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Voids in coarse aggregates: An aspect overlooked in the ACI method of concrete mix design

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ABSTRACT: The effect of different ACI normal concrete mix design parameters in predicting mix proportions and strength attainment has been studied. The parametric study reveals that the inter-particle voids, a function of gradation, in the coarse aggregate plays a significant role in mix proportion prediction. However, the ACI design method has failed to properly address this aspect. This gives unrealistic mix proportions when coarse aggregates of high void ratio is used. In this case, the amount of fine aggregate becomes very high with an increased surface area to be covered by the constant amount of cement. The strength attainment of such mixes should be very poor. The hardened strengths of trial mixes have substantiated this fact.

1 INTRODUCTION

Concrete is a ubiquitous and versatile construction material. Different desirable properties of concrete make it a widely used material for civil engineering constructions throughout the world, specially in the developing countries. Also, the flexibility of using locally available ingredients as the aggregates to produce concrete of required properties makes concrete unique among other construction materials. Although plant mixed concrete is rapidly gaining popularity in the developed countries, concrete in the developing countries is still produced and laid at the field. This calls for proper selection of concrete ingredients and their proportions in the mix design.

Among the different methods available to design a normal concrete mix for a given strength under various weather and workability conditions, American Concrete Institute method (ACI 1996) is one of the most popular ones. The method is based on the following principles:

1. Water content determines the workability for a given maximum size of coarse aggregate.
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 a water content for a given maximum size of coarse aggregate. Cement content is then found out simply from this water content and the w/c ratio, which depends on 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.

However, some recent experiences and subsequent comprehensive studies made at the Bangladesh University of Engineering and Technology (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. In this context, a careful observation shows that in the ACI method, cement content determination process is not directly related with aggregate gradation. But in reality, the binding action of the hydrated cement paste takes place mostly 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 (Amin et al. 1999) reported that ACI method suggests for higher proportion of fine aggregate for the cases where coarse aggregates of lower unit weights are to be used. However, unit weight

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	Unit weight (SSD) of coarse aggregate	kg/m^3	800 – 1900	1200
3	Design strength	Mpa	13.8 – 34.5	27.6
4	Specific gravity (SSD) of fine aggregate	-	2.25 - 3.00	2.65
5	Fineness modulus of fine aggregate	-	1.75 - 3.00	2.4
6	Maximum size of coarse aggregate	Mm	10 – 75	40
7	Slump	Mm	25 – 150	50

of the coarse aggregate is closely related to the inter-particle voids, which depends on the gradation of the coarse aggregate particles. Hence a further but closer look at the initial findings revealed some more interesting conclusion. The inter-particle void has been found to have a governing role on mix proportion prediction in the ACI method, but it has not been duly addressed in the method. The present paper deals with such conclusion together with the experimental substantiation.

2 PARAMETRIC STUDY

2.1 Study methodology

The ACI method of mix design requires in total seven 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 *absolute* specific gravity refers to the volume of the solid material excluding all pores, while the *apparent* specific gravity (ρ) refers to the volume of solid material including the impermeable pores, but not the capillary ones. It is the *apparent* specific gravity that is normally used in concrete technology. 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/m^3) in order to be converted into absolute density. However it must be carefully 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 between them. 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 between the aggregate particles. The relation between *apparent* specific gravity, unit weight and void ratio can be expressed by the following:

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

Here it should be noted that the total void content in a mass of unit volume of coarse aggregate can be equated as follows:

Total void content = Permeable pores + Impermeable pores + Inter-particle voids (2)

However the proportion of permeable and impermeable pores is much lower than the inter-particle voids. In this paper the authors focus on the inter-particle voids. Therefore, the void ratio, as in Equation 1, refers to the inter-particle voids of the coarse aggregate. 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 void ratio has been varied within a selected range, all others being assigned a constant value (Table 1). The effect of this variation on the ratios of fine aggregate to coarse aggregate and cement to aggregate has been investigated. Figures 1, 3, 5, 7, 9 and 11 graphically present the effect of these variations on fine aggregate/coarse aggregate ratio whereas, Figures 2, 4, 6, 8, 10 and 12 illustrate those effects on the cement/aggregate ratio. All these quantities are on weight basis.

2.2 Study Findings

An inspection of the parametric study curves reveals that, with the increase of void ratio in the coarse aggregates, the proportion of the fine aggregate increases in comparison to the coarse aggregate. This increase in the fine aggregate greatly increases the total surface area of the aggregates. As the binding action of cement takes place on the aggregate surface, this increase in total surface area would have required a larger amount of cement, i.e. an increased cement aggregate ratio is expected in a rational design. However, the cement content remains the same in the ACI method of mix design irrespective of the increase in surface area, which leads to a lower cement/aggregate ratio, as depicted in all

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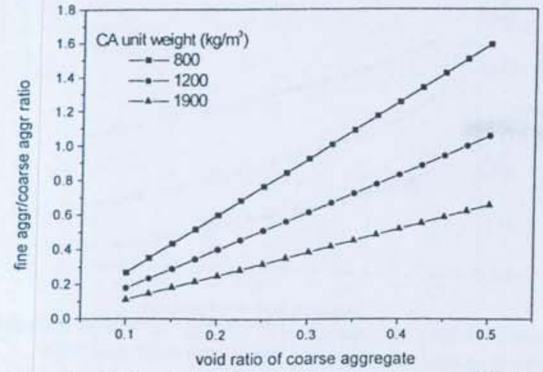

Figure 1. Effect of variation of coarse aggregate void ratio and coarse aggregate unit weight on fine aggr./coarse aggr. ratio

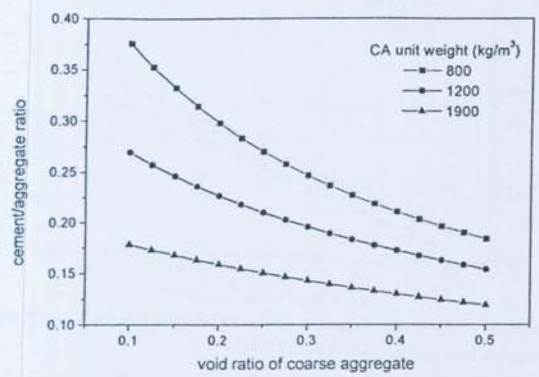

Figure 2. Effect of variation of coarse aggregate void ratio and coarse aggregate unit weight on cement/aggregate ratio

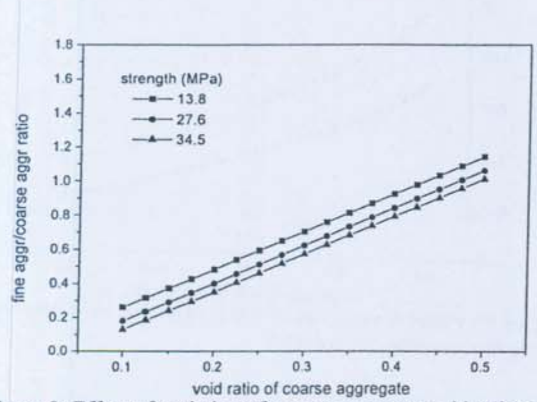

Figure 3. Effect of variation of coarse aggregate void ratio and design strength on fine aggr./coarse aggr. ratio

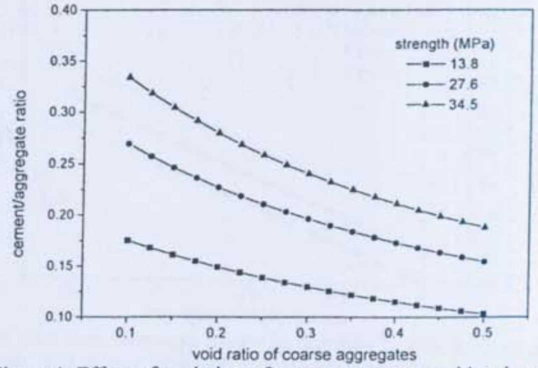

Figure 4. Effect of variation of coarse aggregate void ratio and design strength on cement/aggregate ratio

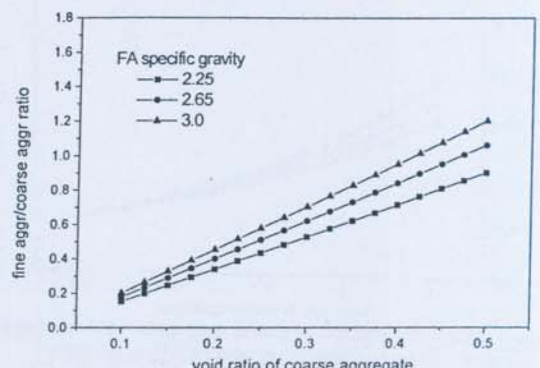

Figure 5. Effect of variation of coarse aggregate void ratio and fine aggregate specific gravity on fine aggr./coarse aggr. ratio

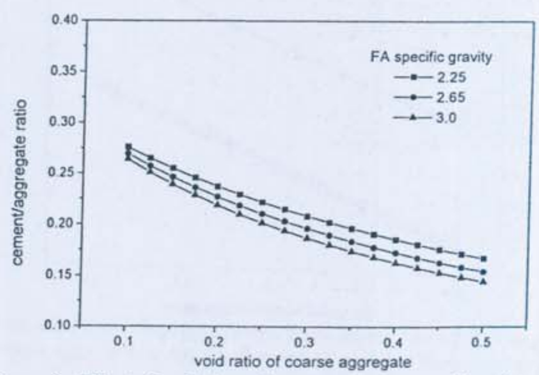

Figure 6. Effect of variation of coarse aggregate void ratio and fine aggregate specific gravity on cement/aggregate ratio

cases of right hand side figures. The situation worsens further when the fineness modulus or specific gravity of the fine aggregates varies, which is explained by the sharper slope of the curves.

However, at a given void ratio of the coarse aggregate, the ACI method suggests a rational design. For example, a higher fineness modulus means a smaller total surface area, requiring a smaller cement/aggregate ratio. This is clearly depicted in Figures 7 and 8, where the cement/aggregate ratio curve for a higher fineness modulus always lies below that for a lower fineness modulus. Similarly at a constant void ratio and fine aggregate/coarse aggregate ratio, it is expected that the cement/aggregate ratio will be higher to achieve a high slump mix, evident from Figures 11 and 12. Therefore the study reveals that the ACI method fails to explain the increase of fine aggregate/coarse aggregate ratio with increase in voids in the coarse aggregate, with consequent decrease in the cement/aggregate ratio.

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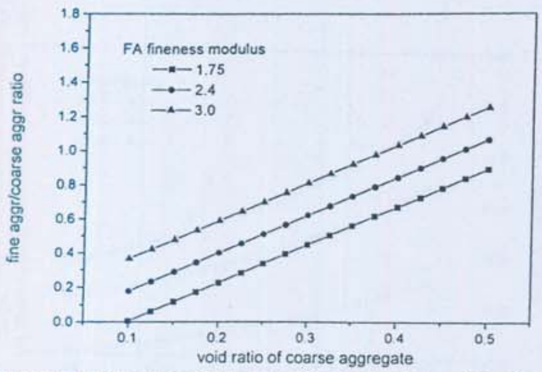

Figure 7. Effect of variation of coarse aggregate void ratio and fine aggregate fineness modulus on fine aggr./coarse aggr. ratio

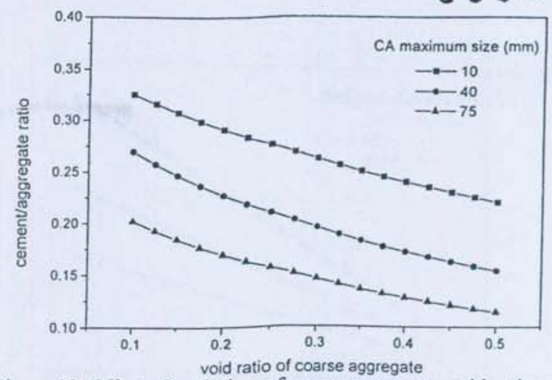

Figure 10. Effect of variation of coarse aggregate void ratio and coarse aggregate maximum size on cement/aggregate ratio

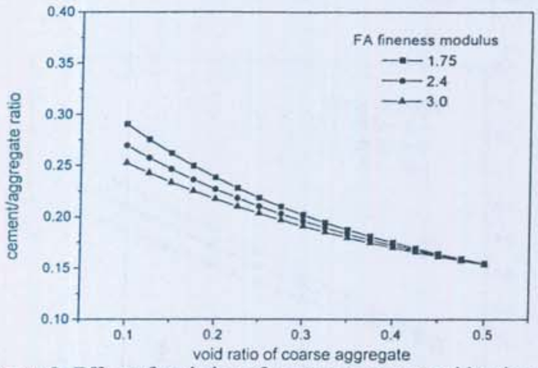

Figure 8. Effect of variation of coarse aggregate void ratio and fine aggregate fineness modulus on cement/aggregate ratio

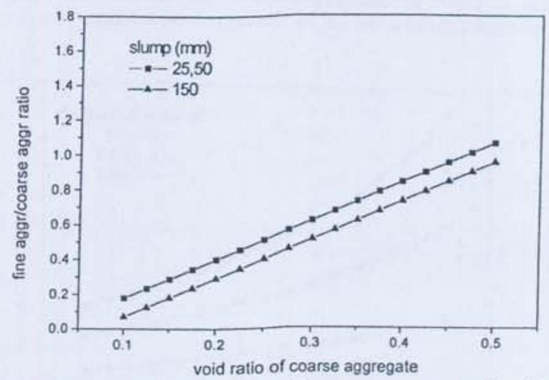

Figure 11. Effect of variation of coarse aggregate void ratio and slump on fine aggr./coarse aggr. ratio

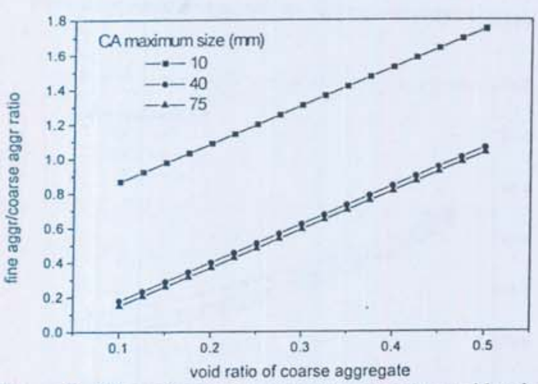

Figure 9. Effect of variation of coarse aggregate void ratio and coarse aggregate maximum size on fine aggr./coarse aggr. ratio

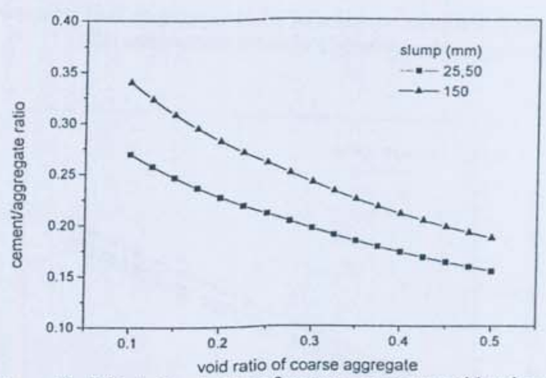

Figure 12. Effect of variation of coarse aggregate void ratio and slump on cement/aggregate ratio

3 EXPERIMENTAL DETAILS

Eight different mixes were designed following the ACI method with a view to substantiate the findings of the parametric study. With these designs at hand, trial mixes were cast in the laboratory following standard ASTM procedures. Apart from these regular trial mixes, two mixes (Mix 3 and Mix 6) were also cast with some readjustment in the proportioning of the mix. The fine aggregate content was arbitrarily reduced by 50% in these cases, as it was found that higher voids of coarse aggregate led to higher fine aggregate content and failed to produce the design strength. The mix design, casting, curing, and testing procedure of cylindrical concrete specimens are presented in the following subsections.

3.1 Materials

In Bangladesh, crushed brick, an indigenous material, is widely used as coarse aggregates because of scarcity of natural stone aggregates. Locally produced brick can attain a compressive strength as high as 35 MPa, with the most commonly found one ranging from 17 to 24 MPa. Earlier studies on brick aggregate concrete (Akhtaruzzaman & Hasnat 1983) revealed that the modulus of elasticity of brick aggregate concrete is 30% lower and the tensile strength 11% higher than the same grade of stone aggregate concrete. The unit weight of brick aggregate concrete is also lower because of the lower unit weight of the brick aggregate and is around 1900 kg/m^3. Because of the high absorption capacity of brick aggregate, the concrete prepared from this has also a high absorption capacity (greater than 10%).

To have a comparative idea involving different types of aggregates, in the present study, both crushed brick and crushed stone were used as coarse aggregates for different mixes. To ensure strength, brick aggregates were produced from well-burnt clay bricks (locally known as *picked jhama* bricks). Local riverbed sand of different gradations were used as fine aggregates. Ordinary Portland Cement (ASTM Type I) was used as the binder. Normal potable water was used for mixing.

Material properties required to design the concrete mix, such as specific gravity, unit weight, fineness modulus and absorption capacity of both fine and coarse aggregates were determined following standard ASTM procedures (1988). These properties are reproduced in Table 2.

3.2 Mix design

Mixes were designed according to ACI method for normal non-air entrained concrete for different strengths with a slump of 50 mm for all of those. The proportions of various ingredients thus obtained are presented in Table 3.

3.3 Preparation of cylinder specimen

On the basis of the design, required quantities of the materials were weighed on SSD weight basis. The coarse aggregate, fine aggregate and cement were mixed thoroughly and continuously in the mixing machine with the required amount of water added gradually until a uniform concrete mix was produced. The slump was checked following standard cone method.

After the mixing was complete, the fresh concrete was placed in reusable cylindrical moulds. Concrete compaction was done by a mechanical vibrator in two layers.

3.4 Curing

After the casting was complete, the cylinders were stored in moulds for 24 hours in moist condition at room temperature. The moulds were then removed and concrete cylinders immersed in saturated lime-water at room temperature for curing. Curing was done continuously until the specimens were removed for strength tests at different durations.

3.5 Testing

Specimens of all the batches were tested for compressive strength at the age of 7 days and 28 days. All of the cylinders were tested in a moist condition. The top surface of the cylinders were capped with sulfur mortar in accordance with standard specification, in order to ensure a uniform stress distribution. Dimensions of the specimens were recorded. The cylinders were then crushed in a Universal Testing

Table 2. Properties of aggregates

Mixes	Aggregates	Unit weight (SSD), kg/m^3	Specific gravity (SSD)	Specific gravity (OD)	Void ratio, %	Absorption capacity, %	Fineness modulus
Mix 1	Brick chips	1145	2.08	1.83	44.91	13.66	6.88
	Sand	1522	2.68	2.66	-	0.75	2.74
Mixes 2 & 3	Brick chips	1185	1.95	1.70	39.18	21.95	6.90
	Sand	1522	2.64	2.60	-	1.54	2.30
Mix 4	Brick chips	1009	1.92	1.69	47.42	13.61	7.13
	Sand	1466	2.82	2.80	-	0.71	2.54
Mix 5	Stone chips	1778	2.27	2.22	21.64	2.25	6.97
	Sand	1458	2.79	2.75	-	1.45	2.40
Mix 6	Stone chips	1470	2.30	2.25	36.07	2.22	6.93
	Sand	1466	2.82	2.80	-	0.71	2.54
Mix 7	Brick chips	1214	2.19	2.03	44.53	7.88	6.77
	Sand	1493	2.84	2.81	-	1.07	2.77
Mix 8	Stone chips	1634	2.67	2.66	38.8	0.38	7.46
	Sand	1493	2.84	2.81	-	1.07	2.77

Table 3. Proportions of ingredients in the ACI mix

	Unit	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
Design strength	MPa	27.6	27.6	20.7	20.7	20.7	20.7	20.7	20.7
Cement	kg/m^3	312	312	262	262	262	262	262	262
Fine Aggr.(FA)	kg/m^3	900	713	756	1009	467	786	994	887
Coarse Aggr. (CA)	kg/m^3	774	854	854	702	1263	1023	819	1098
Water	kg/m^3	180	180	180	180	180	180	180	180
Cement : FA : CA	By weight	1:2.9:2.5	1:2.3:2.7	1:2.9:3.3	1:3.9:2.7	1:1.8:4.8	1:3.0:3.0	1:3.8:3.1	1:3.4:4.2

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Table 4. Performance of the ACI trial mixes

Mixes	% of design strength attained at 7 days	% of design strength attained at 28 days
Mix 1	44.50	67.00
Mix 2	51.50	73.25
Mix 3	33.83	62.10
Mix 4	39.33	64.00
Mix 5	75.00	105.33
Mix 6	50.33	64.67
Mix 7	47.67	72.80
Mix 8	43.23	66.37

Table 5. Performance of the readjusted trial mixes

Mixes	Cement: FA : CA	% of design strength attained at 7 days	% of design strength attained at 28 days
Mix 3a	1:1.5:3.3	72.67	97.33
Mix 6a	1:1.5:3.9	73.33	97.67

Machine. The strength attainment features of all eight mixes are summarized in Table 4. Strength results of the readjusted mixes (Mix 3a and Mix 6a) are presented in Table 5.

3.6 *Experimental findings*

The material properties (Table 2) and subsequent mix design computations (Table 3) of different sets of materials indicate the limitations of the ACI method of mix design in proportioning the fine aggregate content in respective mixes. The prediction of high fine aggregate content is more pronounced for those mixes, where the coarse aggregate void ratio is higher. This is similar to the theoretical predictions of the parametric study. As anticipated, all the mixes except Mix 5, which has a considerably lower void ratio in the coarse aggregate, have failed to attain the design 28-day strength (Table 4).

The two separate mixes (Mix 3a and Mix 6a), in which the fine aggregate content was reduced by 50% from the original mix (Mix 3 and Mix 6), showed much better performance than their parent mixes, very nearly attaining the design strength (Table 5). This is most likely due to the subsequent reduction of fine aggregate surface area, which could be sufficiently covered up by the constant amount of cement, determined earlier.

A graphical presentation (Figure 13), showing the relation between void ratio and percent strength attainment is produced on the basis of the experimental results. This plot clearly shows that the percent design strength attainment varies inversely with the void ratio of the coarse aggregate.

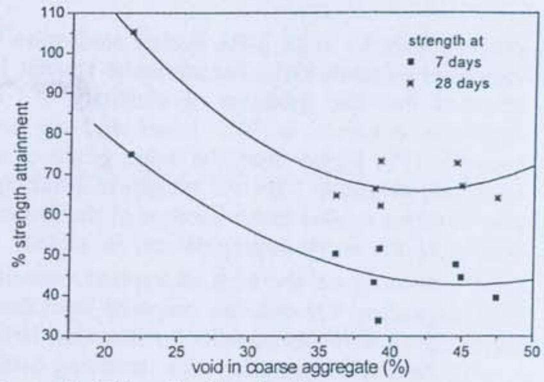

Figure 13. Effect of void ratio of coarse aggregate on strength attainment of cylinder specimens

4 CONCLUSION

The ACI method of mix design for normal concrete mixes fails to rationally design the mixes where coarse aggregates of higher inter-particle voids are used. The occurrence of higher inter-particle voids is related to the gradation of the coarse aggregate. Unfortunately, the ACI method has no adequate parameter to take this aspect into account. In such cases, the design provides higher fine aggregate content, which increases the total surface area of the aggregates. This, accompanied by the fact that the cement content is determined even before the consideration of any aggregate type, implies that the cement/aggregate ratio becomes lower. This is why mixes designed by the ACI method fail to gain the required strength, if coarse aggregates of higher voids are used. The present study indicates the need for further research with a view to incorporate some modifications in the ACI method regarding the voids or gradation of the coarse aggregates.

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