deviation of workability will become lower if the slump in mix design is presented by range of values rather than any single value.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

General

The attribute of this chapter is to summarize all the important findings in this research work. This will give a clear overview as well as understanding about the possible gradation methods of locally available aggregates and proportioning of concrete. This chapter also unwraps some specific potential scopes of further research work for investigating different parameters that affect concrete properties and aggregate gradations.

7.1 CONCLUSIONS

(I) It has been found that the concrete compressive strength and workability are highly affected by its aggregate gradation. Concrete compressive strength can be increased significantly (over 50 %) just by altering the gradation of its aggregates.

(II) Concrete made with suggested aggregate gradations "5-10-14-18" and "5-10-18-22" bands are confirmed to be better concrete than other mixes. It indicates that band gradation of aggregate gives better concrete only if some parameters are maintained within a range, as it is included in suggested "5-10-14-18" and "5-10-18-22" gradations.

(III) Apparently both the Coarseness Factor and Workability Factor might have relationships only with concrete compressive strength. But the precise form of these relationships must be established through a comprehensive research with large scale data sets.

(IV) The concrete properties are more related to fine aggregate FM than that of combined aggregate.

(V) This is observed that, any aggregate gradation that satisfies the 5-10-14-18 (or 5-10-18-22) band requirements will result in concrete properties (workability, strength and density) with little variation keeping the mix proportions constant.

(VI) It has also been observed that FM vs. Fa/ta chart can be applied as a useful tool for selecting optimum aggregate gradation and also to assess the effects of these aggregate parameters on concrete properties.

(VII) This research work also features contours as a new approach for concrete mix design. From the contours plotted here, it is understandable that the application of contours in concrete mix design increases the freedom of user.

(VIII) Proposed concrete mix design addresses the effects of cement – water paste volume on concrete compressive strength and workability which have been ignored in conventional mix design standards.

(IX) Proposed concrete mix design method can accommodate wide variations of concrete compressive strength (2.5 MPa to 55 MPa) and workability (0 to 200 mm) that may be achieved without any kind of chemical additives.

7.2 RECOMMENDATIONS

(I) Concrete mix design should incorporate additional standard deviation due to variation of concrete properties resulted from different cement brands.

(II) The water penetration depth tests can be further extended to address the durability aspects of concrete in to the proposed mix design method.

(III) Same research work can be repeated for different nominal maximum size of aggregates (i.e. 37.5 mm or 40 mm), air entraining concrete and using different types of admixture.

(IV) FM vs. fa/ta chart may have more significant application for controlling concrete properties. This chart can be further explored for proper utilization.

(V) For user convenience, computer programs can be developed following the proposed concrete mix design and aggregate gradation methods.

(VI) Further lab mixtures as well as field mixtures can be prepared to compare the proposed concrete mix design method with other conventional methods.

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APPENDIX-A

Table A.1: Proportion of Source Aggregates Required for Gradation – 10

		Combined aggregate gradation	**Fine Portion (%)**	**Coarse Portion (%)**
Proportions of Source Aggregates	Filler	0	0	
	Local sand	9	28	-
	Sylhet Sand	23	72 %	-
	¼ inch down grade	7	-	10
	½ inch down grade	22	-	32
	3/8 inch	18	-	26
	½ inch	18	-	26
	3/4 inch	3		4
Other Properties	Overall FM	5.61	-	-
	FM	2.62	-	-
	Particles passing #4	42.50	-	-
	Particles retained #4	57.20	-	-

Table A.2: Proportion of Source Aggregates Required for Gradation – 11

		Combined aggregate gradation	**Fine Portion (%)**	**Coarse Portion (%)**
Proportions of Source aggregates	Filler	6	16	
	Local sand	10	26	-
	Sylhet Sand	22	58	-
	¼ inch down grade	0	-	0
	½ inch down grade	23	-	37
	3/8 inch	18	-	29
	½ inch	18	-	29
	3/4 inch	3		5
Other Properties	Overall FM	5.37	-	-
	FM	1.95	-	-
	Particles passing #4	42.07	-	-
	Particles retained #4	57.30	-	-

Table A.3: Proportion of Source Aggregates Required for Gradation – 12

		Combined aggregate gradation	**Fine Portion (%)**	**Coarse Portion (%)**
Proportions of Source aggregates	Filler	1	4	
	Local sand	10	44	-
	Sylhet Sand	12	52	-
	¼ inch down grade	0	-	0
	½ inch down grade	28	-	36.4
	3/8 inch	21	-	27.4
	½ inch	22	-	28.6
	3/4 inch	6		7.8
Other Properties	Overall FM	5.89	-	-
	FM	2.18	-	-
	Particles passing #4	28.52	-	-
	Particles retained #4	71.18	-	-

Table A.4: Proportion of Source Aggregates Required for Gradation – 13

		Combined aggregate gradation	**Fine Portion (%)**	**Coarse Portion (%)**
Proportions of Source aggregates	Filler	0	0	
	Local sand	6	21.4	-
	Sylhet Sand	22	78.6	-
	¼ inch down grade	8	-	11.1
	½ inch down grade	22	-	30.6
	3/8 inch	18	-	25.0
	½ inch	18	-	25.0
	3/4 inch	6		8.3
Other Properties	Overall FM	5.81	-	-
	FM	2.76	-	-
	Particles passing #4	39.47	-	-
	Particles retained #4	60.29	-	-

Table A.5: Proportion of Source Aggregates Required for Gradation – 14

		Combined aggregate gradation	**Fine Portion (%)**	**Coarse Portion (%)**
Proportions of Source aggregates	Filler	0	0.0	
	Local sand	17	44.7	-
	Sylhet Sand	21	55.3	-
	¼ inch down grade	10	-	16.1
	½ inch down grade	18	-	29.0
	3/8 inch	14.5	-	23.4
	½ inch	14.5	-	23.4
	3/4 inch	5		8.1
Other Properties	Overall FM	5.29	-	-
	FM	2.28	-	-
	Particles passing #4	50.20	-	-
	Particles retained #4	49.33	-	-

Table A.6: Proportion of Source Aggregates Required for Gradation – 15

		Combined aggregate gradation	**Fine Portion (%)**	**Coarse Portion (%)**
Proportions of Source aggregates	Filler	8	22.2	
	Local sand	8	22.2	-
	Sylhet Sand	20	55.6	-
	¼ inch down grade	12	-	18.8
	½ inch down grade	18	-	28.1
	3/8 inch	15	-	23.4
	½ inch	15	-	23.4
	3/4 inch	4		6.3
Other Properties	Overall FM	5.20	-	-
	FM	2.19	-	-
	Particles passing #4	49.71	-	-
	Particles retained #4	49.56	-	-

Table A.7: Proportion of Source Aggregates Required for Gradation – 16

		Combined aggregate gradation	**Fine Portion (%)**	**Coarse Portion (%)**
Proportions of Source aggregates	Filler	9	26.5	
	Local sand	7	20.6	-
	Sylhet Sand	18	52.9	-
	¼ inch down grade	1	-	1.5
	½ inch down grade	23	-	34.8
	3/8 inch	18	-	27.3
	½ inch	18	-	27.3
	3/4 inch	6		9.1
Other Properties	Overall FM	5.48	-	-
	FM	1.98	-	-
	Particles passing #4	38.90	-	-
	Particles retained #4	60.37	-	-

APPENDIX-B

Table B.1: Test Results for the Concrete Mixes Prepared with 5-10-18-22 and CEM - II/B-M Cements.

Mix ID	w/c Ratio	A/C Ratio	Slump (mm)	Compressive strength (MPa)			Concrete Density kg/m^3
				3 days	7 days	28 days	
A1	0.50	5.29	80	7	13	19	2356
A2	0.56	5.14	200	5	7	15	2342
A3	0.61	4.99	229	4	6	11	2330
A4	0.68	4.81	254	3	5	9	2252
A5	0.45	4.68	38	14	20	28	2360
A6	0.50	4.54	180	7	13	20	2286
A7	0.55	4.41	216	6	10	15	2304
A8	0.61	4.24	229	5	8	13	2290
A9	0.41	4.17	20	17	26	35	2336
A10	0.45	4.05	165	11	19	24	2338
A11	0.50	3.93	203	7	15	23	2340
A12	0.56	3.78	216	7	11	18	2290
A13	0.36	3.57	0	26	35	50	2360
A14	0.40	3.46	102	18	28	40	2338
A15	0.44	3.35	184	13	21	31	2342
A16	0.49	3.22	203	10	16	24	2336

Table B.2: Test Results for the Concrete Mixes Prepared with 5-10-14-18 and CEM - II/B-M Cements.

Mix ID	w/c Ratio	A/C Ratio	Slump (mm)	Compressive strength (MPa)			Concrete Density kg/m^3
				3 days	7 days	28 days	
B 1	0.50	5.29	76	9	15	27	2356
B 2	0.56	5.14	140	7	15	23	2340
B 3	0.61	4.99	216	5	11	19	2190
B 4	0.45	4.68	57	11	19	35	2328
B 5	0.50	4.54	127	9	19	30	2200
B 6	0.55	4.41	210	7	13	19	2304
B 7	0.41	4.17	13	15	25	39	2326
B 8	0.45	4.05	100	13	22	38	2302
B 9	0.50	3.93	203	8	17	28	2288
B 10	0.36	3.57	0	27	43	53	2294
B 11	0.40	3.46	61	18	31	44	2240
B 12	0.44	3.35	89	14	27	40	2314

Table B.3: Test Results for the Concrete Mixes Prepared with 5-10-18-22 and CEM - I Cements.

Mix ID	w/c Ratio	A/C Ratio	Slump (mm)	Compressive strength (MPa)			Concrete Density kg/m^3
				3 days	7 days	28 days	
C 1	0.50	5.29	88.9	8	11	20	2244
C 2	0.56	5.14	127	6	9	15	2252
C 3	0.61	4.99	158.75	4	8	14	2286
C 4	0.45	4.68	12.7	18	29	40	2182
C 5	0.50	4.54	114	12	24	35	2208
C 6	0.55	4.41	114	10	18	26	2166
C 7	0.41	4.17	12.7	28	39	45	2112
C 8	0.45	4.05	40	22	35	40	2199
C 9	0.50	3.93	127	0	29	36	2152
C 10	0.36	3.57	6.35	27	43	48	2238
C 11	0.40	3.46	12.7	25	39	43	2284
C 12	0.44	3.35	76.2	21	37	40	2290

Table B.4: Test Results for the Concrete Mixes Prepared with 5-10-14-18 and CEM – I Cements.

Mix ID	**W/C Ratio**	**A/C Ratio**	**Slump (mm)**	**Compressive strength (MPa)**			**Concrete Density Kg/m^3**
				3 days	**7 days**	**28 days**	
D 1	0.50	5.29	26	20.00	31.00	39.00	2220
D 2	0.56	5.14	70	13.68	28.00	35.00	2292
D 3	0.61	4.99	100	10.00	25.00	33.00	2318
D 4	0.45	4.68	19	24.00	36.00	43.00	2232
D 5	0.50	4.54	60	18.00	31.00	39.00	2264
D 6	0.55	4.41	93	12.58	27.50	35.00	2992
D 7	0.41	4.17	0	27.50	40.00	47.50	2056
D 8	0.45	4.05	50	23.00	36.50	44.00	2174
D 9	0.50	3.93	88.9	19.00	30.50	37.50	2198
D 10	0.36	3.57	0	32.00	44.00	55.00	2272
D 11	0.40	3.46	12	30.23	43.00	50.00	2264
D 12	0.44	3.35	50.8	26.00	38.50	46.00	2222

APPENDIX-C

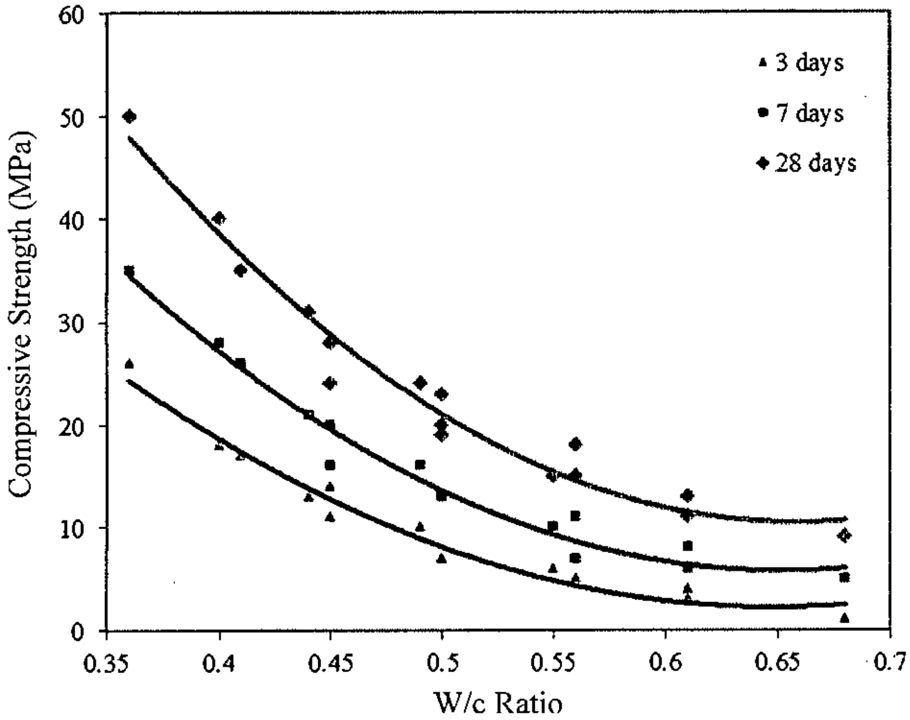


Figure C.1: Variation of Compressive Strength with w/c Ratio for Concrete Mixes Prepared with 5 -10-18-22 Band Gradations and CEM II/B-M cements

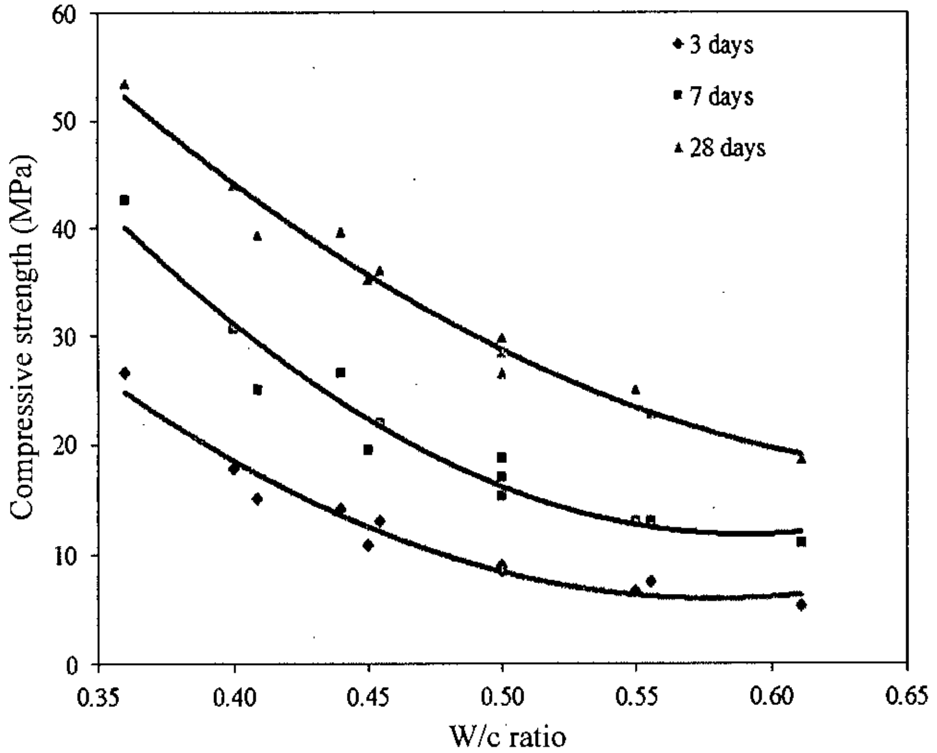


Figure C.2: Variation of Compressive Strength with w/c Ratio for Concrete Mixes Prepared with 5 -10-14-18 Band Gradations and CEM II/B-M cements

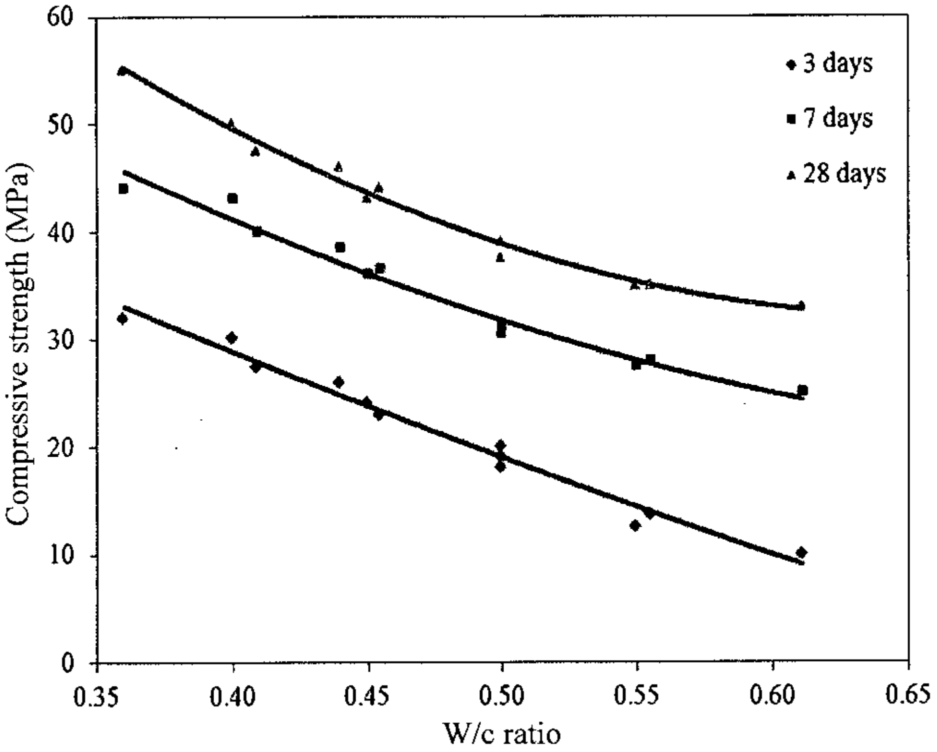


Figure C.3: Variation of Compressive Strength with w/c Ratio for Concrete Mixes Prepared with 5 -10-14-18 Band Gradations and CEM I cements

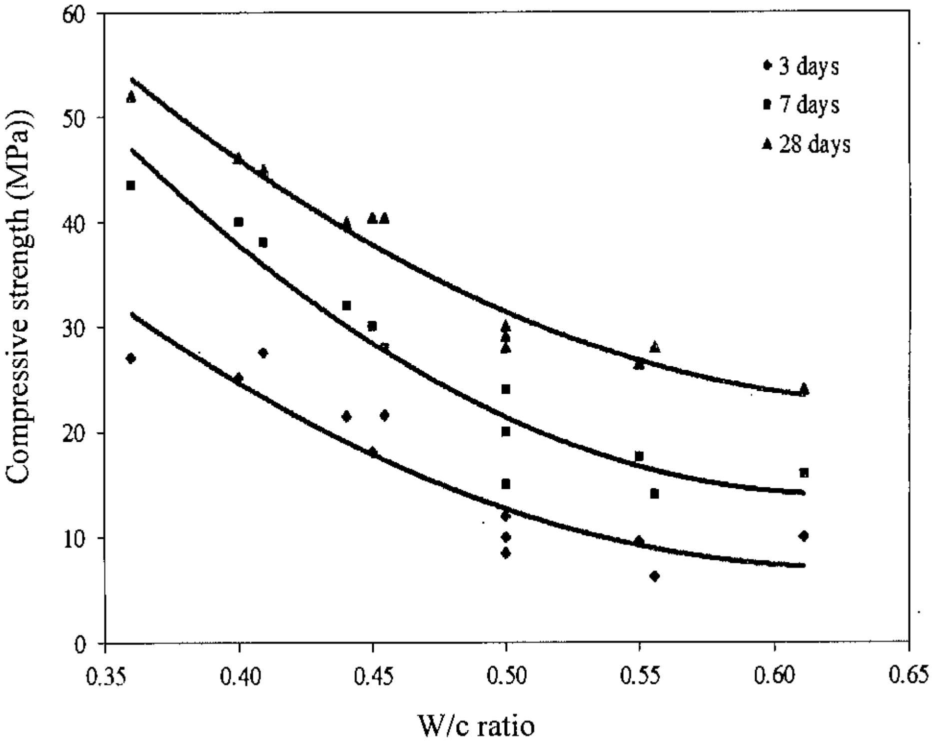


Figure C.4: Variation of Compressive Strength with w/c Ratio for Concrete Mixes Prepared with 5 -10-18-22 Band Gradations and CEM I cements

APPENDIX-D

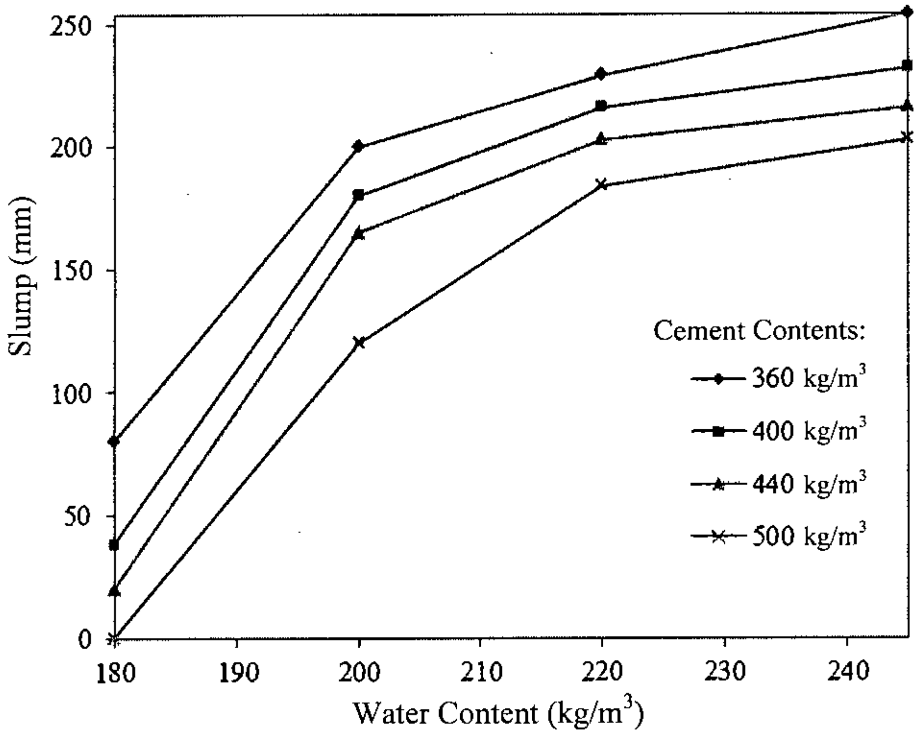


Figure D.1: Variation of Slump with Water Content for Concrete Mixes Prepared with 5 -10-18-22 Band Gradations and CEM II/B-M cements

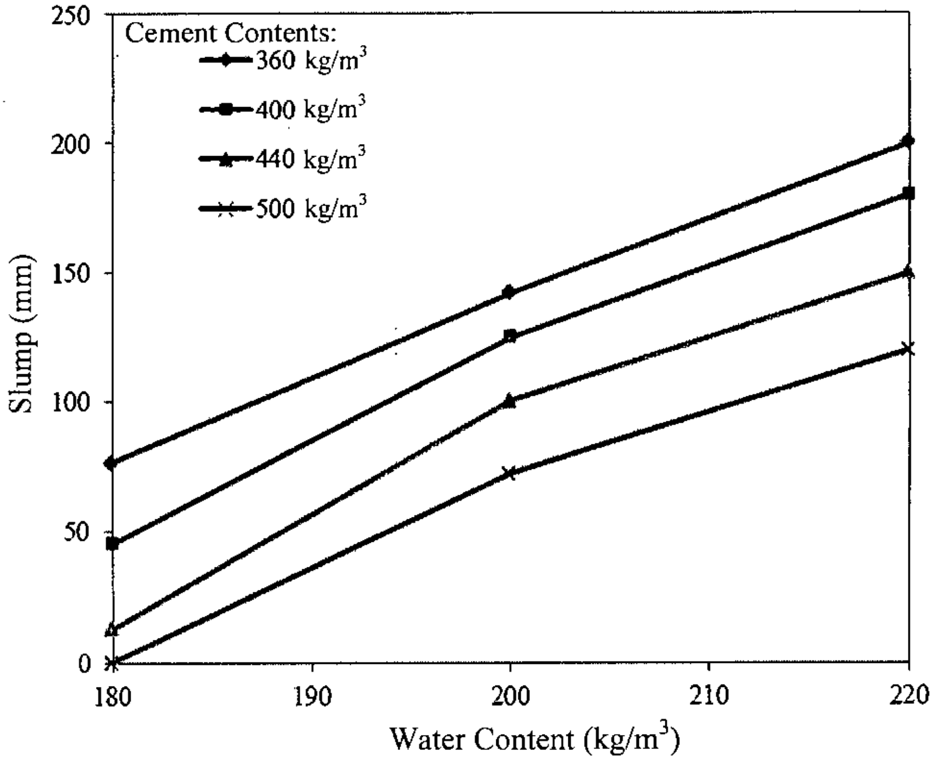


Figure D.2: Variation of Slump with Water Content for Concrete Mixes Prepared with 5 -10-14-18 Band Gradations and CEM II/B-M Cements

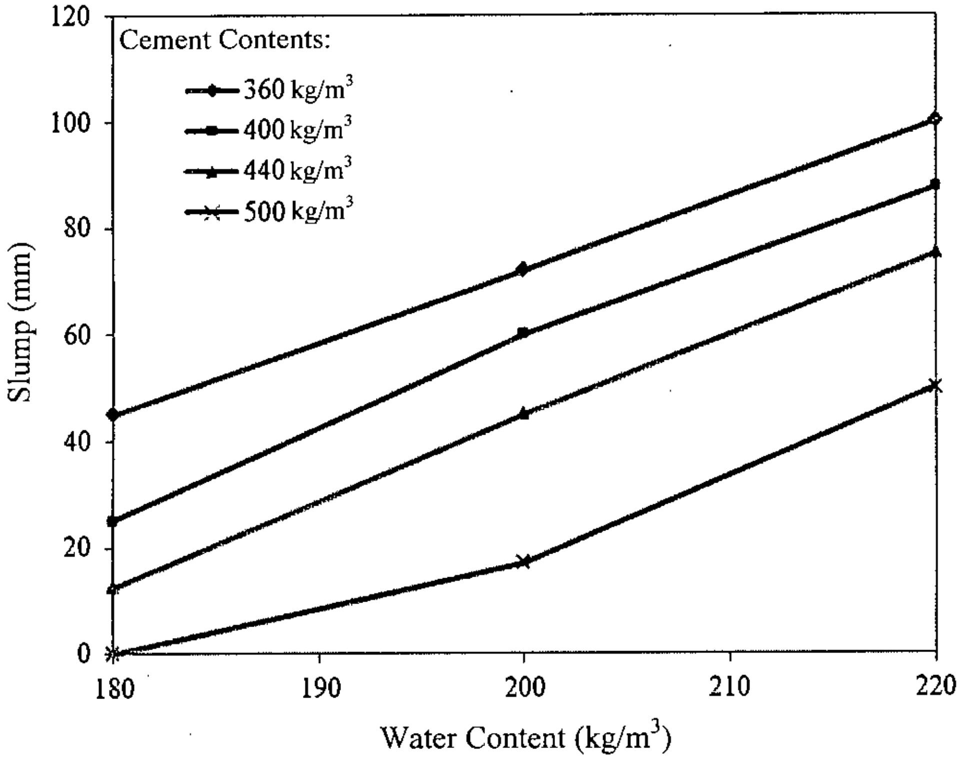


Figure D.3: Variation of Slump with Water Content for Concrete Mixes Prepared with 5 -10-14-18 Band Gradations and CEM I Cements

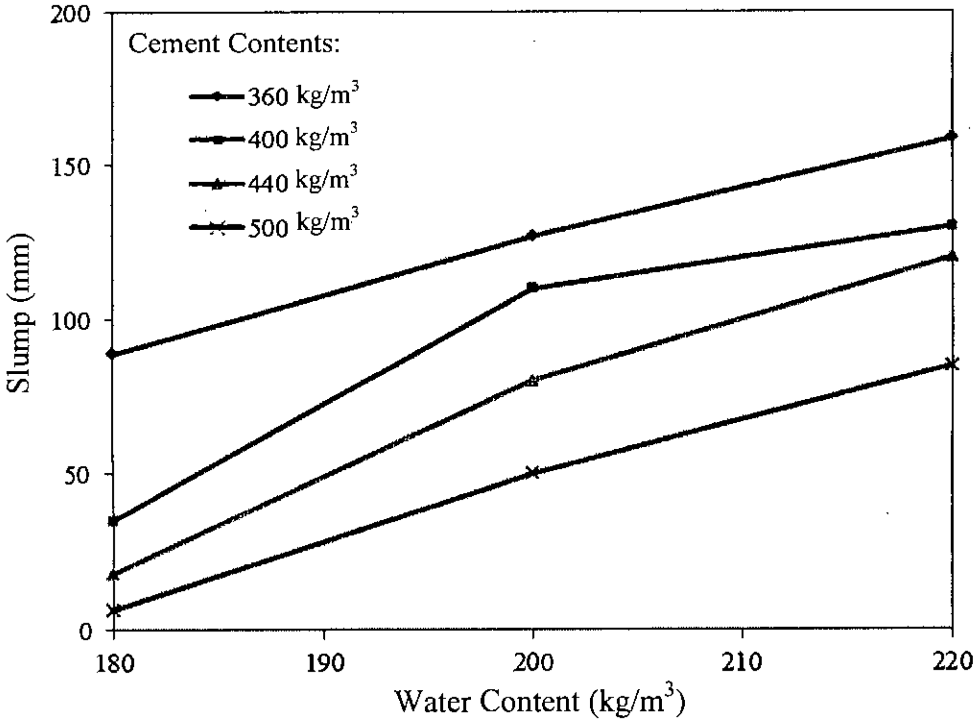
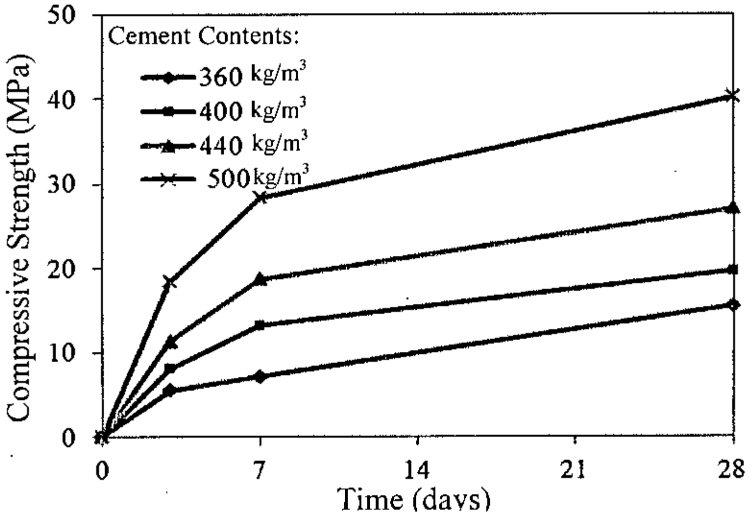
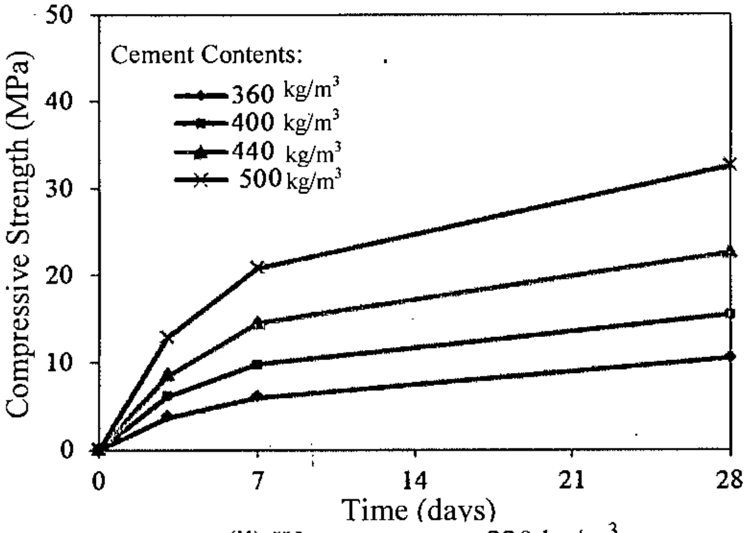


Figure D.4: Variation of Slump with Water Content for Concrete Mixes Prepared with 5 -10-18-22 Band Gradations and CEM I Cements

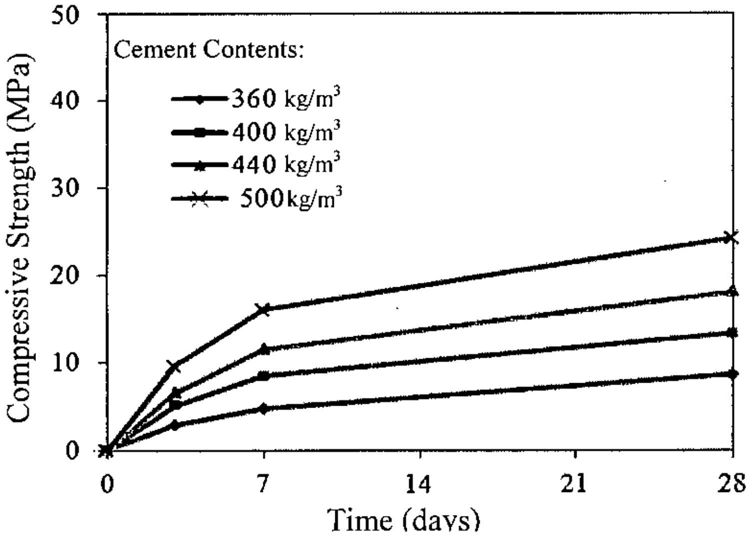
APPENDIX-E



(i) Water content = 200 kg/m^3

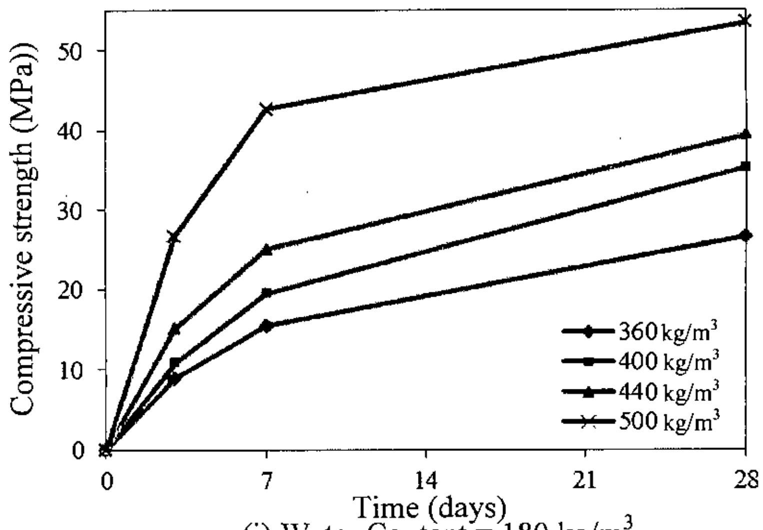


(ii) Water content = 220 kg/m^3

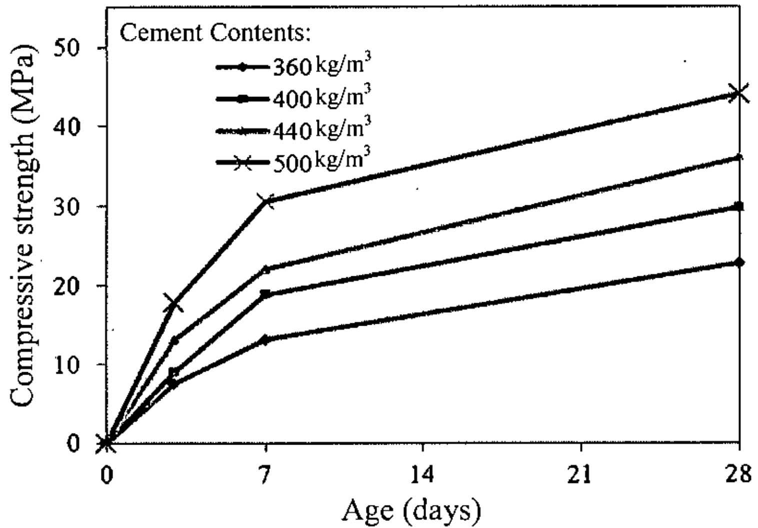


(iii) Water content = 245 kg/m^3

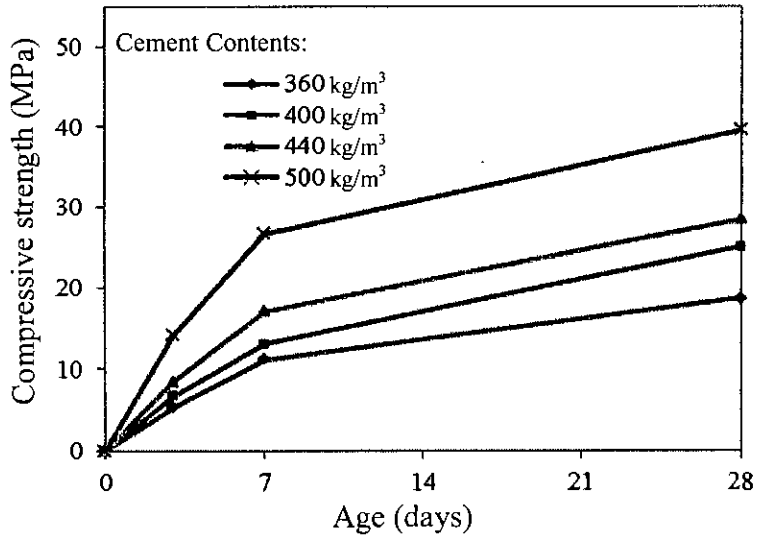
Figure E.1: Rate of Strength Gain with Time for Concrete Mixes Prepared with 5-10-18-22 and CEM - II/B-M Cements.



(i) Water Content = 180 kg/m^3

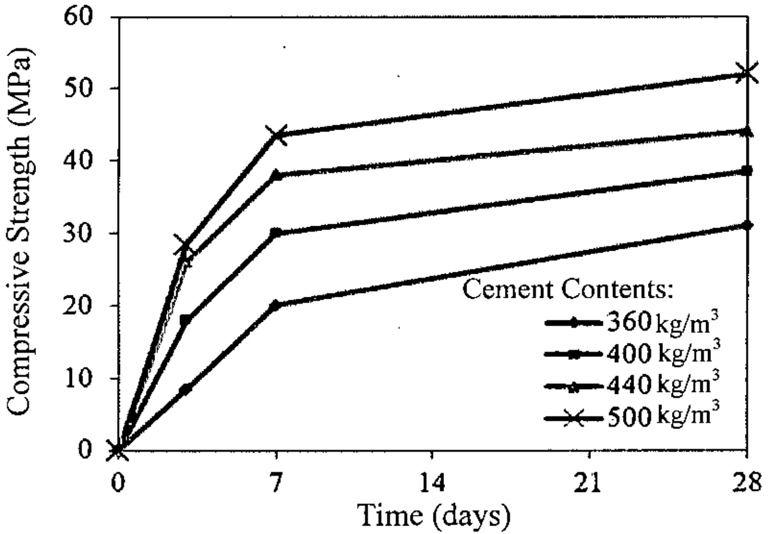


(ii) Water Content = 200 kg/m^3

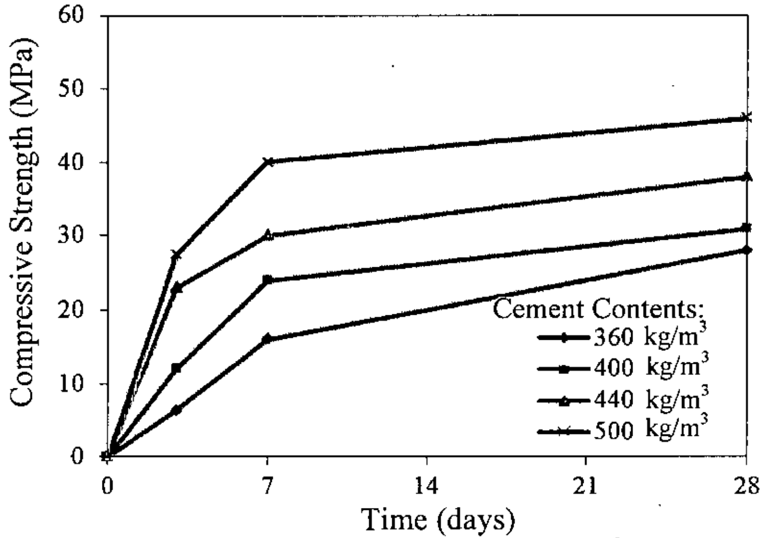


(iii) Water Content = 220 kg/m^3

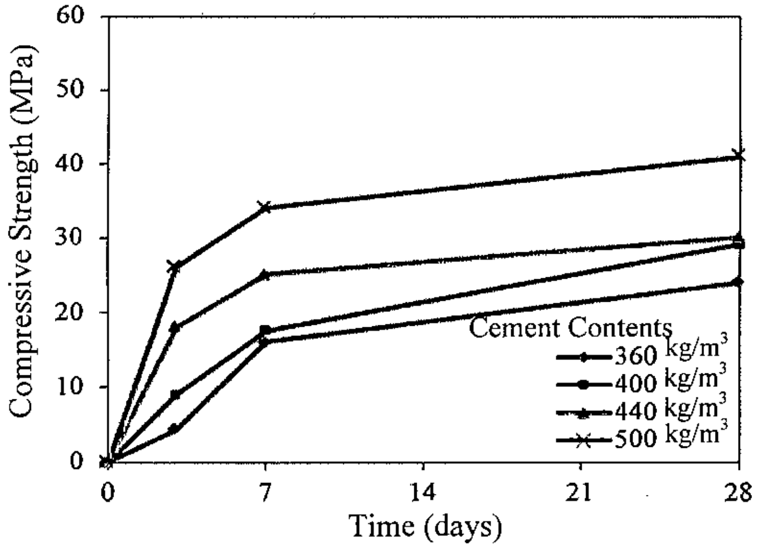
Figure E.2: Rate of Strength Gain with Time Concrete Mixes Prepared with 5-10-14-18 and CEM - II/B-M Cements



(i) Water Content = 180 kg/m^3

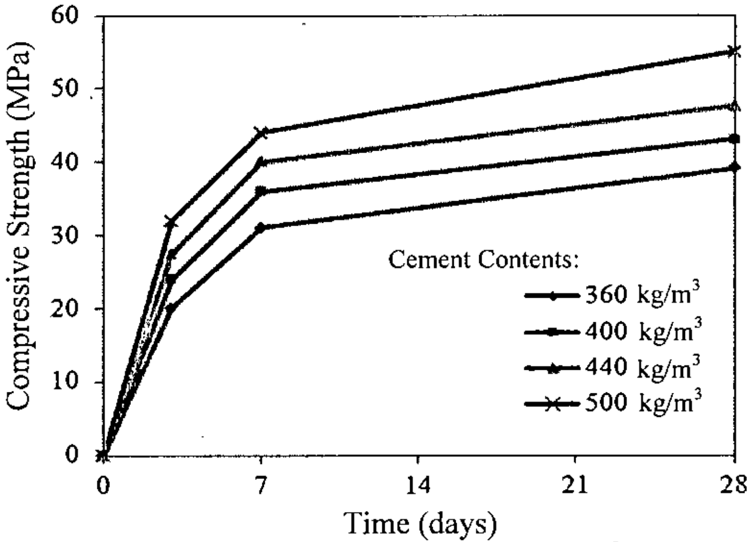


(ii) Water Content = 200 kg/m^3

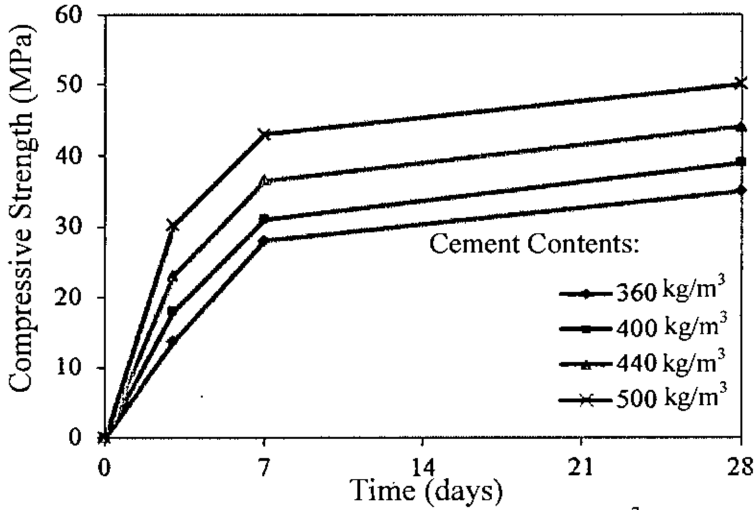


(iii) Water Content = 220 kg/m^3

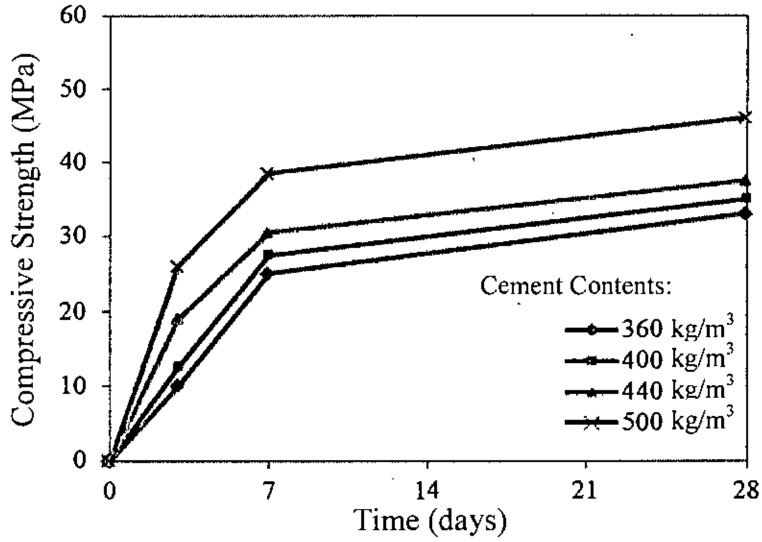
Figure E.3: Rate of Strength Gain with Time for Concrete Mixes Prepared with 5-10-14-18 and CEM - I Cements



(i) Water Content = 180 kg/m^3



(ii) Water Content = 200 kg/m^3



(iii) Water Content = 220 kg/m^3

Figure E.4: Rate of Strength Gain with Time for Concrete Mixes Prepared with 5-10-18-22 and CEM - I Cements

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Chapter 7

CONCLUSION AND RECOMMENDATIONS

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