Mixture Proportioning of Fly Ash-Concretes Based on Mortar Strength and Flow Data

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Abstract

A method of mixture proportioning of fly ash concretes is presented. The method is based on the strength and flow data of a minimum of nine fly ash-cement mortars. The essence of the method is that three fly ash-binder ratios are to be combined with three water-binder ratios in the range of interest. The strength and water demand data are analyzed for constructing mixture proportion charts. The strength vs. water-binder ratio charts are prepared by down-scaling the 50-mm mortar strength to the 150-mm standard concrete cylinders. The method is illustrated with the help of examples. The trial mixtures proportioned using the proposed method have reasonably achieved the 28 day target strengths.

Keywords: Cement replacement; fly ash; mixture proportioning; mortars; moist curing; pozzolana; water requirement; workability

1. Introduction

Nusrat and Tahir [1] and Tahir and Nusrat [2] proposed a method of mixture proportioning for fly ash-concretes. The method was an application of the modified power law presented by Tahir and Goraya [3]. The method was based on the compressive strengths of 9 mortars at three different ages. The original power law proposed by Tahir and Pichai [4] may be written as follows:

$$f_c^{'}(t) = a(t) r_W^{-b(t)} \tag{1}$$

where $f_c^{'}(t)$ denoted the compressive strength of standard moist cured concrete at age of *t* days in the range of 3 to 180 days, r_W the water-binder ratio i.e. $W/(C+F)$ where *W*, *C* and *F* respectively denote the water, cement and fly ash contents per unit volume of concrete. The parameters $a(t)$ and $b(t)$ were expressed by Tahir and Pichai [4] as functions of age of concrete, *t* days:

$$a(t) = C_1 + C_2 \ln(t) \tag{2a}$$

$$b(t) = D_1 \ t^{-D_2} \tag{2b}$$

where C_1, C_2, D_1 and D_2 were the four parametric constants that were calibrated as functions of fly ash-binder ratio. However, it was later shown by Tahir and Goraya [3] that strength development predicted by the power law did not agree quite closely with the experimental results. They showed that compressive strength vs. water-binder ratio relationship of fly ash-concretes or fly ash-cement mortars was best described by the following relationship:

$$f_c^{'}(t) = A(r_w, r_F) + B(r_w, r_F) \ \log\frac{t}{3} \tag{3}$$

It was not surprising that both the parametric constants *A* and *B* followed the Power law presented by Tahir and Pichai [4]. The relationships were expressed as follows:

$$A(r_W, r_F) = a_1(r_F) r_W^{-a_2(r_F)} \tag{4a}$$

$$B(r_W, r_F) = a_3(r_F) r_W^{-a_4(r_F)} \tag{4b}$$

The four constants a_1 to a_4 in Equation 4 were proposed as functions of fly ash-binder ratio, r_F only. It is interesting to note that the parameter $A(r_W, r_F)$ in Equation 3 is exactly three day strength of fly ash-cement mortars or fly ash-concretes. The last and final step in the modified power law was to quantify each of the four constants a_i in terms of fly ash-binder ratio r_F. The general relationship was proposed by Tahir and Goraya [3] as follows:

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$$a_i(r_F) = \alpha_0^i + \alpha_1^i r_F + \alpha_2^i r_F^2 \quad \text{(i=1 to 4)} \tag{5}$$

It may be noticed that a quadratic function was proposed instead of the one suggested by Tahir and Pichai [4] and Gopalan and Haq [5]. The 12 constants of Equation 4 can be determined from the strength of 9 mortars at three different ages. If experimental strengths of 50-mm mortar cubes of 9 mortar mixtures are available at three different ages, modified power law can be used to prepare charts for mixture proportioning for any age from 3 to 180 day strengths. The method has been demonstrated elsewhere [1,2]. However, if one is interested only in proportioning the concrete mixtures at a given age on which mortar strength data of 50-mm cubes is available, the simplified approach outlined in the following may be adopted.

2. The Simplified Approach

The Tahir and Pichai power law [4] may be used to plot strength vs water-binder ratio charts if one is interested in proportioning the concrete mixtures for target strength at one age only. In this case Equation (1) may be specialized as:

$$f_c^{'} = a(r_F) r_W^{-b(r_F)} \tag{6}$$

Where $f_c^{'}$ denotes the strength of mortars at the specified age. Equation 6 can be calibrated from the test results of 9 mortars at the given age. Using the strengths of three mortars with same r_F one set of the parametric constants $a(r_F)$ and $b(r_F)$ can be obtained. The process is repeated for three fly ash-binder ratios to obtain three sets of these constants. These constants can then be used to calibrate Equation 5. In the following strength results of 9 mortars are used from an earlier study [1] to demonstrate the procedure. The mixture proportions and strengths at 28 day of 50-mm mortar cubes are shown in Table 1. The strength data of Table 1 is used to obtain the strength vs. water-binder ratio plots that are shown in Figure 1. The six constants *a* and *b* obtained from this analysis are tabulated in Table 2 and the plots between fly ash-binder ratio and the constants ‘a’ and ‘b’ are shown in Figures 2 and 3.

3. The Preparation of Mixture Proportioning Charts

The two parametric constants *a* and *b* can be expressed as follows:

$$a = 11.554 r_F^2 - 21.339 r_F + 10.229 \tag{7}$$

$$b = -1.7363 r_F^2 - 0.4785 r_F - 1.4111 \tag{8}$$

The constants *a* and *b* are calculated for various values of r_F from Equations 7 and 8. One set of two constants is then substituted in Equation 6 and strength vs water-binder ratio data is obtained. The process is repeated for all desired fly ash-binder ratios. In this study the calculations were performed for four fly ash-binder ratios; 0.05, 0.20, 0.40 and 0.60. The water-binder ratio in Equation 6 is varied for each set of fly ash-binder ratio in the range of 0.35 to 0.80. The results of Equation 7 and 8 plotted

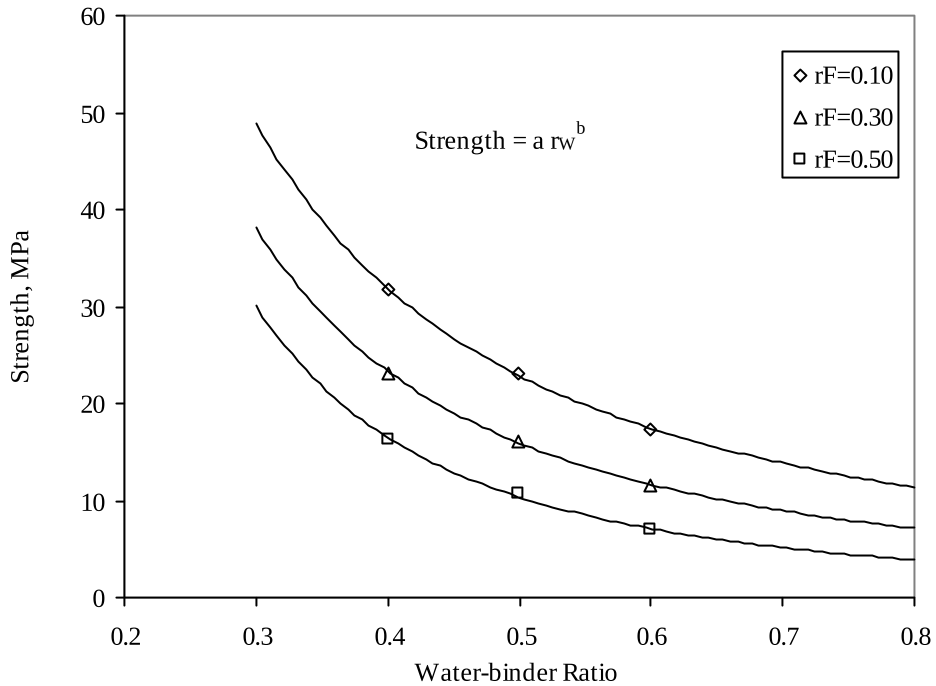

Figure 1: Strength vs Water-binder ratio plots with power fits

Table 1: Mixture proportions and 28 day strengths of 50-mm mortar cubes

Cement	Fly Ash	Sand	W/(C+F)	Strength, MPa	Normalized 150 mm cylinder Strength, MPa
0.90	0.10	2.75	0.40	41.20	31.72
			0.50	30.00	23.10
			0.60	22.50	17.33
0.70	0.30	2.75	0.40	30.07	23.15
			0.50	21.00	16.17
			0.60	15.00	11.55
0.50	0.50	2.75	0.40	21.04	16.20
			0.50	14.03	10.80
			0.60	9.00	6.93

Table 2: Fly ash-binder ratio and parametric constants *a* and *b* from Figure 1

r_F	a	b
0.10	8.2053	-1.4763
0.30	4.8618	-1.7109
0.50	2.4426	-2.0844

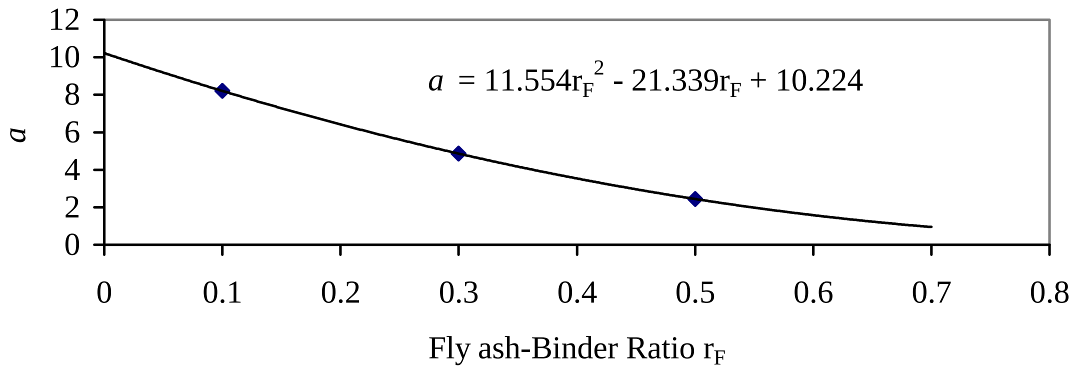

Figure 2: Plot of a vs r_F

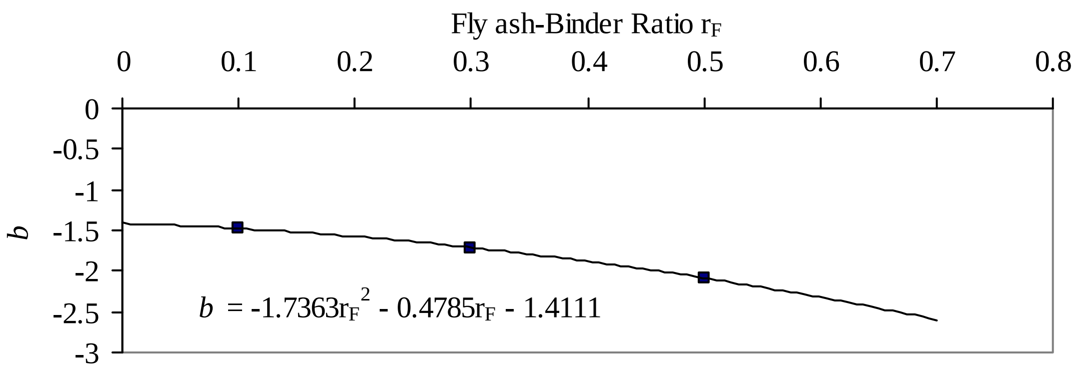

Figure 3: Plot of b vs r_F

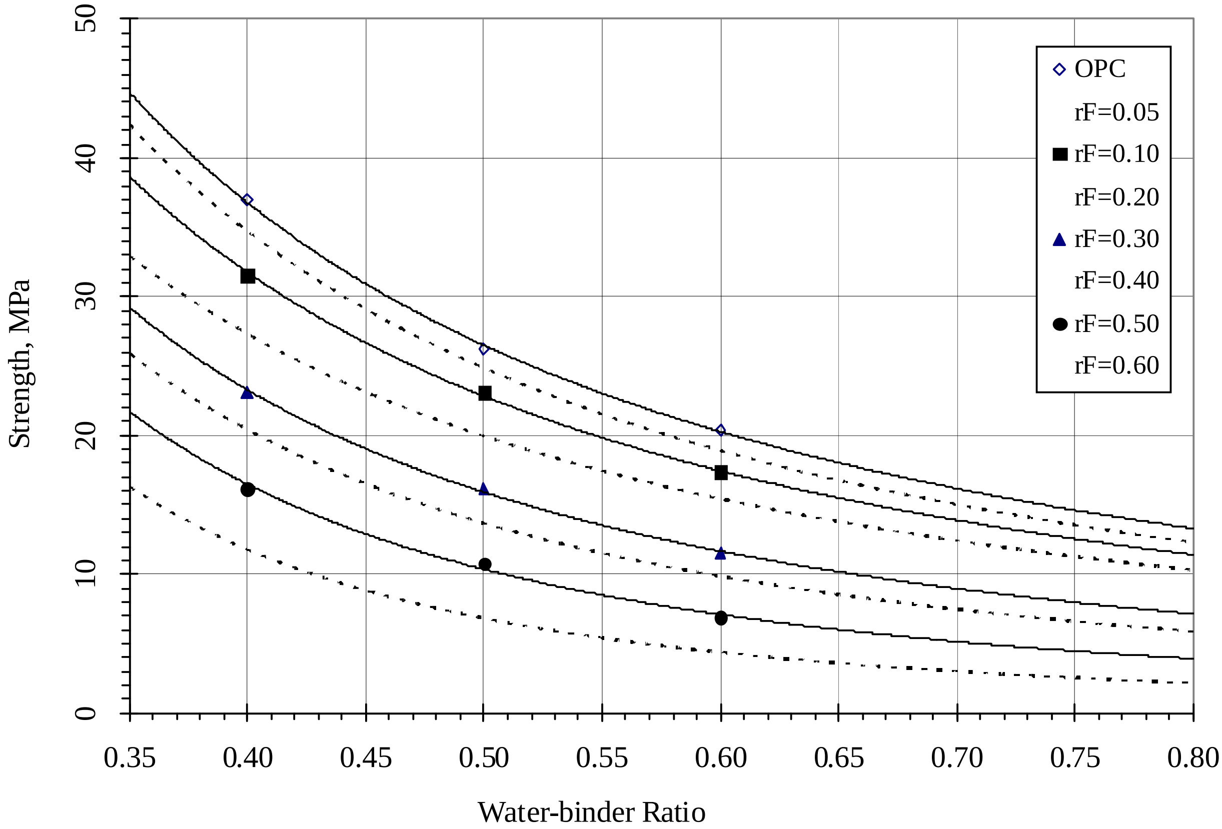

Figure 4: Mixture proportion charts prepared from power law

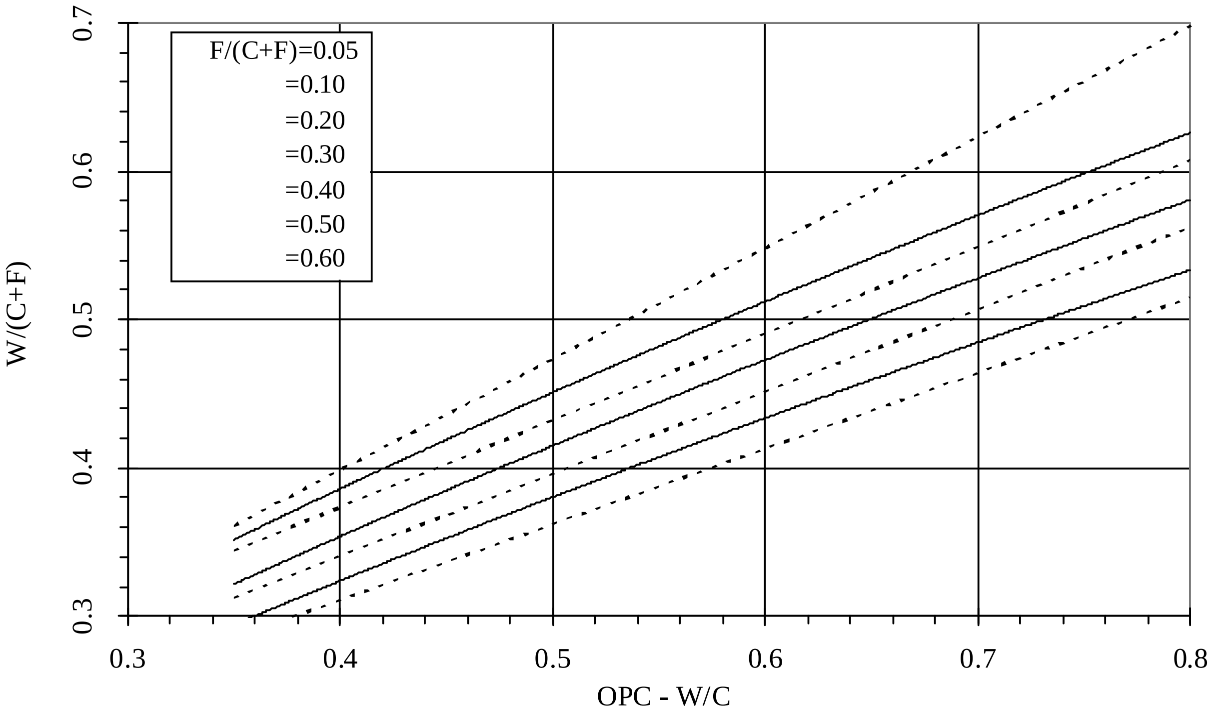

Figure 5: Water-modification chart for high calcium fly ash

along with the experimental data and are shown in Figure 4. The chart of Figure 4 also includes the strength curve of the three cement pastes.

Figure 4 has been plotted from the data presented by Nusrat and Tahir [1] by applying a modification factor of 0.77 to convert the fly ash-cement mortar strengths of 50 mm cubes to the fly ash-concrete strengths of 150x300 mm cylinders for maximum size aggregate up to 25 mm [6-9].

4. Preparation of Water Modification Charts

It can easily be established from the vast literature published [10-21] on fly ash concretes that most of the fly ashes due to their particle shape and size reduce the water requirement of concrete mixtures. Hence a water-reduction chart must be prepared to make use of this good property of fly ash. However, a water modification chart may be prepared for the fly ashes which do not reduce [22, 23] the water demand. In order to prepare such charts, the flows of nine basic mortars are required in addition to flow vs. water-cement ratio plot for neat pastes. The chart of Figure 5 then can be plotted for three fly ash-binder ratios and curves for other fly ash-binder ratios may be plotted by interpolation.

5. Procedure of Mixture Proportioning

In the following the step by step procedure of mixture proportioning is outlined.

Step 1: Decide the degree of workability in terms of slump and the maximum size of aggregate to be used.

Step 2: The free water content per unit volume, W_{OPC}, for the OPC concrete is determined from ACI 211.1 Table A1.5.2.3 [24], with respect to the desired workability and maximum size aggregate.

Step 3: Using Figure 4, determine the water-cement ratio, *W/C*, for OPC corresponding to the required strength. The topmost curve labeled as OPC is used for this purpose.

Step 4: From the Water Modification Charts of Figure 5 for the desired fly ash binder ratio, *W/(C+F)*, read the water-binder ratio *W/(C+F)* corresponding to *W/C* for OPC determined in step 3.

Step 5: Water requirement per unit volume of fly ash concrete, *WR*, is estimated as follows:

$$WR = W_{OPC} \times \frac{W}{C+F} \div \frac{W}{C}$$

where

W_{OPC} = free water content for OPC concrete determined in step 2,

$\frac{W}{C+F}$ = water-binder ratio determined from step 4,

$\frac{W}{C}$ = water cement ratio for OPC corresponding to the desired strength taken from step 3.

Step 6: Using Figure 4, the water-binder ratio, *W/(C+F)*, is read for the desired fly ash-binder ratio corresponding to the target strength.

Step 7: The total binder content per unit volume, *C+F*, is obtained as follows:

$$C + F = WR \div \frac{W}{C+F}$$

WR = water requirement for fly ash concrete as determined in step 5.

$\frac{W}{C+F}$ = water-binder ratio as decided in step 6.

Step 8: Cement content, *C*, and fly ash content, *F*, per unit volume of concrete for the given fly ash-binder ratio, *F/(C+F)*, are determined as follows:

$$F = (C+F) \times \frac{F}{C+F}$$
$$C = (C+F) - F$$

Step 9: The dry rodded volume of coarse aggregate per unit volume of concrete is obtained from ACI 211.1 Table A1.5.2.6 corresponding to the known maximum size aggregate and fineness modulus of the fine aggregate to be used in mixture. Air content in percent, *a,* may also be noted from the same table.

Step 10: The weight of coarse aggregate, *A*, is estimated as follows:

A= dry rodded volume x Bulk density of aggregate

Step 11: Weights of cement, ash, water and coarse aggregate are converted to volumes, V_C, V_F, V_W, and V_A respectively, by dividing by their respective densities.

Step 12: The volume of sand, V_S, is estimated as follows:

$$V_S= 1.00-(V_C+V_F+V_W+V_A+ a/100)$$

Step 13: Finally the weight of sand may be obtained by multiplying the volume of sand by its density. The unit weight of fresh concrete can also be estimated by adding weight of individual ingredients.

6. Illustration of the Procedure

In this section an example of mixture proportioning is presented illustrating the step by step use of procedure outlined in the preceding section. The mixture is to be proportioned for the required strength of 27MPa at 28 day. The densities of cement, fly ash, coarse aggregate and sand were respectively 3150, 2490, 2680 and 2500 kg/m^3. The bulk density of coarse aggregate was 1700 kg/m^3 and fineness modulus of fine aggregate was 2.70. The maximum size of aggregate was 20 mm and the required slump was taken as 60 mm. The strength vs. water-binder ratio curves of Figure 4 and water-modification chart of Figure 5 will be used.

Step 1: Maximum Size Aggregate 20 mm, Slump 60 mm

Step 2: ACI Water requirement W_{OPC}=188 kg/m^3 (ACI 211.1-Table A1.5.2.3)
Step 3: OPC W/C ratio = 0.495 (4 from OPC curve)

Step 4: Water-binder ratio *W/(C+F)* for same workability=0.45 (Figure 5, for *F/(C+F)*=0.1)

Step 5: Water requirement of fly ash-concrete for *F/(C+F)*=0.1=188x 0.45 /0.495= 171 kg/m^3

Step 6: *W/(C+F)* for same strength=0.445 (Figure 5, from Curve for *F/(C+F)*=0.10)

Step 7: Total binder content *(C+F)*=171/0.445=384 kg/m^3

Step 8: Fly ash content, *F*=38 kg/m^3 and Cement content, *C*=346 kg/m^3

Step 9: Dry Rodded Volume of Aggregate=0.63 m^3/unit volume of concrete for MSA=20 mm, FM=2.70, % air content *a*=2%. (ACI 211.1 Table A.1.5.2.6)

Step 10: Weight of coarse aggregate, *A*= 0.63x 1700= 1071 kg.

Step 11: Volumes of various ingredients:

V_C=346/3150=0.110 V_F=38/2490=0.015
V_W=171/1000=0.171 V_A= 1071/2700=0.40
V_a=2/100=0.02

Step 12: Volume of Sand, V_S=1-0.02-0.110-0.015-0.171-0.400=0.284

Step 13: Weight of Sand, *S*=0.284x2500=711kg/m^3 and
Density of fresh concrete=346 +38+171+1071+711= 2337 kg/m^3

The calculations of above example are presented in tabular form (Tables 3 and 4) along with proportions of three other concrete mixtures. The solutions are made for the data given earlier and with reference to the Figures 4, 5.

7. Discussion

The method of mixture proportioning is based on strength vs. water-binder ratio plots with the help of power law. The method requires compressive strengths of 9 fly ash-cement mortars at the specified age. The mixture proportioning charts are then plotted by scaling-down the strengths of 50 mm mortar cubes to the concrete strength of 150 mm diameter standard

Table 3: Mixture proportions using ACI 211.1 and Charts of Figures (4) and (5).

F/(C+F)	Free Water	W/C	W/(C+F)	WR	W/(C+F)	Weight, kg/m^3 of concrete: W	C+F	C	F	A
	Step 2	Step 3	Step 4	Step 5	Step 6	1x4	Step7	Step 8		Step 9,10
High Calcium Fly Ash Specified Strength=27MPa, MSA=20mm, Slump=6cm, FM=2.7										
0.10	188	0.495	0.450	171	0.445	171	384	346	38	1071
0.20	188	0.495	0.430	163	0.400	163	408	326	82	1071
0.30	188	0.495	0.410	156	0.370	156	421	295	126	1071
High Calcium Fly Ash: Specified Strength =14MPa, MSA =20mm, Slump = 6cm, FM =2.7										
0.30	188	0.770	0.565	138	0.540	138	256	179	77	1071

Table 4: Calculations of Step 11

Mixture	Volume, m^3							S, Kg/m^3
	V_a	V_W	V_A.	V_C	V_F	$1\text{-}V_S$	V_S	
	(1)	(2)	(3)	(4)	(5)	(6)=Σ1 to 5	(7)=1-(6)	(7)x γ_s
High Calcium Fly Ash Specified Strength =27MPa, MSA =20mm, Slump =6cm, FM =2.7								
F/(C+F)=0.10	0.020	0.171	0.400	0.110	0.015	0.696	0.284	711
F/(C+F)=0.20	0.020	0.163	0.400	0.104	0.033	0.699	0.281	701
F/(C+F)=0.30	0.020	0.156	0.400	0.094	0.051	0.700	0.280	701
High Calcium Fly Ash: Specified Strength =14MPa, MSA =20mm, Slump =6cm, FM =2.7								
F/(C+F)=0.30	0.02	0.138	0.400	0.057	0.031	0.625	0.355	887

Note: γ_s denotes density of sand.

cylinder. The scaling factor for maximum size aggregate of 25 mm is proposed as 0.77 [7, 8]. This eliminates the need of increasing the specified strength to higher target strength. The basic ACI method of mixture proportioning is integrated with the proposed charts. The free water is estimated by ACI method which is then modified for fly ash concretes from water-modification charts. The water modification charts are obtained from similar flows of cement pastes for different water-cement ratios and fly ash-mortars of different fly ash-binder ratios. The volume of coarse aggregates and approximate air content are estimated with reference to fineness modulus of fine aggregates and maximum size of coarse aggregate using ACI method.

The proposed method is quite simple and efficient. It is founded on well-established ACI method of mixture proportioning. It may, however, be noted that density of fresh concrete will vary to greater extent due to inclusion of fly ash, hence, the density of fresh fly ash-concrete is not estimated by ACI method. Instead, the approximate ACI air content is used and the combined volume of cement, fly ash, water, entrained air and coarse aggregate is subtracted from $1m^3$ to obtain the volume of sand. The weight of sand is finally estimated by multiplying this volume by density of sand.

The actual strength results of proportioned concrete mixtures presented elsewhere [1] has shown that target strengths were achieved with a good accuracy. There is no need to enhance the specified strength by adding any margin for 20 mm maximum size aggregates. However, it will be prudent if the target strength is increased by 5% for each increase of 6 mm in maximum size of aggregate beyond 19/20 mm. In other words the concrete mixtures may be designed for 105% and 110% of required strength if maximum size aggregate used is taken as 25 mm and 31 mm respectively.

8. Conclusions and Recommendations

The method presented for mixture proportions of fly ash-concretes is quite simple, systematic and accurate. In the proposed method a strong theoretical basis is combined with a highly accurate and sophisticated practical method of mixture proportioning for plain cement concretes. The charts are derived from Power law, which is more suited to fly ash-concretes than Abrams water-cement ratio law. The simplicity of the method may be noted from the fact that it is based on water demand of cement and fly ash and strength results of nine mortars at required age only. The proposed method is highly recommended for mixture proportioning of structural grade fly ash-concretes as it integrates the strength data of fly ash under consideration with the well-established ACI method of mixture proportioning.

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