Some Thoughts on the ACI Method of Concrete Mix Design

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Abstract

The applicability of ACI method of concrete mix design using brick aggregate is studied. Six sets of materials with different material properties as available in the local situation of Bangladesh are considered. After determining the relevant material properties, the mixes were designed by ACI method. The results obtained from mix design calculation suggest a higher proportion of fine aggregate content when the designer goes for using coarse aggregate with lower maximum size. However, such designs eventually fail to attain the design strengths due to low cement content suggested in ACI method that only considers the relation between the w/c ratio and strength and ignores the effect of total surface area of aggregates, specially the fine aggregates. Test results obtained from concrete cylinders cast with these mix designs have substantiated the fact. To this end, the paper outlines an alternate method that considers the inter-particle void area that exists within the coarse aggregate particles to estimate the fine aggregate content. The performance of the ACI method is compared with the proposed method through limited test results that show improved performance of the latter one.

INTRODUCTION

Concrete is a versatile construction material, usually consisting of aggregates bound together in hardened cement paste matrix. The material so obtained literally forms the basis of our modern society and competes with other materials in terms of economy and durability. Furthermore other various unique properties of concrete mark its superiority over many other construction materials. The versatility and mouldability of concrete, high compressive strength along with the discovery of reinforcing and prestressing techniques have contributed largely to its widespread use. The possibility of using locally available ingredients as the aggregates to produce concrete of required strength makes concrete unique among all construction materials. This is an important characteristic that goes a long way in offseting its other shortcomings. In Bangladesh, unlike other countries of the world, broken brick aggregate, commonly known as *khoa* is extensively used as a cheaper local substitute. Investigation from previous research reveals that specific gravity and unit weight of brick chips are much lower and absorption capacity is much higher than the natural stone aggregates (Akhtaruzzaman and Hasnat 1983). During research on the effect of curing conditions on concrete strength at BUET (Ahmad and Amin 1998), it has been found that due to higher porosity, brick aggregate concrete suffers less in discontinuous curing. However to achieve particular design strength the engineer has to follow a specified method of mix design.

In designing concrete mix, there are different published methods of mix design. Among those ACI Method is the most widely used now. Recent research over last few years in BUET (Amin et al. 1999 and Wadud et al. 2001) has shown that there are cases in which the ACI method fails in proper proportioning of the mix.

To find out the reasons why ACI Method fails in gaining proper design strength, the design procedure suggested by American Concrete Institute (ACI 1996) is briefly reviewed. The design starts with the selection of water content for a given maximum size of coarse aggregate. Cement content is then found out simply from the w/c ratio, which depends on the design strength. The volume of coarse aggregate is then determined, 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 cement content is thus determined before the determination of the fine aggregate content. In reality, hydrated cement paste is the material that binds the aggregate particles, and this binding action takes place only on the surface of the aggregate particles. Therefore the total surface area of the aggregates is also an important factor that needs to be addressed. As fine aggregate has larger surface area in comparison to the coarse aggregate, the quantity of fine aggregate is essential to the determination of the cement content. In addition, in the ACI method of mix design when the maximum size of coarse aggregate decreases the volume of coarse aggregate also decreases which in turn increases the volume of fine aggregate giving a higher surface area of aggregates to be covered by the previously determined quantity of cement (Fig.1). This is the case where the ACI method fails to provide desired results.

With this background, the present study attempts to find out the cases where ACI method fails in suggesting proper mix proportion. The surface area of fine aggregate has been found to play a governing role in this failure which has not been duly addressed in the ACI method. These findings have been substantiated by mix design computation of six different material sets and subsequent strength test results of trial mixes. Based on these findings, attempt has been made to outline a method of mix design. The performance of the outlined method of mix design is compared with ACI method through limited test results.

MATERIALS

Though the strength of concrete depends on a multitude of factors, and may vary widely with the same production technology, the successful use of concrete depends on the intelligent application of its properties. For this reason, a thorough understanding of the material properties of the concrete is essential to obtain a rational mix design. In Bangladesh, crushed brick, an indigenous material, is used in parallel to stone aggregate as coarse aggregates because of scarcity of natural stone. Locally produced brick can attain a compressive strength as high as 34.5 MPa, with the most commonly found ones ranging from 17 to 24 MPa. Earlier studies on brick aggregate concrete (Akhtaruzzaman and 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.

In the present study, aggregates produced by crushing well-burnt clay bricks were used as coarse aggregates for different batches. The local river bed 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 presented in Table 1.

EFFECT OF AGGREGATE GRADATION ON INTER-PARTICLE VOIDS

Based on the previous research, it was suspected that void ratio and gradation of coarse aggregate might have some effect on the short comings of ACI Method of mix design. So further investigation has been carried out to find the void ratio of coarse aggregate for different gradation. But from experimental investigation it has been observed that void ratio is not the only factor for which ACI Method of mix design fails to attain designed strength in some cases when broken brick chips are used as coarse aggregate. Therefore, some other factors as noticed in previous research (Wadud et al. 2001) must also be looked into.

MIX DESIGN BY ACI METHOD

Six different mixes were designed following the ACI method with a view to compare the mix proportions and to find out the effect of variation of material properties on mix design. 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 2a and Mix 3a) were also cast with some adjustment in the proportions of the mixes. The fine aggregate contents were arbitrarily reduced by 50% in these cases, since higher amount of fine aggregate gives higher aggregate surface area. The proportions of various ingredients are presented in Table 2.

ACI MIX PERFORMANCE

On the basis of the design, required quantities of the materials were weighed on SSD condition. The coarse aggregate, fine aggregate and cement were put in the mixing machine and water was gradually added to the mix. These ingredients were then mixed thoroughly and continuously with the required amount until a uniform concrete mix was produced. Proper and uniform quality and homogeneity of the fresh concrete were maintained. The slump was then checked following standard cone method. After the mixing was complete, the fresh concrete was placed in reusable cylindrical moulds according to the standard requirements. Concrete compaction was done by a

mechanical vibrator in two layers. After the casting was complete, the cylinders were stored in moulds for 24 hours in moist condition at room temperature. The moulds were then carefully removed and concrete cylinders immersed in saturated limewater at room temperature for the purpose of curing. Curing was done continuously until the specimens were removed for strength tests at different duration.
Specimens of all batches were tested for compressive strength at the age of 7 days and 28 days. The cylinders were crushed in Universal Testing Machine following ASTM specification. The strength attainment features of all the mixes are summarized in Table 3.

The material investigation (Table1) and subsequent mix design computations (Table 2) of different sets of materials indicate the limitations of the ACI method of mix design in proportioning the fine aggregate content. The presence of higher fine aggregate content is more pronounced for those mixes, where the coarse aggregate void ratio is higher. It has been noticed that all the mixes except Mix 5 having considerably lower fine aggregate contents, have failed to attain the design 28-day strength (Table 3). Two separate mixes (Mix 2a and Mix 3a), in which the fine aggregate content was reduced by 50% from the original mixes (Mix 2 and Mix 3), showed much better performance than their parent mixes, very nearly attaining the design strength (Table 4). This must be due to the subsequent reduction of fine aggregate surface area, which could be sufficiently covered up by the amount of cement, determined earlier.

A GUIDELINE FOR IMPROVEMENT

It is inevitable that the best mix approach is that in which we will obtain the design strength with some factor of safety. Table 3 shows that ACI method of mix design fails to attain desired strength in most cases. So the present study indicates the need for a modified approach with a view to finding the appropriate fine aggregate content as well as cement. So apart from the regular trial mix, another mix was also cast in two batches with some adjustment in the proportioning of the mix using the same materials used in Trial Mix 6. In this method, the fine aggregate content was determined to fill the total inter-particle voids of coarse aggregate and cement content was determined to fill the voids of fine aggregate. Thus, sufficient cement is available to ensure better bonding between aggregates that has been schematically presented in Fig. 2. Same water cement ratio was used for both the design procedures.

In this method for Trial Mix 6 lesser amount of fine aggregate and greater amount of cement content was required than the original mix (Table 5). It also showed much better performance than its parent mixes (Table 6).

CONCLUDING REMARKS

The ACI method of concrete mix design fails to design concrete mixes in some cases. In such cases, the design suggests for higher fine aggregate content, which increases the surface area of the aggregates. As the cement content is determined before the consideration of any aggregate type, sufficient cement paste is not available for proper bonding, leading to failure. Again so far as aggregate surface area is concerned, the fine aggregate is the major contributor which has not been duly addressed in the ACI method. The present study indicates the need for further research with a view to considering the aggregate and cement surface areas in the mix design procedure to overcome the shortcomings.

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Table 1 Properties of the aggregates for different mix design

Mixes	Aggregates	Unit weight (SSD) Kg/m^3	Specific gravity (SSD)	Void Ratio (%)	Fineness Modulus
Mix 1	Brick chips	1145	2.08	44.91	6.88
	Sand	1522	2.68	--	2.74
Mix 2	Brick chips	1185	1.95	39.18	6.90
	Sand	1522	2.64	--	2.30
Mix 3	Brick chips	1214	2.19	44.53	6.77
	Sand	1493	2.84	--	2.77
Mix 4	Brick chips	1282	1.85	30.70	--
	Sand	1536	2.63	--	2.59
Mix 5	Brick chips	1355	1.85	26.77	--
	Sand	1536	2.63	--	2.59
Mix 6	Brick chips	1277	2.28	44.00	--
	Sand	1507	2.78	--	2.50

Table 2 Proportions of ingredients in the ACI mix

Mix	Design Strength	Max size of CA	Cement	Fine Aggr. (FA)	Coarse Aggr. (CA)	Water
Unit	MPa	mm	kg/m^3	kg/m^3	kg/m^3	kg/m^3
Mix 1	27.6	25.4	312	900	774	180
Mix 2	27.6	25.4	312	713	854	180
Mix 3	20.7	25.4	262	994	819	180
Mix 4	27.6	19.0	328	641	822	187
Mix 5	27.6	19.0	328	575	869	187
Mix 6	27.6	25.4	312	880	891	178

Table 3 Performance of the trial mixes

Mix No.	% of Design Strength Attained at 7 days	% of Design Strength Attained at 28 days
Mix 1	44.5	67.0
Mix 2	51.5	73.2
Mix 3	47.7	72.8
Mix 4	74.0	93.0
Mix 5	81.0	110.0
Mix 6	70.8	98.4

Table 4 Performance of the adjusted trial mixes

Mixes	Cement: FA : CA	% of Design Strength Attained at 7 days	% of Design Strength Attained at 28 days
Mix 2a	1:1.5:3.3	72.7	97.3
Mix 3a	1:1.5:3.9	73.3	97.7

Table 5 Comparison between proportions of Trial Mix 11 by ACI method and by the proposed method

Ingredients	Quantity, kg/m^3	
	ACI Method	Proposed Method
Cement	312	627
FA	880	660
CA	891	1267
Water	180	357
W/C ratio	0.57	0.57
Cement:	1: 2.82: 2.85	1: 1.05: 2.01

Table 6 Performances of the trial Mixes

Mixing Method	% of Design Strength Attained at 7 days	% of Design Strength Attained at 28 days
ACI	70.8	98.4
Proposed	83.7	108.0

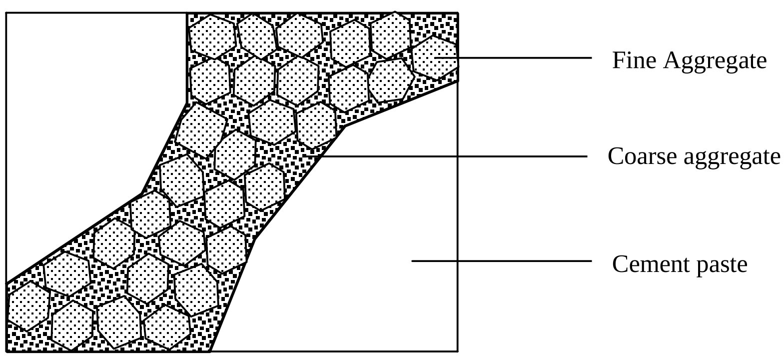

Fig. 1 Schematic representation of Inadequate binding due to low cement content

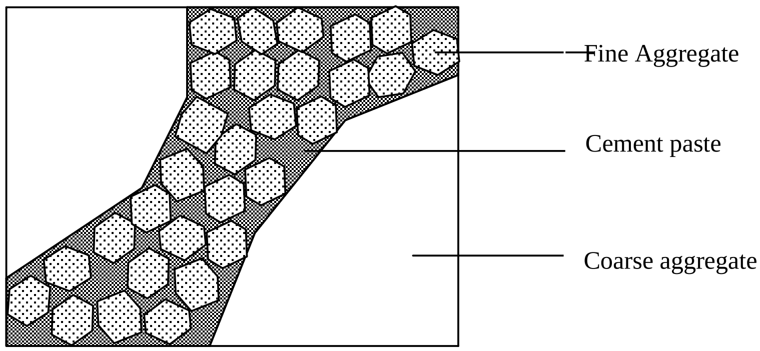

Fig. 2 Schematic representation of the case of binding due to presence of sufficient cement content.