

ACI METHOD OF CONCRETE MIX DESIGN: A PARAMETRIC STUDY

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ABSTRACT: Concrete mix design by the ACI method requires various material properties as the input. The effect of variation of these input parameters on mix proportions has been studied here, with reference to strength attainment in few cases. The sensitivity of the mix has been expressed by volume ratios of fine aggregate to coarse aggregate and cement to fine aggregate. It is found that inter-particle voids of coarse aggregates, a function of gradation, plays a significant role in the prediction of mix proportions. The study reveals that ACI method fails to rationally predict the proportion of the ingredients when coarse aggregates of higher voids is used in making the concrete. In such cases, the amount of fine aggregate is over estimated. This over estimation leads to a higher surface area to be covered by the same amount of cement, which is determined without any reference to aggregate grading. As a result, the mix fails to attain the design strength. Test results have confirmed these findings.

KEYWORDS: Concrete, mix design, ACI method, fine aggregate/coarse aggregate ratio, cement/fine aggregate ratio, void ratio

1. INTRODUCTION

Concrete is one of the most widely used construction materials throughout the world. Many desirable properties such as high compressive strength, excellent durability and fire resistance contributed toward its wide range of applicability. The most advantageous and unique feature of concrete is that it can be produced using locally available ingredients as aggregates. Therefore, in countries where steel is not readily available, as in Bangladesh, concrete is the most used construction material. However the advantage of using local materials as concrete ingredients has its own demerits as well. Because of the variations in properties of locally available aggregates, the properties of concrete may vary widely. Although plant mixed concrete is gaining popularity day by day, and in many big projects concrete is produced in a centrally located plant, in small projects concrete is still produced and laid in the field. This calls for the proper selection of the concrete ingredients and their relative proportions in a concrete mix. The proportioning of ingredients in a concrete mix to achieve a target property (often strength) is known as the concrete mix design.

Different methods are available to design a normal concrete mix for a given strength under various weather and workability conditions. Among the various methods in use, the method proposed by the American Concrete Institute (ACI) [1] is probably the most popular one. However, some recent experiences and subsequent studies made at the Bangladesh University of Engineering and Technology (BUET) have revealed that the ACI method of mix design fails to predict the relative ratio of fine and coarse aggregates for some cases. In such cases the designed mixes fail to attain design strength. A parametric study has been carried out by the authors to look into the matter. This paper deals with the outcome of the parametric study.

2. ACI METHOD OF NORMAL CONCRETE MIX DESIGN

ACI suggests concrete mix design processes for both air-entrained and non-air-entrained concrete. Both the methods are based on the following principles:

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1. The workability of the mix depends on the water content and the maximum size of aggregates.
2. The water-cement ratio (w/c ratio) is solely dependent upon the design strength with a restriction from the durability point of view. The w/c ratio is inversely proportional to the design strength.
3. The bulk volume of coarse aggregate per unit volume of concrete depends on the maximum size of the coarse aggregate and the grading of the fine aggregate, expressed as the fineness modulus.

The design starts with the selection of water content for a given maximum size of coarse aggregate and workability required for the type of work, with workability being expressed by slump. Cement content is then found out simply from this water content and the w/c ratio, determined earlier on the basis of the design strength. The volume of coarse aggregate is then determined as per 3, and fine aggregate content is found out by subtracting the volume (or weight) of other ingredients from the total volume (or weight) of concrete. The weight basis is a trial and error approach while the volume basis is more direct and gives a more accurate result.

3. PAST STUDIES AT BUET

Earlier studies made at BUET have revealed that there are cases where the ACI mix design philosophy fails in proportioning the relative ratio of coarse and fine aggregates for a particular amount of cement content. In such cases, the designed mix fails to attain the desired strength [2,3]. In this context, a careful observation shows that in the ACI method, cement content determination process is not directly related to aggregate gradation. But in reality, the binding action of the hydrated cement paste always takes place on the surface of the aggregate particles. Again, so far as the aggregate surface area is concerned, fine aggregate is the major contributor. Therefore, the quantity of fine aggregate is essential to the determination of the cement content. In this course, the earlier communication by the authors [2] has reported that ACI method gives higher proportion of fine aggregate for the cases where coarse aggregates of lower unit weights are to be used. However, unit weight of a particular coarse aggregate is closely related to the inter-particle voids, which depends on the gradation of the coarse aggregate particles. Hence a further look at the initial findings revealed some more interesting points. The inter-particle void has been found to have a governing role on mix proportion prediction in the ACI method, which has not been duly considered in the method [3].

4. PARAMETRIC STUDY

4.1 Choice of the Parameters

The ACI method requires in total seven input parameters to design a non-air-entrained normal concrete mix. These are: coarse aggregate unit weight, design compressive strength, fine aggregate specific gravity, coarse aggregate specific gravity, fine aggregate fineness modulus, coarse aggregate maximum size and slump.

Specific gravity has been defined as the ratio of mass (or weight in air) of a unit volume of material to the mass (or weight) of same volume of water at a specified temperature. However, as the aggregate contains pores, both permeable and impermeable, specific gravity term may have different meanings. The apparent specific gravity (ρ) refers to the volume of solid material including the impermeable pores, but not the capillary ones. It is defined as the ratio of the weight of the aggregate particle (oven-dried at 100°C to 110°C for 24 hours) to the weight of water occupying the volume equal to that of the solid including the impermeable pores. This specific gravity has to be multiplied by the unit weight of water (γ_w , approximately 1000 kg/m³) in order to convert it into absolute density. However it must be noted that this absolute density refers to the volume of individual particles only, and it is not physically possible to pack these particles such that there are no voids. This is where the unit weight (or bulk density, γ) comes into action. It is defined as the weight of the aggregate as a whole per unit volume, the volume including all void spaces within the aggregate particles. The relation between apparent specific gravity, unit weight and void ratio can be expressed by the following:

$$\text{Void ratio} = 1 - \gamma / (\rho \gamma_w) \quad (1)$$

It is evident from Equation 1 that the unit weight and specific gravity of the coarse aggregate can be replaced by the void ratio of the coarse aggregate and either of unit weight or specific gravity of the same. The authors opt for void ratio and unit weight of the coarse aggregate. The effect of the variation of input parameters on the weight ratios of fine aggregate to coarse aggregate and cement to total aggregate has been investigated earlier [3].

A closer look into the mix design procedure reveals that, of the seven parameters, only five are directly used to determine the volume of the ingredients. Coarse aggregate unit weight and fine aggregate specific gravity have only the function of merely converting the quantities from volume basis to weight basis. This leaves five basic input parameters to work with: workability expressed as slump, fineness of fine aggregate expressed as fineness modulus, design strength, void ratio of coarse aggregates and maximum aggregate size. The sensitivity of the mix design output is therefore expressed in volume ratio instead of previously used weight ratio to avoid the effect of specific gravity and unit weight of aggregates. This is a more logical approach because, as long as the aggregate is strong enough to withstand the loads, the weight of the aggregate is not a concern to the designer, unless from construction and transportation point of view. Moreover, the binding action of cement on aggregates depends on the surface area of the aggregates, and the total surface area is more a function of the volume and fineness rather than weight and fineness of the aggregates. Again the fine aggregate, because of its higher specific surface as compared to the coarse aggregate, is the major contributor to the surface area to be covered by cement. Therefore, the ratio of cement to fine aggregate has been chosen as an output parameter to study the effect of variation of the basic input parameters.

4.2 Study Methodology

In the parametric study, the void ratio of coarse aggregate has been varied within a range while keeping all other input parameters constant (Table 1). The effect of this variation on the ratio of fine aggregate to coarse aggregate and cement to fine aggregate has been investigated. Figures 1, 3, 5 and 7 graphically present the effect of these variations on fine aggregate/coarse aggregate ratio whereas, Figures 2, 4, 6 and 8 illustrate those effects on the cement/fine aggregate ratio. All the ratios are on volume basis.

Table 1. ACI mix design parameters, variation ranges and assigned values

Sl. No.	Mix design parameters	Unit	Variation range	Assigned value
1	Void ratio of coarse aggregate	-	0.1 – 0.5	-
2	Design strength	Mpa	13.8 – 34.5	27.6
3	Fineness modulus of fine aggregate	-	1.75 - 3.00	2.4
4	Maximum size of coarse aggregate	Mm	10 – 75	40
5	Slump	Mm	25 – 150	50

4.3 Study Findings

A look into the parametric study curves shows that, the volumetric proportion of the fine aggregates increases with respect to that of the coarse aggregates, when the void ratio of the coarse aggregates increases. The corresponding cement/fine aggregate ratio decreases with the increase in the voids in coarse aggregates.

It is very logical that the fine aggregate/coarse aggregate ratio increases with increasing voids in the coarse aggregate, as the voids in the coarse aggregates have to be filled up by the fine aggregates. However, the increase in the fine aggregate content greatly increases the total surface area of the aggregates, because fine aggregates have a higher specific surface than the coarse aggregates. As the binding action of cement takes place on the aggregate surface, this increase in total, specially fine

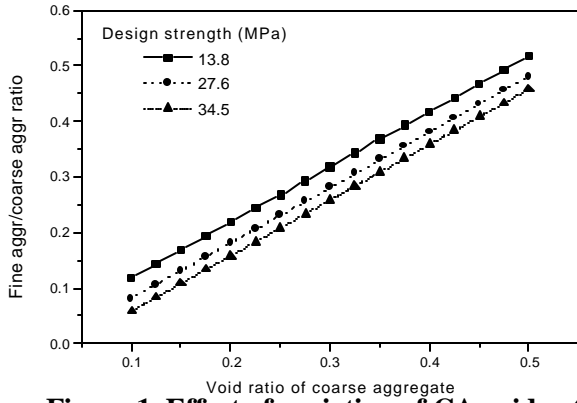


Figure 1. Effect of variation of CA void ratio and design strength on FA/CA ratio

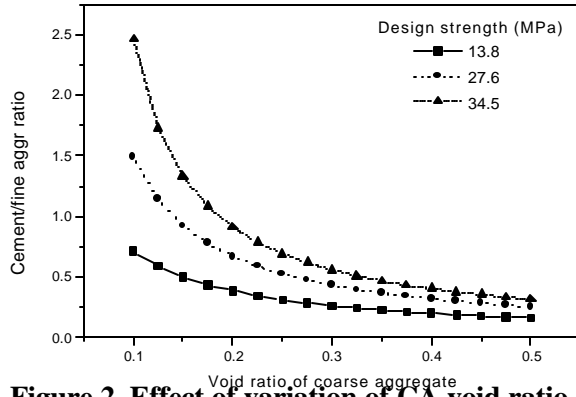


Figure 2. Effect of variation of CA void ratio and design strength on cement/FA ratio

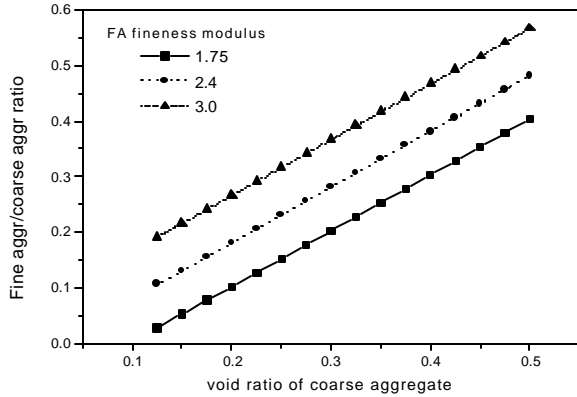


Figure 3. Effect of variation of CA void ratio and FA fineness modulus on CA/FA ratio

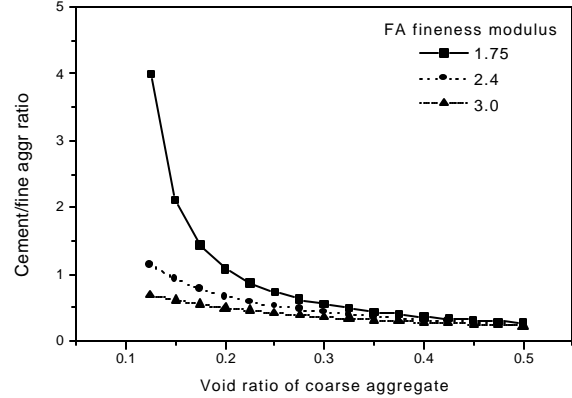


Figure 4. Effect of variation of CA void ratio and FA fineness modulus on cement/FA ratio

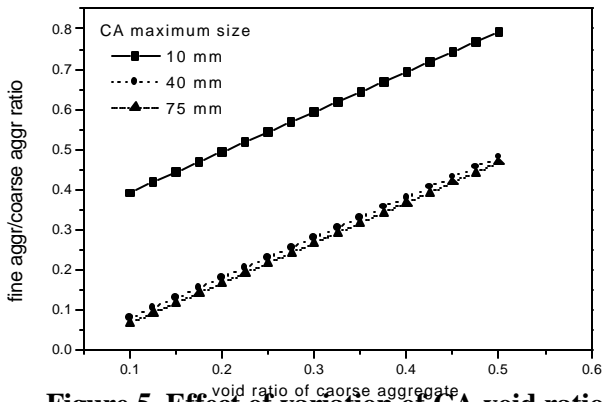


Figure 5. Effect of variation of CA void ratio and CA maximum size on FA/CA ratio

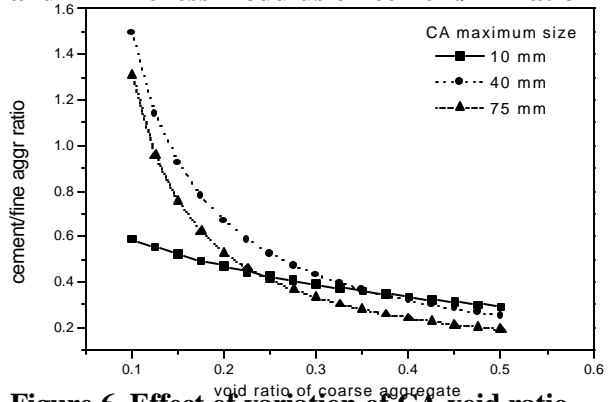


Figure 6. Effect of variation of CA void ratio and CA maximum size on cement/FA ratio

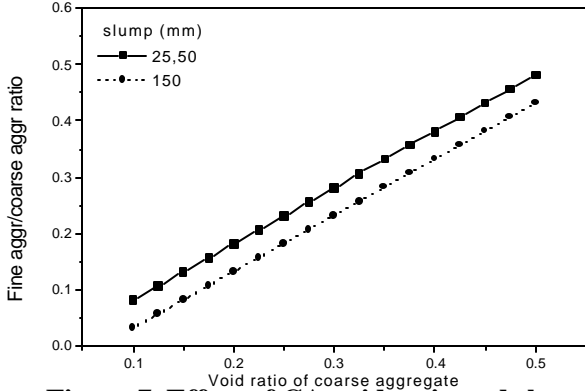


Figure 7. Effect of CA void ratio and slump on FA/CA ratio

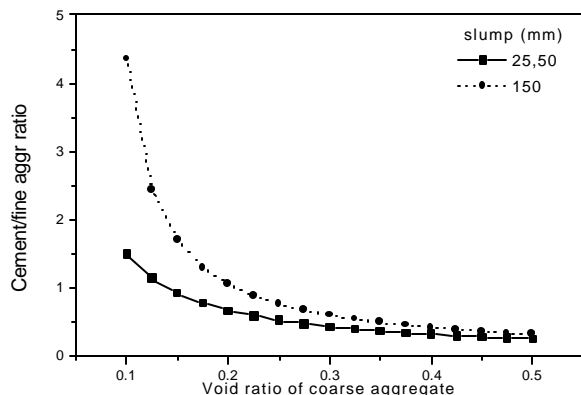


Figure 8. Effect of CA void ratio and slump on cement/FA ratio

aggregate, surface area would require a higher amount of cement. On the contrary, according to ACI, the cement/fine aggregate ratio decreases! This is because, the cement content is determined early, solely on the basis of design strength, before any consideration is given to the properties of aggregates.

On the brighter side, as long as the void ratio of the coarse aggregate is constant, the ACI method suggests a rational design. For example, a higher fineness modulus means a coarser fine aggregate, which leads to a smaller total surface area, requiring a lower cement/fine aggregate ratio. This is clearly depicted in Figure 4, where the cement/fine aggregate ratio curve for a higher fineness modulus always lies below that for a lower fineness modulus. Again, for a given void ratio of the coarse aggregate and fine aggregate/coarse aggregate ratio, the cement/fine aggregate ratio should be higher to achieve a high slump mix, which is confirmed by Figure 8. Therefore, the study reveals that the ACI method fails to cater for the increase of fine aggregate/coarse aggregate ratio with increase in voids in the coarse aggregate, with consequent decrease in the cement/fine aggregate ratio.

5. EXPERIMENTAL FINDINGS

Crushed brick, an indigenous material, is widely used as coarse aggregates in Bangladesh because of scarcity of natural stone aggregates. To have a comparative idea involving different types of aggregate, both crushed brick and crushed stone have been used as coarse aggregates for various mixes. Eleven such mixes have been designed following the ACI method. Trial mixes have been cast in the laboratory following the standard ASTM procedures [4]. In addition, two other mixes have been cast with some readjustment in the fine aggregate content of mixes 3 and 6. In these two mixes the fine aggregate content has been arbitrarily reduced by 50% from that found by the ACI method. Significant material properties and the mix proportions are shown in Table 2.

Table 2. Properties of aggregates and mix proportions

Mixes	Properties of aggregates					Proportion of ingredients in the mix by ACI				
	Type	Unit wt. (SSD), kg/m ³	Specific gravity (SSD)	Void ratio %	Fineness modulus	Design strength (MPa)	Cem. kg/m ³	FA kg/m ³	CA kg/m ³	Water kg/m ³
Mix 1*	Brick	1145	2.08	44.91	6.88	27.6	312	900	774	180
	Sand	1522	2.68	-	2.74					
Mix 2*	Brick	1185	1.95	39.18	6.90	27.6	312	713	854	180
	Sand	1522	2.64	-	2.30					
Mix 3*	Brick	1185	1.95	39.18	6.90	20.7	262	756	854	180
	Sand	1522	2.64	-	2.30					
Mix 4*	Brick	1009	1.92	47.42	7.13	20.7	262	1009	702	180
	Sand	1466	2.82	-	2.54					
Mix 5*	Stone	1778	2.27	21.64	6.97	20.7	262	467	1263	180
	Sand	1458	2.79	-	2.40					
Mix 6*	Stone	1470	2.30	36.07	6.93	20.7	262	786	1023	180
	Sand	1466	2.82	-	2.54					
Mix 7*	Brick	1214	2.19	44.53	6.77	20.7	262	994	819	180
	Sand	1493	2.84	-	2.77					
Mix 8*	Stone	1634	2.67	38.8	7.46	20.7	262	887	1098	180
	Sand	1493	2.84	-	2.77					
Mix 9 [#]	Brick	1356	1.85	26.67	-	27.6	328	575	869	187
	Sand	1537	2.63	-	2.59					
Mix 10 [#]	Brick	1315	1.85	28.85	-	27.6	328	612	843	187
	Sand	1537	2.63	-	2.59					
Mix 11 [#]	Brick	1283	1.85	30.6	-	27.6	328	641	822	187
	Sand	1537	2.63	-	2.59					

* maximum aggregate size 20 mm

maximum aggregate size 25 mm

The strength attainment features of all the mixes are summarized in Table 3. Tables 2 and 3 show that the mixes having a higher void in the coarse aggregate results in a higher fine aggregate content. This is similar to the theoretical predictions of the parametric study. All the mixes having a considerably higher void in the coarse aggregate have failed to attain the 28-day design strength. The readjusted mixes (Mix 3a and Mix 6a) with lower fine aggregate content and thus lower surface area show much better performance than their parent mixes, very nearly attaining the design strength.

Table3. Performance of the trial mixes

Mixes	Cement: FA: CA (by wt)	% of design strength	
		7 days	28 days
ACI mix			
Mix 1	1 : 2.9 : 2.5	44.50	67.00
Mix 2	1 : 2.3 : 2.7	51.50	73.25
Mix 3	1 : 2.9 : 3.3	33.83	62.10
Mix 4	1 : 3.9 : 2.7	39.33	64.00
Mix 5	1 : 1.8 : 4.8	75.00	105.33
Mix 6	1 : 3.0 : 3.9	50.33	64.67
Mix 7	1 : 3.8 : 3.1	47.67	72.80
Mix 8	1 : 3.4 : 4.2	43.23	66.37
Mix 9	1 : 1.8 : 2.7	81.20	110.25
Mix10	1 : 1.9 : 2.6	72.62	104.65
Mix 11	1 : 2.0 : 2.5	73.94	93.09
Readjusted mix			
Mix 3a	1 : 1.5 : 3.3	72.67	97.33
Mix 6a	1 : 1.5 : 3.9	73.33	97.67

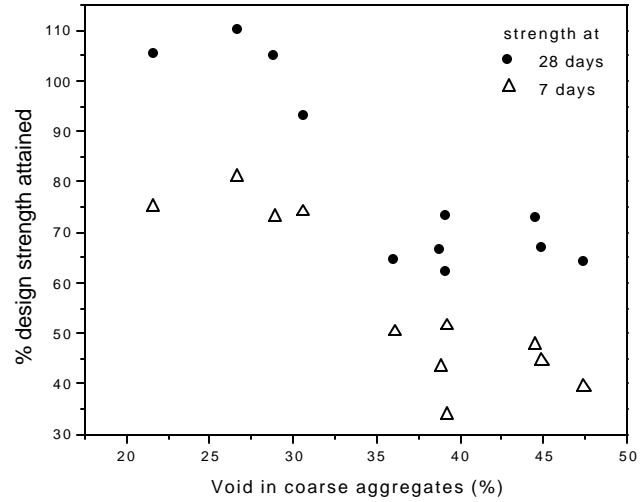


Figure 9. Effect of void ratio of coarse aggregate on strength attainment of cylinder specimens

A more interesting representation of the experimental results is Figure 9, showing the relation between void ratio of coarse aggregates and percent strength attainment. The scatter plot clearly shows that the percent design strength attainment varies inversely with the void ratio of the coarse aggregate.

6. CONCLUSION

Inter-particle voids, a function of the coarse aggregate grading, is an important parameter in the mix design. The ACI method has no adequate parameter to take this aspect into account. This leads to higher fine aggregate content, with consequent increase in the surface area of aggregates, when coarse aggregates of higher voids are used. In addition, the cement content is determined even before the consideration of any aggregate type, resulting in a lower cement/fine aggregate ratio. This is why mixes designed by the ACI method fail to gain desired strength, when coarse aggregates of higher voids are used. Further research is being carried out at BUET to see what modifications can be suggested in the ACI method regarding voids or gradation of coarse aggregates.

7. REFERENCES

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