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EFFECT OF ACI CONCRETE MIX DESIGN PARAMETERS ON MIX PROPORTION AND STRENGTH

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ABSTRACT

The effect of different mix design parameters in predicting mix proportions by ACI method and their strength attainment has been studied. The parametric study revealed that ACI method fails in rational proportioning of fine aggregate content where coarse aggregate of lower unit weight is to be used. In such events, the overestimation of fine aggregate content with increased surface area, together with underestimation of coarse aggregate content, brings a total failure in realistic prediction of mix proportions. The situation deteriorates further in the cases of designing low slump mixes; using fine aggregate of higher specific gravity or greater fineness modulus. The mix design computations and subsequent trial mix castings on different material sets were found to conform to these findings. This indicates the necessity of some modifications in ACI normal mix design method to make it usable for wider needs.

INTRODUCTION

Concrete is a composite material which essentially consists of cement, coarse aggregate (CA), fine aggregate (FA) and water. Coarse aggregate gives the volume to the concrete and fine aggregate makes the concrete denser by filling the voids of coarse aggregate. Water hydrates and sets the cement which thus acts as a binder for all the ingredient particles of concrete. The ultimate properties of concrete in terms of its strength, durability and economy depend not only on the various properties of its ingredients but also on the mix design standards, method of preparation, handling and curing conditions.

The possibility of the use of locally available ingredients as aggregates to produce concrete of a particular design strength makes concrete exclusive among the major construction materials. Due to the dependence on the natural sources, the engineering properties of the aggregates are found to vary widely. But to attain a particular design strength, the engineers generally follow different mix design methods that involve selection of suitable ingredients of concrete and determination of their relative quantities for producing concrete in an economic way not withstanding the workability, strength and durability requirements. The process of mix design is also important in having an approximate idea about the required material quantity and subsequent cost estimation.

Among different available mix design methods, American Concrete Institute (ACI) method (1996) is one of the most popular methods for design of normal concrete mixes. The method utilises the fact that water content determines the workability for a given maximum size of coarse aggregate. A further assumption is made that coarse aggregate volume per unit volume of concrete depends on maximum size of aggregate and fineness modulus of fine aggregate. In this course, water content and air content are obtained from specified slump value and maximum size of aggregate from ACI suggested table (1996). The water/cement ratio is obtained from its inversely proportional relation with concrete strength. Knowing the water content, the cement quantity is directly determined from strength vs. water/cement ratio curve. In regard to the determination of coarse aggregate proportion per unit concrete volume, maximum size of aggregate and fineness modulus of fine aggregate are considered as the governing parameters. After determining coarse aggregate proportion, the fine aggregate proportion is determined by subtracting the volume (or weight) of other ingredients from the total volume (or weight) of concrete.

In reality, hydrated cement paste is the material that binds different aggregate particles to give desired concrete strength and this binding action takes place just on the aggregate surface. Therefore, the total surface area of the aggregates (specially fine aggregate) in relation to the cement content is also a major factor that needs to be addressed in attaining desired concrete strength. Some recent experiences and subsequent comprehensive studies made at the Bangladesh University of Engineering and Technology (BUET) have revealed that there are cases where ACI mix design philosophy fails to appreciate the effect of aggregate surface area vs. cement content relation in regard to the attainment of desired strength. With this background, the paper, through a parametric study, presents the cases where ACI method fails in suggesting rational mix proportion. The findings of the parametric study have been substantiated by mix design computation of five different material sets and subsequent strength test results of trial mixes. The paper suggests that some modification in ACI method is a must to make it widely usable.

METHODOLOGY FOR PARAMETRIC STUDY

For designing a non-air entrained normal concrete mix of a particular strength by using ACI method, seven parameters are required to be considered. In the present study, the effects of variation of these parameters within their assigned ranges (Table 1) on the FA/CA ratio and cement/total aggregate ratio have been investigated.

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

Mix Design Parameters	Variation ranges	Assigned values
Design strength	2000 psi - 5000 psi	4000 psi
Specific gravity (SSD) of fine aggregate	2.25 – 3.00	2.65
Specific gravity (SSD) of coarse aggregate	1.50 – 3.00	2.40
Fineness modulus of fine aggregate	1.75 – 3.00	2.40
Unit weight (SSD) of coarse aggregate	50 – 120 pcf	75 pcf
Maximum size of aggregate	3/8 – 3.0 inch	1.5 inch
Slump	1.0 – 6.0 inch	2 inch

The unit weight of coarse aggregate was varied and the respective values of the other parameters were assigned to their initial ones (Table 1). After having a picture of the effect of this variation on the FA/CA ratio and cement/total aggregate ratio, other parameters were also varied from their initial ones. Figures 1 to 6 graphically present the effect of these variations on FA/CA content, while Figures 7 to 12 illustrate those effects on cement/total aggregate content. All these presentations are on weight basis.

FINDINGS OF PARAMETRIC STUDY

Figures 1 to 6 reveal that with the decrease of unit weight of coarse aggregate, the proportion of fine aggregate increases in comparison to coarse aggregate content. The increase of fine aggregate proportion in turn increases the total aggregate surface area.

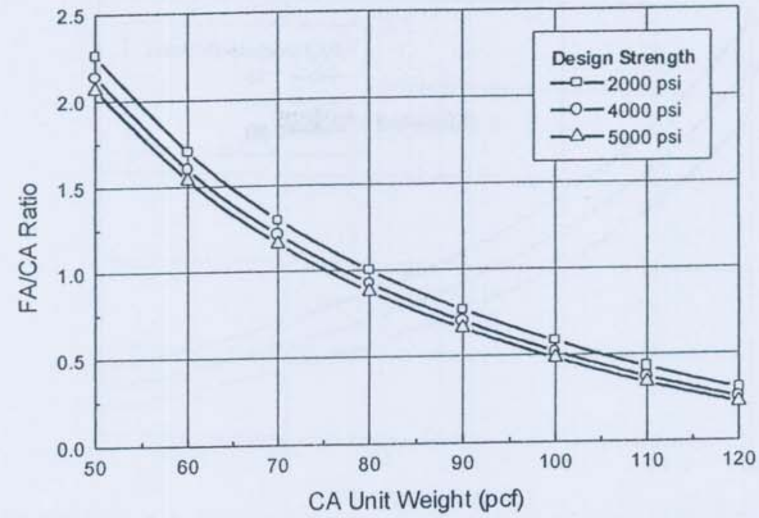

Fig. 1 Effect of variation of CA unit weight and design strength on FA/CA ratio

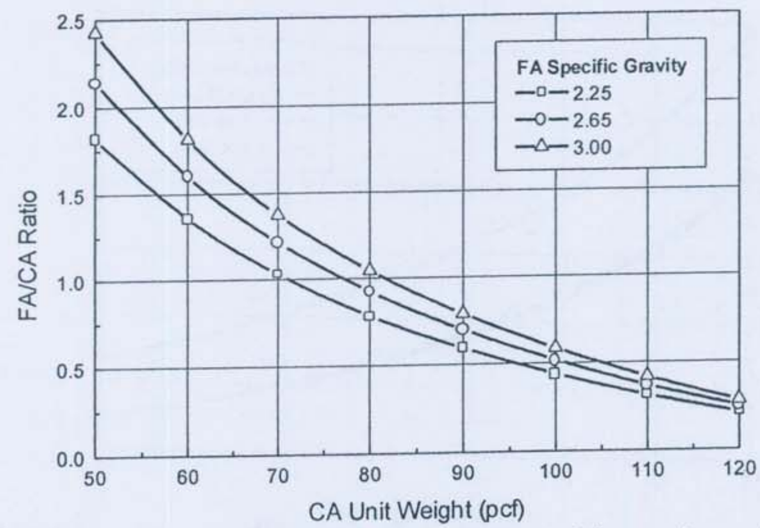

Fig. 2 Effect of variation of CA unit weight and FA specific gravity on FA/CA ratio

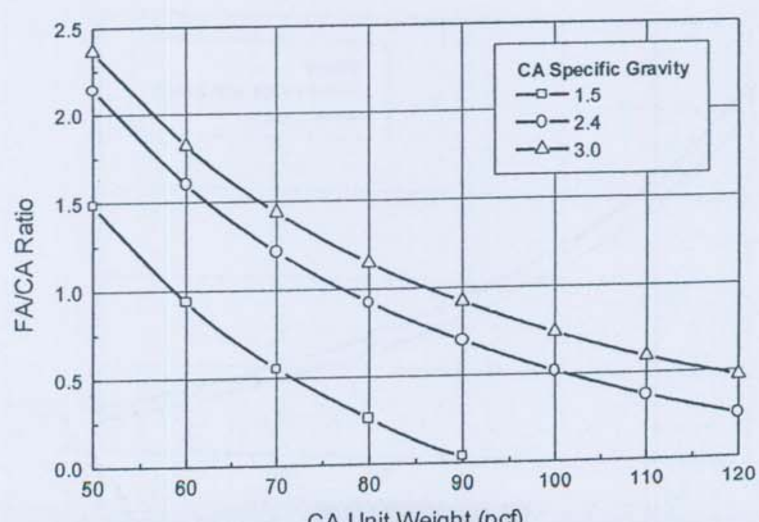

Fig. 3 Effect of variation of CA unit weight and CA specific gravity on FA/CA ratio

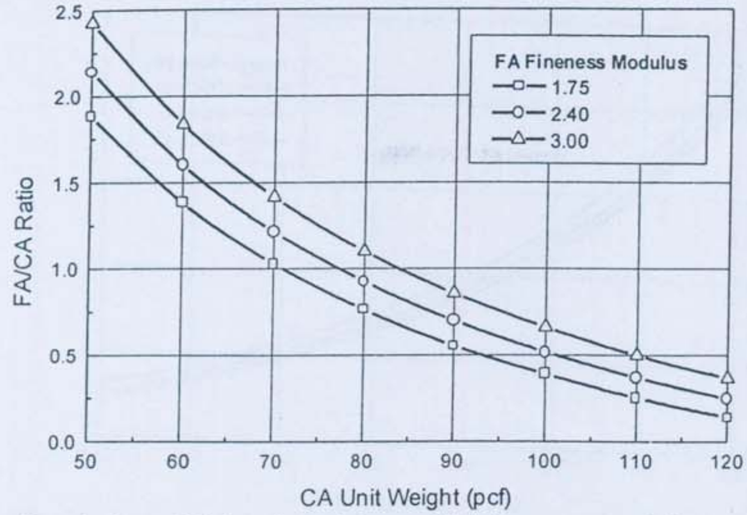

Fig. 4 Effect of variation of CA unit weight and FA fineness modulus on FA/CA ratio

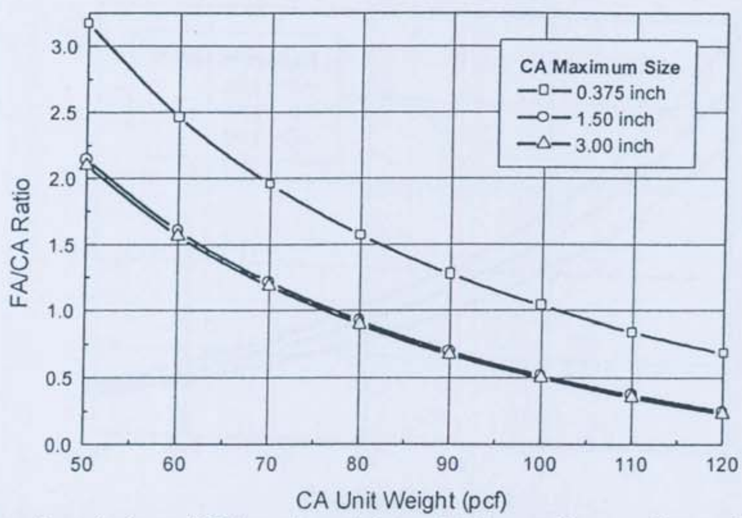

Fig. 5 Effect of variation of CA unit weight and CA maximum size on FA/CA ratio

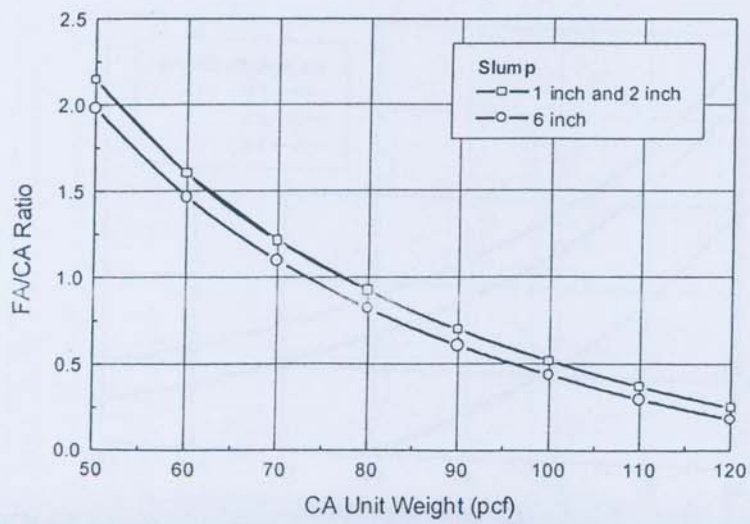

Fig. 6 Effect of variation of CA unit weight and slump on FA/CA ratio

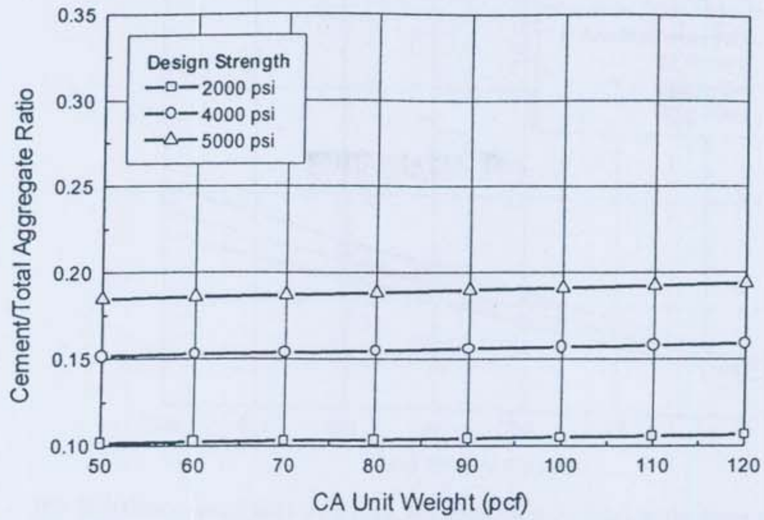

Fig. 7 Effect of variation of CA unit weight and design strength on Cement/Total aggregate ratio

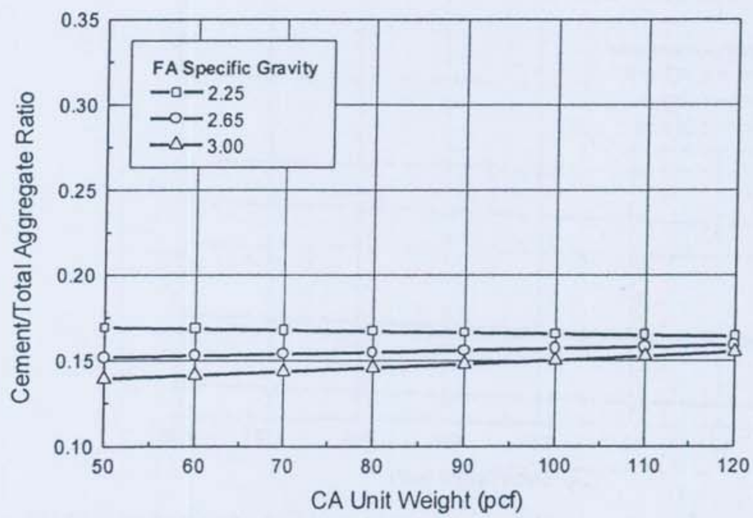

Fig. 8 Effect of variation of CA unit weight and FA specific gravity on Cement/Total aggregate ratio

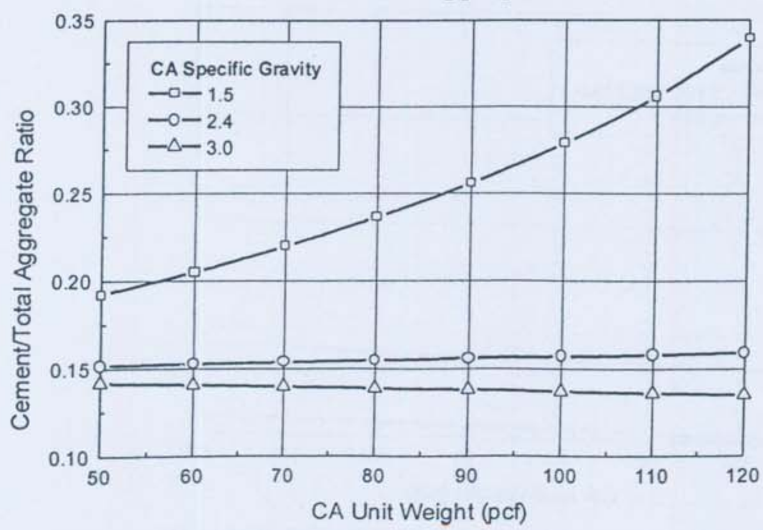

Fig. 9 Effect of variation of CA unit weight and CA specific gravity on Cement/Total aggregate ratio

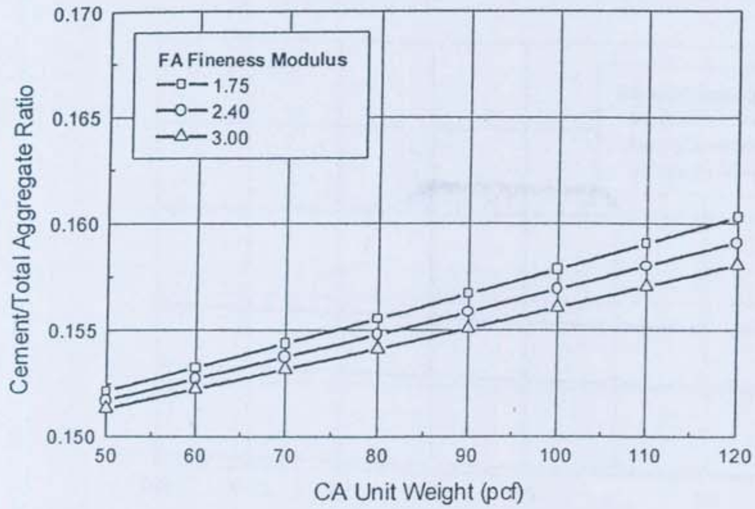

Fig. 10 Effect of variation of CA unit weight and FA fineness modulus on Cement/Total aggregate ratio

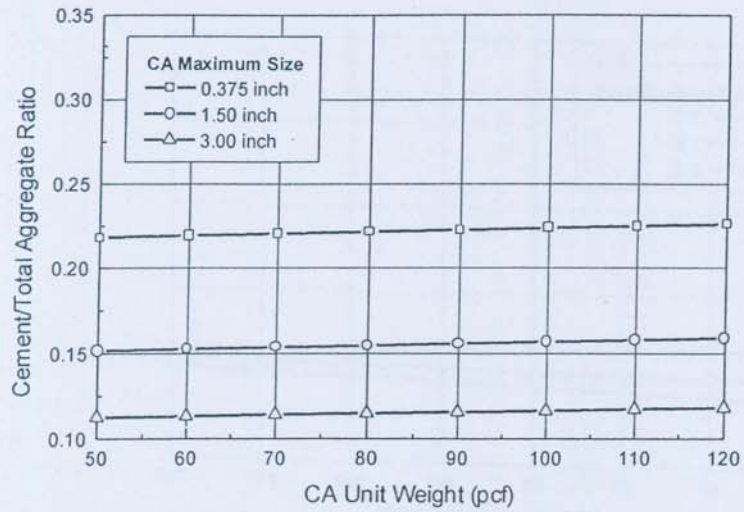

Fig. 11 Effect of variation of CA unit weight and CA maximum size on Cement/Total aggregate ratio

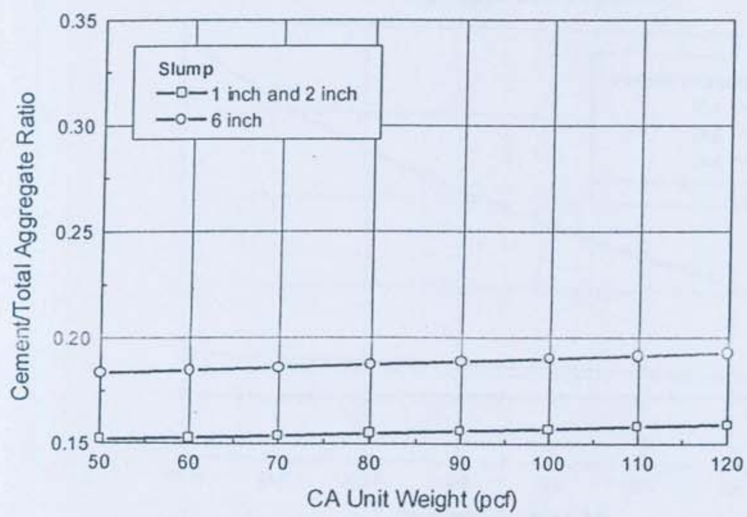

Fig. 12 Effect of variation of CA unit weight and slump on Cement/Total aggregate ratio

Thus in case of designing a mix with lighter coarse aggregates, the ACI method gives higher quantity of fine aggregate content with larger surface area. Hence, though not ideal, the increase of fine aggregate content must accompany a suggestion for increased cement/aggregate ratio, as cement is the only binding ingredient of the aggregates. But in most cases, the ACI suggests for lower cement/aggregate ratio (Figures 7 to 12). Further study of the parametric variations unveiled that the situation further worsens when the designer goes for designing mixes of low slump (Figures 6 and 12); uses fine aggregate of higher specific gravity (Figures 2 and 8) or greater fineness modulus (Figures 4 and 10).

METHODOLOGY FOR EXPERIMENTAL STUDY

With a view to substantiating the findings of the parametric study, six different concrete mixes were designed following ACI method. After designing the mixes, trial mixes were cast in the laboratory according to standard methods. However, apart from casting the specimens of trial mixes, two mixes (Mix 3 and Mix 6 in Table 2) were also cast with some readjustment in the mix design. In that case, fine aggregate content was reduced arbitrarily to 50% of its designed value. The mix design, casting, curing and testing procedure of cylindrical concrete specimens illustrating their strength attainment behaviour in comparison to design strength are presented in the following sections.

MATERIALS AND MIX DESIGN

Crushed brick aggregates are widely being used in parallel to stone aggregates in Bangladesh and other countries of the world where the sources of natural aggregates are not abundant. Earlier investigations on properties of brick aggregate concrete by Akhtaruzzaman and Hasanat (1983) revealed that modulus of elasticity of brick aggregate concrete is 30% lower and tensile strength was about 11% higher for the same grade of stone aggregate concrete. Brick aggregate concrete was also characteristically found to be of lower unit weight to the extent of around 120 pcf. Ahmad and Amin (1998) reported the significance of very high absorption capacity (more than 10%) of brick aggregates in the compressive strength attainment behaviour of discontinuously cured concrete.

In the present study, two types of aggregates produced by crushing of well-burnt clay bricks and crushed stones were used as coarse aggregates for different batches. The local river bed sands of different gradations were used as fine aggregates for designing different mixes. Ordinary Portland Cement (Type I) was used as binder. The required material properties, such as specific gravity, unit weight, fineness modulus of coarse and fine aggregate and absorption capacity were determined to design the concrete mixes following ASTM method (1988a-d). The engineering properties of coarse and fine aggregates are presented in Table 2.

Based on material properties, the mixes were designed for different design strength with 2 inch slump following ACI method for normal concrete (1996). The proportions of the mix ingredients as obtained from mix design are summarised in Table 3.

PREPARATION OF CYLINDER SPECIMENS

On the basis of mix design, the required quantities of the materials were calculated and measured on SSD weight basis. The coarse aggregate, fine aggregate and cement were then mixed in a mixing machine and water was gradually added. Thorough mixing was continued until uniform concrete mix was prepared. Proper and uniform quality of concrete was maintained. Then the slump of the mix was checked according to ASTM method (1978).

Table 2 Properties of the aggregates for different mix designs

Mixes	Aggregates	Unit weight (SSD) pcf	Specific gravity (SSD)	Specific gravity (OD)	Absorption capacity %	Fineness modulus
Mix 1	Brick chips	71.50	2.08	1.83	13.66	6.88
	Sand	95.00	2.68	2.66	0.75	2.74
Mix 2, 3	Brick chips	74.00	1.95	1.70	21.95	6.90
	Sand	95.00	2.64	2.60	1.54	2.30
Mix 4	Brick chips	63.00	1.92	1.69	13.61	7.13
	Sand	91.50	2.82	2.80	0.71	2.54
Mix 5	Stone chips	111.00	2.27	2.22	2.25	6.97
	Sand	91.00	2.79	2.75	1.45	2.40
Mix 6	Stone chips	91.75	2.30	2.25	2.22	6.93
	Sand	91.50	2.82	2.80	0.71	2.54

Table 3 Proportion of ingredients in the mix

Ingredients	Quantity, lb/cu yd					
	Mix 1#	Mix 2#	Mix 3*	Mix 4*	Mix 5*	Mix 6*
Cement	526	526	441	441	441	441
FA	1514	1201	1274	1700	787	1324
CA	1305	1439	1439	1184	2128	1724
Water	300	300	300	300	300	300
Cement: FA: CA	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	1:3.0:3.9

Concrete of 4000 psi design strength; * Concrete of 3000 psi design strength.

After mixing, the concrete was placed in reusable cylindrical moulds according to ASTM requirements (1988e) in two layers. The concrete was compacted by using a vibrator following ASTM (1988f). The cylinders were then stored in moulds for 24 hours in moist condition at room temperature. The moulds were then carefully removed. The cylinders were stored in saturated limewater at room temperature to provide necessary moisture during curing as suggested by ASTM (1988f).

TESTING OF CYLINDER SPECIMENS

The continuously cured specimens of all the batches were tested for compressive strength at the age of 7 days and 28 days. All the cylinders were tested in moist condition. The top surfaces of the cylinders were capped with sulphur mortar in accordance with ASTM specification (1988g) before testing. The cylinders were crushed in a Universal Testing Machine following ASTM specification (1988h). The strength attainment features of all the six designed mixes have been presented in Table 4, whereas those of the readjusted Mix 3 and Mix 6 (with 50% of the designed fine aggregate content) are presented in Table 5.

Table 4 Performance of trial mixes designed in ACI method

Mixes	% of designed strength attained at	
	7 days	28 days
Mix 1	44.50	67.00
Mix 2	51.50	73.25
Mix 3	33.83	41.10
Mix 4	39.33	64.00
Mix 5	75.00	105.33
Mix 6	50.33	64.67

Table 5 Performance of readjusted trial mixes

Mixes	% of designed strength attained at	
	7 days	28 days
Mix 3	72.67	97.33
Mix 6	73.33	97.67

EXPERIMENTAL FINDINGS

The material investigation (Table 2) and subsequent mix design computation (Table 3) of different sets of materials indicate the limitations of ACI method of mix design in proportioning the fine aggregate content in respective mixes. The prediction of fine aggregate content in high proportion is more pronounced for the mixes where lighter coarse aggregates have been used in contrast to the other mix (Mix 5). This phenomenon is also similar to theoretical predictions (Figures 1 to 6). As expected, all the mixes except Mix 5 have failed to attain the designed 28-day strength in their trial casting (Table 4). The two separate batches of concrete which were cast following readjusted Mix 3 and Mix 6 (fine aggregate content was reduced by 50% of the designed value), the trial mixes were found nearly to attain the designed strengths (Table 5). This must be due to the subsequent reduction of aggregate surface area.

CONCLUSION

The ACI method of mix design for normal mixes cannot rationally design the mixes for the cases where coarse aggregates of lower unit weights are to be used. In such cases, the design suggests for higher value of fine aggregate/coarse aggregate ratio, which in turn increases the total aggregate surface area to a great extent. The situation worsens further when the designer goes for designing low slump mixes; uses fine aggregate of higher specific gravity or greater fineness modulus, since the ACI design method, in such cases gives lower cement/total aggregate ratio. The present study indicates the need for further research with a view to incorporating some modifications into ACI method in predicting coarse and fine aggregate contents. Such efforts will evidently enable the ACI method to address a wider user community.

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