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Concrete Mix Design Methods, Verification Study

Shailendra Singh[1], Suchi Sharma[2],

[1,2] Department of Civil Engineering, Government Polytechnic College,

Daulatpura, Bundi (India)

ABSTRACT

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 2 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 compressive strength of hardened concrete which is generally considered to be an index of its other properties, depends upon many factors, e.g. quality and quantity of cement, water and aggregates; batching and mixing; placing, compaction and curing. The cost of concrete is made up of the cost of materials, plant and labour. The variations in the cost of materials arise from the fact that the cement is several times costly than the aggregate, thus the aim is to produce as lean a mix as possible. From technical point of view the rich mixes may lead to high shrinkage and cracking in the structural concrete, and to evolution of high heat of hydration in mass concrete which may cause cracking. The actual cost of concrete is related to the cost of materials required for producing a minimum mean strength called characteristic strength that is specified by the designer of the structure. This depends on the quality control measures, but there is no doubt that the quality control adds to the cost of concrete. The extent of quality control is often an economic compromise, and depends on the size and type of job. The cost of labour depends on the workability of mix, e.g., a concrete mix of inadequate workability may result in a high cost of labour to obtain a degree of compaction with available equipment.

I. REQUIREMENTS OF CONCRETE MIX DESIGN

The requirements which form the basis of selection and proportioning of mix ingredients are :

a) The minimum compressive strength required from structural consideration

b) The adequate workability necessary for full compaction with the compacting equipment available.

c) Maximum water-cement ratio and/or maximum cement content to give adequate durability for the particular site conditions

d) Maximum cement content to avoid shrinkage cracking due to temperature cycle in mass concrete.

II. TYPES OF MIXES

2.1. Nominal Mixes

Advertisements In the past the specifications for concrete prescribed the proportions of cement, fine and coarse aggregates. These mixes of fixed cement-aggregate ratio which ensures adequate strength are termed nominal mixes. These offer simplicity and under normal circumstances, have a margin of strength above that specified. However, due to the variability of mix ingredients the nominal concrete for a given workability varies widely in strength.

2.2. Standard mixes

The nominal mixes of fixed cement-aggregate ratio (by volume) vary widely in strength and may result in under- or over-rich mixes. For this reason, the minimum compressive strength has been included in many specifications. These mixes are termed standard mixes. IS 456-2000 has designated the concrete mixes into a number of grades as M10, M15, M20, M25, M30, M35 and M40. In this designation the letter M refers to the mix and the number to the specified 28 day cube strength of mix in N/mm . The mixes of grades M10, M15, M20 and M25 correspond approximately to the mix proportions (1:3:6), (1:2:4), (1:1.5:3) and (1:1:2) respectively.

2.3. Designed Mixes

In these mixes the performance of the concrete is specified by the designer but the mix proportions are determined by the producer of concrete, except that the minimum cement content can be laid down. This is most rational approach to the selection of mix proportions with specific materials in mind possessing more or less unique characteristics. The approach results in the production of concrete with the appropriate properties most economically. However, the designed mix does not serve as a guide since this does not guarantee the correct mix proportions for the prescribed performance. For the concrete with undemanding performance nominal or standard mixes (prescribed in the codes by quantities of dry ingredients per cubic meter and by slump) may be used only for very small jobs, when the 28-day strength of concrete does not exceed 30 N/mm . No control testing is necessary reliance being placed on the masses of the ingredients.

III. FACTORS AFFECTING THE CHOICE OF MIX PROPORTIONS

The various factors affecting the mix design are:

3.1. 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.

3.2. 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.

3.3 . 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.

3.4. 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.

3.5. 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.

3.6. 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.

IV. MIX PROPORTION DESIGNATIONS

The common method of expressing the proportions of ingredients of a concrete mix is in the terms of parts or ratios of cement, fine and coarse aggregates. For e.g., a concrete mix of proportions 1:2:4 means that cement, fine and coarse aggregate are in the ratio 1:2:4 or the mix contains one part of cement, two parts of fine aggregate and four parts of coarse aggregate. The proportions are either by volume or by mass. The water-cement ratio Is usually expressed in mass

4.1 Factors to be considered for mix design

- The grade designation giving the characteristic strength requirement of concrete.

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- The type of cement influences the rate of development of compressive strength of concrete.
- Maximum nominal size of aggregates to be used in concrete may be as large as possible within the limits prescribed by IS 456:2000.
- The cement content is to be limited from shrinkage, cracking and creep.
- The workability of concrete for satisfactory placing and compaction is related to the size and shape of section, quantity and spacing of reinforcement and technique used for transportation, placing and compaction.

V. PROCEDURE FOR MIX DESIGN

1 Determine the mean target strength f from the specified characteristic compressive strength at 28-day f and the level of quality control.

f = f + 1.65 S

where S is the standard deviation obtained from the Table of approximate contents given after the design mix.

2 Obtain the water cement ratio for the desired mean target using the empirical relationship between compressive strength and water cement ratio so chosen is checked against the limiting water cement ratio. The water cement ratio so chosen is checked against the limiting water cement ratio for the requirements of durability given in table and adopts the lower of the two values.

3 Estimate the amount of entrapped air for maximum nominal size of the aggregate from the table.

4. Select the water content, for the required workability and maximum size of aggregates (for aggregates in saturated surface dry condition) from table.

5. Determine the percentage of fine aggregate in total aggregate by absolute volume from table for the concrete using crushed coarse aggregate.

6. Adjust the values of water content and percentage of sand as provided in the table for any difference in workability, water cement ratio, grading of fine aggregate and for rounded aggregate the values are given in table.

7. Calculate the cement content form the water-cement ratio and the final water content as arrived after adjustment. Check the cement against the minimum cement content from the requirements of the durability, and greater of the two values is adopted.

8. From the quantities of water and cement per unit volume of concrete and the percentage of sand already determined in steps 6 and 7 above, calculate the content of coarse and fine aggregates per unit volume of concrete from the following relations:

$$V = \left[W + \frac{C}{S_c} + \frac{1}{p}\frac{f_a}{S_{fa}}\right] \times \frac{1}{1000}$$

$$V = \left[W + \frac{C}{S_c} + \frac{1}{1-p}\frac{C_a}{S_{ca}}\right] \times \frac{1}{1000}$$

where V = absolute volume of concrete

= gross volume (1m) minus the volume of entrapped air

S = specific gravity of cement

W = Mass of water per cubic metre of concrete, kg

C = mass of cement per cubic metre of concrete, kg

p = ratio of fine aggregate to total aggregate by absolute volume

f_a C_a= total masses of fine and coarse aggregates, per cubic metre of concrete, respectively, kg, and

S_{fa} , Sc_a = specific gravities of saturated surface dry fine and coarse aggregates, respectively

9. Determine the concrete mix proportions for the first trial mix.

10. Prepare the concrete using the calculated proportions and cast three cubes of 150 mm size and test them wet after 28-days moist curing and check for the strength.

11. Prepare trial mixes with suitable adjustments till the final mix proportions are arrived at.

VI. MIX METHOD OF ACI , BS , SSA AND HCS

6.1 AMERICAN CONCRETE INSTITUTE (ACI) MIX DESIGN METHOD

Summarizes the steps of the design using the American Concrete Institute mix design method. The method adopts few assumptions as follows;

1. The mix consistency, expressed in either the slump test, VeBe test or the compacting factor, depends solely on the water content regardless of the mix proportions.
2. The optimum ratio of the bulk volume of coarse aggregate per unit volume of concrete depends solely on the nominal maximum size of the coarse aggregate and the fine aggregate grading.
3. The characteristic strength of the concrete mix may be defined using the available degree of control during the production of concrete, the standard deviation and the percentage of defects.
4. The method does not differentiate between different types of hydraulic cements or different types of aggregates.

6.2 BRITISH STANDARD (BS) MIX DESIGN METHOD

Illustrates the steps of the design using the British Standard mix design method. The method adopts few assumptions as follows;

1. The method is applicable to Ordinary Portland cement (type I), Rapid-Hardening Portland cement (type II) and Sulphate Resisting Portland cement (type V).
2. The method differentiates between crushed and uncrushed aggregate since the difference in the behaviour is quite significant. It ignores the grading of the coarse aggregate providing that it satisfies the BS 882-1973. However, it considers the grading of the fine aggregate as it will affect the degree of workability of the concrete mix.
3. The water content in the concrete mix is affected solely by the required degree of workability, expressed in either the slump test or VeBe test, for a particular nominal maximum size of the particular type of coarse aggregate, regardless of the mix proportions.
4. The optimum ratio of the bulk volume of coarse aggregate per unit volume of concrete depends on the nominal maximum size of the coarse aggregate and the grading of the fine aggregate.
5. The characteristic strength of the concrete mix may be defined using the available degree of control during the production of concrete, the coefficient of variation and the percentage of defects.

6. The method adopts a hypothetical concrete mix with moderate cement content with w/c ratio of 0.5, well compacted, properly cured, cast with different types of cement and coarse aggregate and tested at different ages. The optimum water/cement ratio may be defined using this hypothetical concrete mix and the characteristic strength of the concrete mix.

6.3. SPECIFIC SURFACE AREA (SSA) MIX DESIGN METHOD

The Specific Surface Area method is referred to as Ain-Shams University mix design method the steps of the design using the Specific Surface Area mix design method. The method adopts few assumptions as follows;

1. The compressive strength of the concrete mix depends on the specific surface area of the combined aggregate for a given cement content and degree of workability. The range at which the optimum compressive strength is achieved ranges between 22-26 cm^2/gm, the higher the cement in the mix, the lower the optimum specific surface area.

2. The water content is directly related to the specific surface area of the combined aggregate for a given cement content and degree of workability.

3. Although the experimental basis of the method was carried out using ordinary portland cement, it assumes that the relation in not sensitive to the type of cement.

4. The method is applicable to any type of coarse and fine aggregates providing that the shape factor can be easily calculated as the ratio between the percentage of voids in loose and fully compacted aggregate.

5. The degree of workability was defined in loose terms such as low, medium and high workability and was not related to any of the standard tests.

6.4 . HIGH-STRENGTH CONCRETE (HSC) MIX DESIGN METHOD

shows the steps of the design using the High-Strength Concrete mix design method[9]. The method adopts few assumptions as follows;

1. The method uses irregular gravel or crushed granite with two nominal maximum sizes and natural sand at a fixed mixing ratio of 30% sand in the combined aggregate. It assumes that choosing suitable mix proportions and aggregate with high ceiling of strength will achieve high strength concrete.

2. The required mix is defined with a reference number that is defined using the characteristic strength, the cement type, the type of coarse aggregate and the age of the concrete at which the strength is required.

3. The water/cement ratio depends on the characteristic strength of the mix, the cement type, the aggregate type and the required degree of workability that is well defined using either the slump cone test or the compacting factor.

4. The aggregate-to-cement ratio depends on the same factors as the water/cement ratio and the nominal maximum size of the aggregate and the water/cement ratio. Although aggregate-to-cement ratio is of secondary influence on the concrete strength, it was noted that the leaner the concrete mix the higher the strength.

5. Similar to the BS mix design method, the characteristic strength of the concrete mix may be defined using the degree of control available during the production of concrete, the coefficient of variation and the percentage of defects.

VII. CRITICAL COMPARISON BETWEEN CONCRETE MIXES

The results, presented in Table 2, may lead to the following remarks;

1. The ACI mix design method produced a mix with fine aggregate-to-cement ratio of 1:1. It may be regarded as coarse aggregate bonded together with rich mortar. The design proportions had led to the minimum water/cement ratio thus confirming to the stiff mix requirements. Since, the mix design method accounted for the air entrapped voids, it had led to the lowest wet density. Yet, it was still within acceptable limits.

2. The BS mix design method produced a mix with the lowest cement content. This implies that it would be the most economic mix. Yet, the method resulted in the highest water content. Thus it is expected to produce the highest workability. The method resulted in the highest density suggesting that it will possess sufficient strength and durability.

3. The SSA mix design method produced a mix with moderate proportions and was pretty much similar to the BS mix. Yet, it was the easiest mix design method since it needs very limited computational efforts. The method produced the highest coarse aggregate content due to the specific surface area requirements of the combined aggregate.

4. The HSC mix design method resulted in a mix that is pretty much similar to the ACI mix. Yet, it is the richest mix implying that it is an uneconomic design. Special care should be taken to reduce the effect of shrinkage due to the high cement content. As was expected, the mix produced the highest wet density suggesting higher strength.

VIII. CONCLUSION

The concrete mix design is an art and is not an automatic procedure. It requires a lot of experience knowledge about the ingredients and the methods of mixing, placing, compaction, curing, ...etc. As a rule, the concrete properties depend on the properties of its ingredients. The more information the designer engineer knows about the ingredients and their properties, the more accurate the concrete mix “design” would be. The report leads to the following conclusions:

1. All the concrete mix design methods seemed to be just an intelligent guess about the relative share of the concrete constituents in the mix. This may be due to the variation in the interpretation of the ingredients’ properties among the methods, especially the aggregate and the different assumptions implied in each mix design method. Thus, it was expected that the design reached by each method would differ from the others.

2. Concrete mix design is not a theoretical process and can not be 100% automated. A comprehensive computer code “CONMIX” was built to carry out the design by means of four different methods. It may be used to facilitate the mathematical computations that is required in the design process. The computer code may help in the design process by trying different scenarios and speeding up the calculations. However, the engineering sense and experience were essential in understanding the design.

3. It was obvious from "CONMIX" results that each mix design method gave concrete properties substantially different from the other methods. Yet, the target strength, the required workability and all the concrete main input properties were kept constant. This may be due to the different assumptions implied in each mix design method.

4. The experimental results of the fresh concrete, for all the mix design methods, were in excellent agreement with the required workability. This may be due to the well-defined degree of workability in "most" methods.

5. All the four mixes had led to a higher 28-days strength than what was expected. The mean strength of the concrete mix should be higher than the minimum strength. In addition, this may be due to the vigorous quality control, good compacting and optimum curing that was easily achieved in a laboratory environment and on the small batches used for each mix.

6. The results from this small verification study can not be generalized unless a comprehensive experimental program is carried out to check different strength requirements at different degrees of workability. The designer engineer is advised to exercise good care when using any of the mix design methods and to use their results only after checking them with trial mixes. Trial mixes and successive adjustment to the concrete mix were essential in any concrete mix design. They are the only accurate and available way to achieve the desired concrete mix although it seems to be a non-scientific design.

7. The durability requirements were ignored in all methods except in the ACI method that specified a certain percentage of air entrained voids for air-entrained concrete. The report had dealt with the concrete mix design from the point of view that concrete with adequate strength would be durable enough under normal conditions of exposure. Durability is vital in hardened concrete subjected to any of the common deterioration problems. It is advised to develop an expert system based on the recommendations of the ***ACI Guide to Durable Concrete*** to help the designer engineer speed up the design process based on durability and strength requirements.

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