Optimum Utilization of Fly Ash by Different Cementing Efficiency Models in Concrete with C&D Waste

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Abstract

India alone generates Construction and Demolition (C&D) waste of 150 million tonnes annually. It can be utilised in concrete to overcome the disposal problem of C&D waste and to reduce the demand for Natural Coarse Aggregates (NCA). Using C&D waste as coarse aggregates in concrete will have a negative impact on its compressive strength. This may be enhanced by improving the pozzolanic property of cement by adding supplementary cementitious mineral admixtures. The optimum quantity of mineral admixture to be added can be determined by finding the cementing efficiency of the same by different methods such as Regression Method, Bolomey's Equation, Relative Strength Method and Strength Based Model. This study attempts to assess cementing efficiency of class C fly ash in concrete of M20 grade with C&D waste as 20% replacement for NCA. Recycled Concrete Aggregates (RCA) were obtained from site-tested concrete specimens. The scope of the work is restricted to replacement of cement by 5 wt. % to 20 wt. % of class C fly ash. Nominal Mix of M20 grade concrete without fly ash and RCA was selected as control specimen. Class C fly ash with replacement level of 15 wt. % cement showed optimum results. The cementing efficiency factor ('k' value) at an optimum replacement level of 15% was found to be greater than one.

Keywords: *Cementing Efficiency Factor, Construction and Demolition Waste (C&D Waste), Fly Ash*

1.0 Introduction

Demolition of old structures produces enormous waste leading to large quantities of concrete ruins, causing adverse effect on the environment. Construction of new structures requires a huge quantity of materials, and one of the essential materials required is coarse aggregate. Natural Coarse Aggregates (NCA) are extensively used in construction activities. With the rising demand and price of NCA, there is need to recycle C&D

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waste. Reusing C&D wastes reduces demand for NCA. The main drawback in using C&D waste in new concrete is its inconsistent quality, particularly when it is obtained from the demolition of old concrete structures [1]. When C&D wastes are suitably selected, ground, cleaned and sieved in appropriate industrial crushing plants, it can profitably be used in concrete as recycled aggregates [2]. There are different types of recycled coarse aggregates such as demolished masonry [3], recycled red clay ceramic [4], recycled waste from ready mix concrete [5], recycled ceramic [6], Recycled Concrete Aggregates (RCA) [7, 8] and recycled brick [9] with different density and strength. The difference in densities of different recycled aggregates is due to the presence of mortar particles adhered to the recycled aggregates [10]. Among all types of recycled aggregates, those obtained from concrete specimen is reported to possess highest density [11]. Compressive strength of concrete depends on density and strength of recycled aggregates and hence variation in mechanical properties of RCA is governed by amount of hydrated cement paste on the aggregate and density of RCA.

Reduction in strength of concrete with RCA can be overcome by using supplementary cementitious material such as Fly Ash as a partial replacement for cement. Fly ash is a by-product of combustion of coal in thermal power plants. It gets carried away by flue gases to the electrostatic precipitator [12]. It is a micro-filler mineral admixture and possesses cementitious properties [13]. Fly ash participates in secondary hydration, i.e., it reacts with calcium hydroxide ($Ca(OH)_2$) liberated during primary hydration of cement with water to form Calcium-Silicate-Hydrate (CSH) gel. This results an increase in strength of concrete due to the formation of extra CSH gel. Therefore, partial replacement of cement by fly ash in concrete plays a vital role in strength improvement and hence it can be used as a substitute for cement in concrete [14]. Class C fly ash based concrete exhibits improved compressive strength as compared to that of concrete with Class F fly ash [15].

Earlier studies on utilization of C&D waste reported an optimum replacement of natural aggregates of 20% to 30% [16]. Partial replacement of cement by fly ash is also restricted to 15% to 30%. Table 1 of Indian Standard Specification IS 383: 2016 [17] suggests that the extent of utilization of RCA in reinforced concrete of M25 grade is capped up to 20 % of the total aggregate content in concrete. In this study, an attempt is made to assess the compressive strength of concrete made using C&D waste as a replacement to natural aggregates and fly ash as partial substitute to cement. Conventional natural aggregate was replaced with 20 % of C&D waste. The RCA obtained from site-tested concrete specimens included concrete of different grades varying from M20 to M40. Ordinary Portland cement of grade 53 was replaced with class C fly ash by 5%, 10%, 15% and 20 wt. % cement. The objective of the study is to determine the optimum percentage of replacement level of fly ash in concrete when 20% of NCA is replaced with RCA by finding the cementing efficiency factor ‘k’ of fly ash.

2.0 Cementing Efficiency Factor (k)

Cementing efficiency factor (k) of pozzolana is the ratio of number of parts of cement in a concrete mix to one part of pozzolana in the same concrete mix for the same w/c ratio [18]. In terms of performance, the ‘k’ value of a given pozzolana of weight ‘f’ is also defined as the ‘kf’ weight of pozzolana which is equivalent to Portland cement. This is one of the practical ways to assess the impact of pozzolana on strength of hardened concrete. It is dependent on factors such as type of cement, pozzolana content, curing conditions, age, and dosage of superplasticizer. Efficiency factor indicator of how pozzolana can be used in a most efficient way in structural concrete applications.

Different models proposed for finding the cementing efficiency factor ‘k’ of a pozzolana are:

(i) **Regression Method:** The compressive strength obtained for the samples are plotted as a function of curing age and fitted to a power function. Equation (1) shows the function that can be used to represent the compressive strength of the mix substituted with a pozzolanic ingredient, and subsequently to calculate the ‘k’ values for the supplementary cementitious materials [15].

$$f_c = a\,.\,t^{kb} \qquad (1)$$

where, f_c is the compressive strength of the concrete (MPa), t is the curing age of mortar specimen (days) and a & b are numerical constants obtained from fitting the above equation to the mix [19].

(ii) **Bolomey’s Equation:** Bolomey’s compressive strength equation for structural concrete is given by equation (2) [20],

$$f_c = A\,.\left[\frac{c}{w} - 0.5\right] \qquad (2)$$

where, f_c is the compressive strength of concrete (MPa), C is the cement content (kg/m^3), W is the water content (kg/m^3) and A is a constant depending upon the type of cement and time of curing respectively. The efficiency factor ‘k’ can be computed using modified Bolomey’s equation given by equation (3).

$$f_c = A \cdot \left[\frac{c+kf}{w} - 0.5\right] \tag{3}$$

where, f is the mineral additive content (kg/m^3) replaced by percentage weight of cement. The value of A can be found from the compressive strength of nominal mix concrete at 7, 28 and 96 days.

(iii) Relative Strength Method: This method follows the basic principle of Abram's rule, which states that for a particular concrete mixture, the strength of fully compacted concrete is inversely proportional to the w/c ratio [21]. The strength equation for normal concrete is given by equation (4) and for blended concrete is given by equation (5).

For normal mixture: $$f_c = K_1 \cdot \left[\frac{1}{w/c}\right] \tag{4}$$

For blended mixture: $$f_p = K_2 \cdot \left[\frac{1}{w/(c'+kp)}\right] \tag{5}$$

where, f_c is the strength of normal mixture (MPa), f_p is the strength of blended mixture (MPa), W is the water content (kg/m^3), K_1 and K_2 are the proportionality constants, C is the cement content of normal mixture (kg/m^3), C' is the cement content of blended mixture (kg/m^3) and P is the pozzolanic material content (kg/m^3). Since the materials proportion, water-to-binder ratio, curing history and testing conditions for both normal and blended mixture are similar, it is assumed that the proportionality constants K_1 and K_2 are equal. Hence the strength development for the normal mixture is principally dependent on the rate of hydration of cement, while for the blended mixture, it is dependent on the combination of cement hydration and pozzolonic reaction. The relative strength is the ratio of strength of the blended mixture to the strength of normal mixture. The efficiency factor 'k' computed using Relative Strength Method is given by equation (6).

$$R_S = \frac{fp}{fc} = \frac{C'+kP}{C} \qquad k = \frac{Rs\,C - C'}{P} \tag{6}$$

In the methods discussed above, value of 'k' greater than 1 indicates enhanced pozzolanic performance [19].

(iv) Strength Based Model: The compressive strength of two concrete mixes (normal and blended) having the similar functionality is represented by equation (7) [21]. One mixture contains only cement, while the second mixture has cement and fly ash. The binder content of both the mixtures is same. The 28 days compressive strength of normal mix (f_c) and blended mix (f_b) differs by the contribution of fly ash.

$$k = \frac{fb - fc}{fc} \tag{7}$$

According to this method, positive value of 'k' indicates enhanced pozzolanic performance. This equation can be used only for 28 days compressive strength values. The results of 'k' values vary from model to model depending upon different parameters considered, an approach adapted, type of pozzolana used and production conditions that may include compactness, concrete mix design, curing conditions, and so on.

3.0 Experimental Details

3.1 Materials

The materials used in this research include Ordinary Portland Cement of 53 grade, class C fly ash, M-sand as fine aggregate, Natural Coarse Aggregate (NCA) and Recycled Concrete Aggregates (RCA). The Coarse aggregates passed through 20mm sieve (IS standard sieve) and were retained on 4.75 mm sieve. The RCA were obtained from the site tested concrete specimen which included concrete of various grades with strength varying from M20 to M40. The process of obtaining RCA included manual breaking of the site tested concrete specimen, mixing the material in drum mixer to remove loose mortar particles attached to the original aggregates, washing with water and sun-drying (Fig. 1).

Fig. 1 Recycled Concrete Aggregate (RCA)

Table 1 shows the properties of the materials used. Fig. 2 and Fig. 3 show the distribution of particle sizes of coarse and fine aggregates respectively.

Table 1. Properties of the Materials used in the study

Sl. No.	Material	Property Description	Test Results
1	Cement	Normal Consistency	29 %
		Fineness	4%
		Initial Setting Time	44 min
		Specific Gravity	2.99
		7-days Compressive Strength	38.69 N/mm^2
2	Fly Ash	Specific Gravity	1.90
3	M-Sand	Sieve Analysis	Zone II
		Specific Gravity	2.65
		Water Absorption	2.40%
4	NCA	Specific Gravity	2.70
		Water Absorption	1.60%
5	RCA	Specific Gravity	2.45
		Water Absorption	4.65%

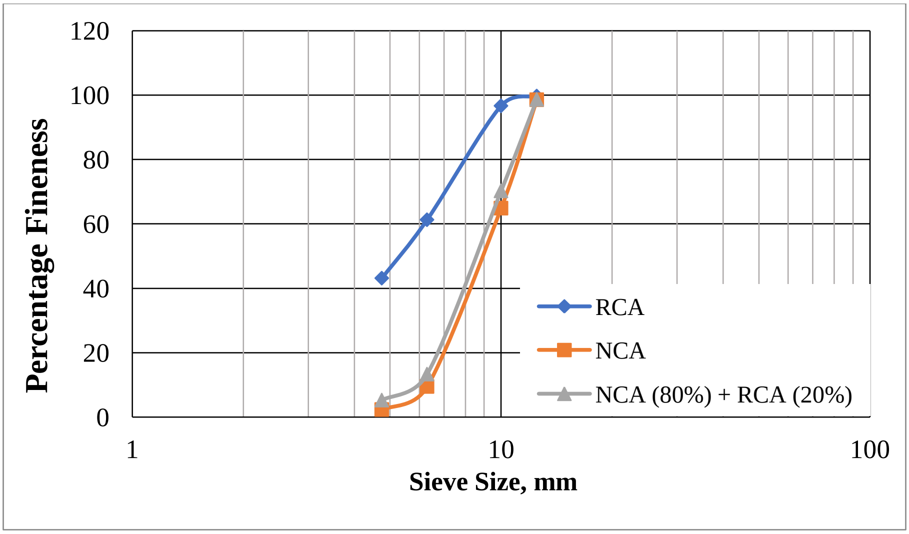

Fig. 2. Distribution of particle sizes of coarse aggregates

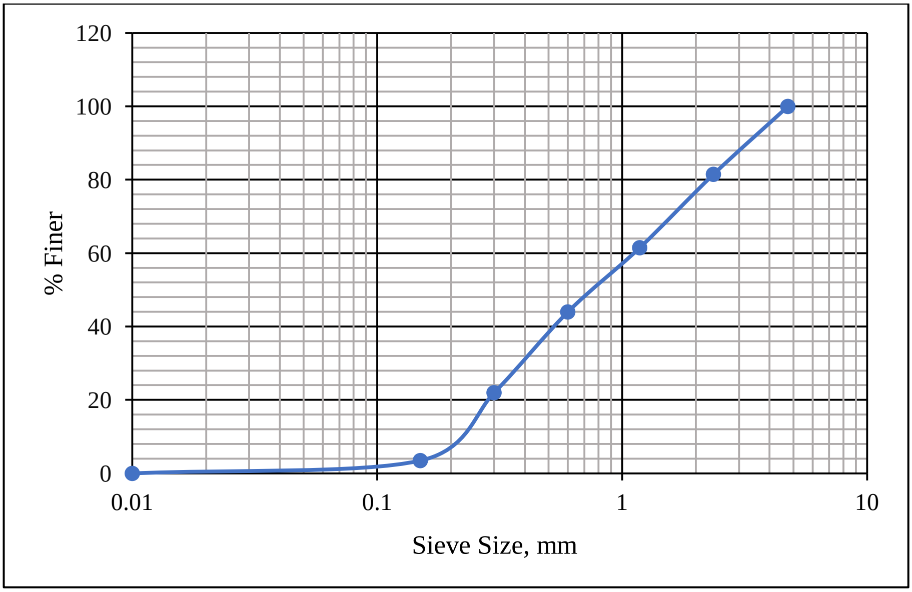

Fig. 3. Distribution of particle sizes of fine aggregates

3.2 Mix Proportioning

A control mix of Nominal Mix (NM) with grade M20 concrete was prepared without fly ash and RCA. This is considered to be the benchmark as the efficiency of NM is considered to be unity and the efficiency of all other mix proportions are determined in comparison to the unit value of NM. The cementing efficiency was attempted on concrete mix designed as per IS 10262: 2019 [22] with class C fly ash as a substitute to cement by 5%, 10%, 15% and 20% and replacing 20% of NCA with RCA. The Mix Proportions for different fly ash content is presented in Table 2. As per elsewhere studies, use of RCA reduces the workability of the fresh concrete. For better workability of concrete, water to binder ratio of 0.55 is considered in this research and water to binder ratio is maintained constant for all the mix proportions.

Table 2. Mix Proportion in kg/m^3

Replacement of Fly Ash Level	Cement	Fly Ash	Water	NCA	RCA	Fine Aggregates
Nominal Mix (NM)	358.47	0.00	197.16	1115.97	0.00	700.27
5% FA	340.55	17.92	197.16	887.94	203.90	696.48
10% FA	322.63	35.85	197.16	883.10	202.79	692.69
15% FA	304.70	53.77	197.16	878.27	201.68	688.90
20% FA	286.78	71.69	197.16	873.43	200.56	685.10

Cubes of size 0.15 m x 0.15 m x 0.15 m each for 7 days, 28 days and 96 days were cast and cured. A total of 135 cubes were tested in compression in accordance with IS 516: 1959 [23].

4.0 Results and Discussion

The 7 days, 28 days and 96 days mean compressive strength of cubes for different replacement levels of fly ash are shown in Table 3. Table 3 illustrates the strength of respective concrete mix proportion indicating strength gain and strength loss respectively. The variation in strength of cement modified concrete is compared with the strength of nominal mix concrete. Based on experimental investigations it can be observed that the mean compressive strength was found to vary from +10% to -10% when cement was replaced by fly ash up to 20% except for 5% fly ash blended cement. It was interesting to note that, when 15% of cement was replaced by fly ash, compressive strength of blended cement-based concrete was equivalent to nominal mix. Compressive strength of concrete was found to increase with increase in curing time and highest mean compressive strength value is observed for 96 days with 15% replacement of cement with fly ash.

Table 3. Mean Compressive Strength of Cubes

Sl. No.	Design Mix	Mean Compressive Strength (MPa) and variation (%) w.r.t. NM					
		7 days		28 days		96 days	
		N/mm^2	variation	N/mm^2	variation	N/mm^2	variation
1	NM	14.92	-	24.45	-	34.54	-
2	5% FA	13.07	-12.40	22.81	-6.71	28.88	-16.39
3	10% FA	14.28	-4.29	23.14	-5.36	33.58	-2.78
4	15% FA	14.96	0.27	24.59	0.57	36.67	6.17
5	20% FA	14.80	-0.80	23.42	-4.21	33.69	-2.46

Variation in mean compressive strength with its age in days for different mix proportions is shown in Fig. 4. The pozzolanic performance for 10% and 20% replacement levels are almost same (Fig. 4). Highest pozzolanic performance based on the mean compressive strength for 7 days, 28 days and 96 days is for 15% replacement level. Mean compressive strength of nominal mix concrete and 15 % fly ash based cement concrete is marginally equivalent for 7 days and 28 days. However, the strength gain after 28 days was greater for 15% fly ash based cement concrete. This is due to the secondary reaction between fly ash with the calcium hydroxide ($Ca(OH)_2$) liberated on hydration, to form compounds having cementitious properties.

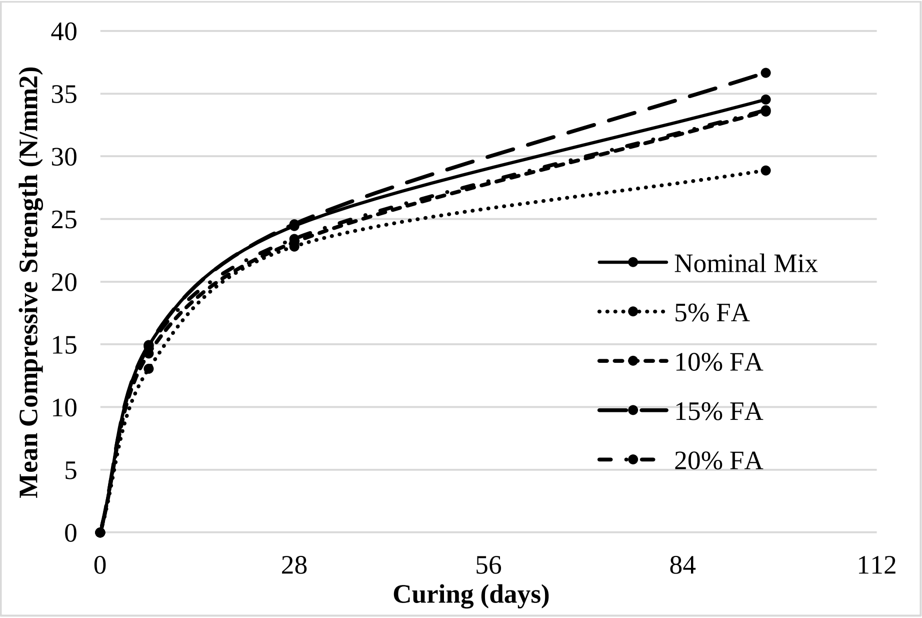

Fig. 4. Variation of Mean Compressive Strength of Cubes

Cementing efficiency factor (k) was determined for different mix proportions using different methods and the results are presented Table 4. Values of ‘k’ determined by different methods and at different time intervals exhibit an increase in efficiency factor when replacement level of fly ash was increased from 5% to 15%. Further increase in fly ash content resulted in reduction in efficiency factor. The reduction in efficiency factor for 7 days strength of concrete was found to vary from 1.8% to 6% across all the methods used for assessment. Efficiency factor ‘k’ increased with curing period of concrete except for values obtained for Regression method. Highest efficiency factor ‘k’ of the order 1.4108 corresponded to 15% of cement substituted with class C fly ash and the samples cured for 96 days.

Table 4. ‘k’ values determined by different methods for different durations in days

Sl. No	Mix Design	Regression Method			Bolomey's Equation			Relative Strength Method			Strength Based Model
		7	28	96	7	28	96	7	28	96	28
1	**5% FA**	0.7636	0.9661	0.8662	-0.7983	0.0277	-1.3743	-1.4804	-0.3411	-2.2749	-0.067
2	**10% FA**	0.9052	0.9745	0.9690	0.6911	0.6089	0.7986	0.574	0.4606	0.7224	-0.0539
3	**15% FA**	0.9796	1.0362	1.0234	1.0141	1.0264	1.2979	1.0194	1.0363	1.4108	0.0055
4	**20% FA**	0.9624	0.9907	0.9712	0.9713	0.8448	0.9099	0.9625	0.7880	0.8777	-0.0424

Graphical representation of ‘k’ values by Regression Method, Bolomey’s Equation and Relative Strength Method for 28 days and for 10%, 15% and 20% replacement level of fly ash (Fig. 5). The use of 5% fly ash resulted in non-reliable values of ‘k’ by Bolomey’s Equation and Relative Strength Method (Table 4). From Fig. 5 it can be seen that, the ‘k’ value for 10% and 20% replacement level of fly ash lies below the datum line i.e., for k=1. But for 15% replacement level of fly ash, the ‘k’ value by all three methods lie above the datum line indicating that 15% replacement level of fly ash shows reliable results which can even be observed by the compressive strength values tabulated in Table 3. The positive value of ‘k’ is obtained for 15% replacement level of fly ash calculated from Strength Based Model indicating enhanced pozzolanic performance for this replacement level of fly ash. Hence for the concrete materials used for study, it is economical to substitute 15% of cement with class C fly ash to arrive at improved performance of concrete.

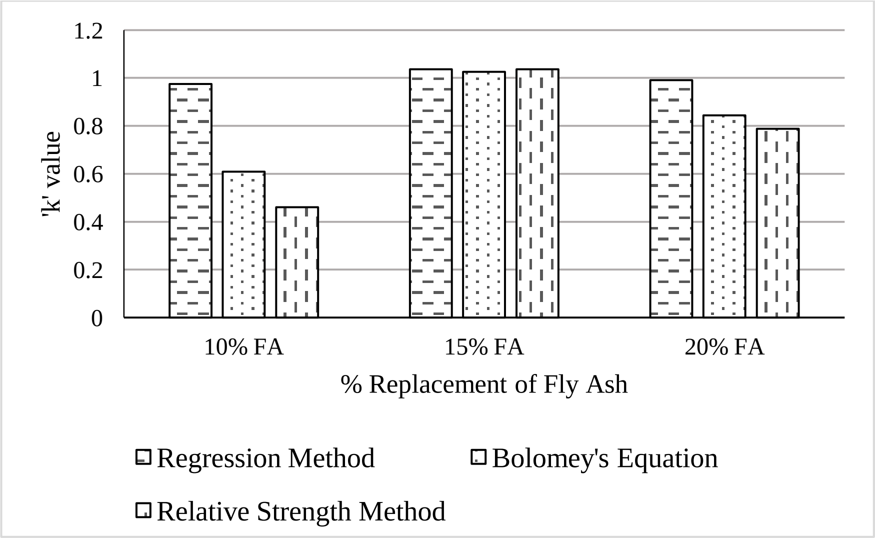

Fig. 5. Plot of ‘k’ values for 28 days

Conclusion

The conclusions derived from this study are as follows.

i. The compressive strength of concrete was found to marginally higher relative to control mix (nominal concrete) when 15% cement was replaced by class C fly ash. This indicates increased pozzolanic performance which is reflected by its compressive strength.
ii. The compressive strength of concrete at 15% replacement level of cement by class C fly ash is nearly equal to the strength of nominal concrete for 7days and 28days but gains more strength after 28days. This gain in strength after 28days achieved is due to the pozzolanic action of fly ash.
iii. The maximum value of cementing efficiency factor ‘k’ obtained is 1.4108 for concrete at an age of 96days which has cement being replaced by 15% fly ash. This replacement level result in a more efficient concrete compared to the nominal mix concrete. Hence the optimum replacement level of cement by fly ash is 15%.
iv. This approach of replacing cement by fly ash would result in reduction of carbon footprint as the consumption of cement will be reduced.

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