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Strength Behaviour of Mortar Using Fly Ash as Partial Replacement of Cement

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Abstract

This paper reports the results of an experimental investigation carried out to study the effects of fly ash on strength development of mortar and the optimum use of fly ash in mortar. Cement was partially replaced with six percentages (10%, 20%, 30%, 40%, 50% and 60%) of class F fly ash by weight. Ordinary Portland cement (OPC) mortar was also prepared as reference mortar. Compressive as well as tensile strengths of the mortar specimens were determined at 3, 7, 14, 28, 60 and 90 days. Test results show that strength increases with the increase of fly ash up to an optimum value, beyond which, strength values start decreasing with further addition of fly ash. Among the six fly ash mortars, the optimum amount of cement replacement in mortar is about 40%, which provides 14% higher compressive strength and 8% higher tensile strength as compared to OPC mortar.

Keywords: Fly Ash, Cement, Mortar, Compressive Strength, Tensile Strength, Hydration.

1. Introduction

Portland cement concrete is and will remain a major construction material of choice in Civil Engineering construction. Portland cement is the most important constituent of concrete. Unfortunately, cement manufacturing consumes large amount energy about $7.36*10^6$ kJ per tone of cement [1]. Also, approximately 1 tonne of CO_2 is released into the atmosphere during the production of 1 tonne of cement [2]. Thus partial replacement of Portland cement by mineral by-products such as fly ash, slag, silica fume can significantly reduce CO_2 emission [3]. Fly ash is used in concrete to achieve energy conservation and economic, ecological and technical benefits [4]. It is used as pozzolanic mineral admixture in concrete. According to ASTM C125, Pozzolan is a siliceous or siliceous and aluminous material which itself possesses little or no cementitious value but will in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Fly ash is usually found to improve workability and contribute to strength development and hence considered to be an effective cementitius component of concrete [5]. It also has been widely used as replacement of cement in normal and high strength concrete. The main objectives of using fly ash in high strength concrete are to reduce heat generation and to obtain better durability properties [6]. Fly ash also has high fineness, which decreases the porosity and pore size and increases the compressive strength [7].

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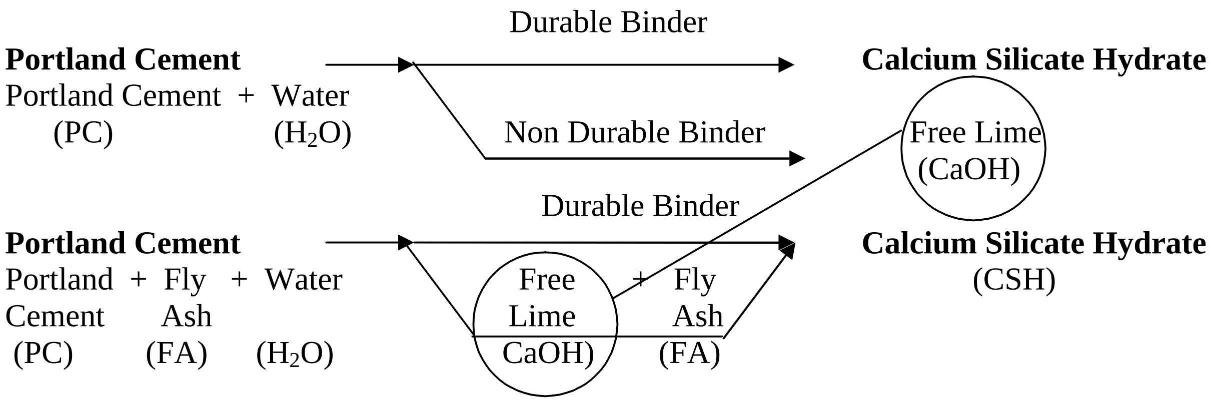
Fly ash is comprised of the non-combustible mineral portion of coal. When coal is consumed in the power plant, it is first ground to the fineness of powder. Blown into the power plants boiler, the carbon is consumed, leaving molten particles rich in silica alumina and calcium. These particles solidify as microscopic, glassy spheres that are collected from the power plants exhaust before they can fly away- hence the products name fly ash [8]. There are two basic types of fly ash: Class F and Class C. According to ASTM C618, fly ash belongs to Class F if (SiO_2+Al_2O_3+Fe_2O_3) > 70% and belongs to Class C if 70% > (SiO_2+Al_2O_3+Fe_2O_3) > 50% [9]. Both these fly ashes undergo pozzolanic reaction with lime (Calcium hydroxide) created by hydration of cement and water to form calcium silicate hydrate like cement. In addition, some Class C fly ashes may possess enough lime to be self cementing in addition to the pozzolanic reaction with lime from cement hydration.

Hydration Products of Cementing Binders:



Through pozzolanic activity, fly ash combines with free lime to produce the same cementitious compounds formed by the hydration of Portland cement [10]. Due to this series of chemical reaction, rate of strength gain for fly ash concrete is relatively slower at early ages of curing. During the last few years, some cement companies have started using fly ash in manufacturing cement, which is known as "Pozzolana Portland Cement," but the overall percentage utilization remains very low and most of the fly ash is dumped at landfills [11].

2. Research Significance

The net cement production in the world is expected to increase form about 1.4 billion tones in 1995 to almost 2 billion tonnes in the year 2010. This would lead to the emission of about 2 billion tonnes to CO_2 in the atmosphere every year [12]. In order to reduce the emission of harmful green house gasses, use of cement must be replaced with other environmentally friendly and efficient cmentitious material such as fly ash [13]. It also ensures the proper utilization of fly ash, by-product of coal combustion in power plants, in an effective way which otherwise been dumped making environmental hazard. In the present study, fly ash mortar specimens were made with different cement replacement levels and cured up to 90 days. Compressive as well as tensile strength tests were carried out at different period to observe the performance of fly ash mortar.

3. Experimental program

The experimental program was planed to quantify the compressive strength and tensile strength of mortars using fly ash as replacement of cement. Cement replacement at various percentage levels were used in this investigation to observe the effects of different fly ash levels in mortar in contributing the compressive and tensile strength at various ages of curing.

(a) Cement: ASTM Type-I Portland Cement conforming to ASTM C-150 [14] was used as binding material. The physical properties and chemical compositions of OPC are given in Table-1.

(b) Fly ash: A low calcium ASTM Class F fly ash was used in this investigation. Physical properties and chemical compositions of the used fly ash are given in Table-1.

TABLE 1 : PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF ORDINARY PORTLAND CEMENT AND FLY ASH

Physical properties	**ASTM Type-I Cement**	**ASTM Class F Fly ash**
Fineness		
Passing #200 Sieve, %	95%	99%
Blains, m^2/kg	3400	4000
Vicat Setting Time, min		
Initial	145	--
Final	190	--
Compressive Strength, MPa		
3 days	15.4	--
7 days	19.9	--
28 days	30.2	--
Specific gravity	3.15	--
Chemical analysis, %		
Calcium oxide, CaO	65.18	8.6
Silicon dioxide, SiO_2	20.80	59.3
Aluminum oxide, Al_2O_3	5.22	23.4
Ferric oxide, Fe_2O_3	3.15	4.8
Magnesium oxide, MgO	1.16	0.6
Sulfur trioxide, SO_3	2.19	0.1
Sodium Oxide, Na_2O	--	3.2
Loss on ignition	1.70	--
Insoluble residue	0.6	--

(c) Sand: Locally available natural sand passing through 4.75 mm sieve and retained on 0.015 mm sieve was used for this program. Gradation of this sand is given in Table-2.

TABLE 2 : GRADING OF FINE AGGREGATE

Sieve size	**Cumulative % Passing (for Compressive Strength)**	**Cumulative % Passing (for Tensile Strength)**
1.18 mm (No. 16)	100	100
850 µm (No. 20)	--	90
600 µm (No. 30)	97	0
425 µm (No. 40)	73	--
300 µm (No. 50)	28	--
150 µm (No. 100)	3	--

3.1. Variables studied

(a) Mortar quality: Six different mix proportions of cement fly ash (90:10, 80:20, 70:30, 60:40, 50:50, 40:60) were used as cmentitious material. Cement fly ash mix ratio of 100:0 i.e. plain cement mortar specimens were also cast as reference mortar for comparing the properties of fly ash mortars. The fly ash mortar means the mortar made by using cement and fly ash as cementitious material with sand and water.

(b) Exposure period: Specimens were tested periodically after the specified curing periods of 3, 7, 14, 28, 60 and 90 days.

(c) Size of specimens: 50 mm x 50 mm x 50 mm cube for compressive strength and briquet specimens of standard size for tensile strength tests were prepared as per ASTM standard.

(d) Mortar mix ratios: The mix ratio of cementitious material and sand was 1:2.75 for compressive strength and 1:3 for tensile strength test specimens. Details of mix proportion and materials are shown in Table-3.

TABLE 3: MIX PROPORTIONS OF VARIOUS INGREDIENTS OF CEMENT: FLY ASH MORTAR

Sl. No	Specimen Type/ Materials	For Compressive strength test	For Tensile strength test	Remarks
1.	Specimen	50 mm Cube*	25 mm Briquette**	Materials required for 6 specimens
2.	Cementitious materials (Cement + Fly Ash)	500 gm	300 gm	
3.	Sand	1375 gm	900 gm	
4.	w/cm ratio	0.485	0.44***	
4.	Water	242 ml	132 ml	

*ASTM C109-87 ; **ASTM C190-85; *** For Normal Consistency = 27%; cm= Cementitious material

(e) Curing environment and testing: A total of 400 mortar specimens were cast in the laboratory. After casting, the specimens were kept at 27°C temperature and 90% relative humidity for 24 hours. After demoulding, all the specimens were cured in water in a curing tank at room temperature. After specific exposure period, specimen was tested for compressive strength and tensile strength in accordance with test procedure ASTM C109-87 [15] and C190-85 [16].

4. Results and Discussion

4.1. Compressive Strength

The compressive strength of OPC and fly ash mortars as listed in Table-4, has been graphically represented in Figure-1. Also for the ease of comparison, the relative compressive strengths are plotted in Figure-2.

TABLE 4 : COMPRESSIVE STRENGTH (MPa) OF CEMENT : FLY ASH MORTARS FOR VARIOUS REPLACEMENT LEVEL

Replacement Level	Ce:FA	Ce:FA	Ce:FA	Ce:FA	Ce:FA	Ce:FA	Ce:FA
Curing Period (days)	**100:0**	**90:10**	**80:20**	**70:30**	**60:40**	**50:50**	**40:60**
3	14.3	13.0	12.2	11.5	10.6	7.0	3.7
7	20.3	19.1	18.4	17.0	16.2	13.0	7.2
14	23.6	22.7	22.1	21.5	20.8	17.7	10.5
28	28.0	27.2	26.9	27.0	27.7	26.5	20.2
60	30.9	30.5	31.1	31.8	33.2	30.4	28.1
90	33.3	33.9	35.0	36.5	38.0	34.9	31.7

Ce : Cement ; FA: Fly Ash

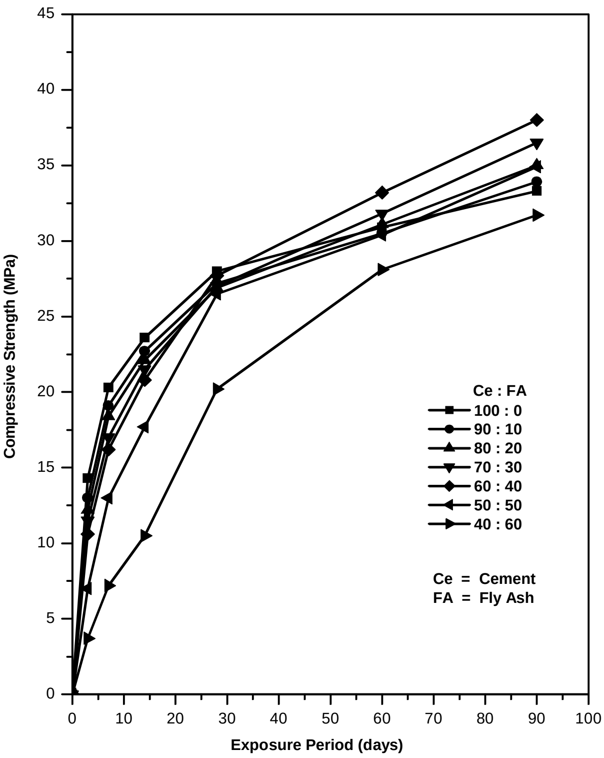


Figure 1: Compressive strength- exposure time relation for cement:fly ash mortars

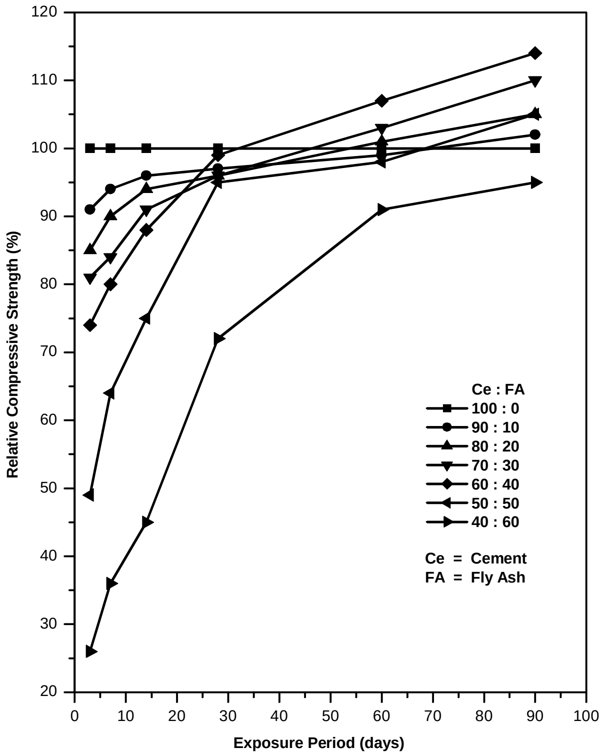


Figure 2: Relative compressive strength-exposure time relation for cement:fly ash mortars

Among all the mixes, for 3 days and 7 days compressive strength, no fly ash concrete achieved maximum strength. Test result showed that the 3 days compressive strength for OPC mortar is 9%, 15%, 19%, 26%, 51% and 74% higher than fly ash mortar of replacement level 10%, 20%, 30%, 40%, 50% and 60%. Up to curing period of 14 days, compressive strength is seen to decrease with the increase in fly ash content when compared with no fly ash mortar.

28 days compressive strength test result of the specimens up to 50% replacement level were very similar with OPC mortar strength. Compressive strength are slightly lower by 3%,4%, 4%, 1% and 5% for fly ash mortar of cement fly ash ratio 90:10, 80:20, 70:30, 60:40 and 50:50 respectively. 28 days strength for the 60% fly ash replacement mortar was lower by 28% when compared with no fly ash mortar.

60 days compressive strength data obtained for 20%, 30% and 40% fly ash replacement mortar were respectively 1%, 2% and 7% higher than no fly ash mortar. 10%, 50% and 60% replacement level mortar strength were lower than no fly ash mortar by 1%, 2% and 9%.After 90 days, maximum compressive strength was obtained for 30% and 40% replaced mortar specimens with an increase in strength of 10% and 14% respectively as compared to OPC mortar. Also 10%, 20% and 50% replacement provided an increase in strength of 2%, 5% and 5% respectively when compared with no fly ash mortar.

Cement normally gains its maximum strength within 28 days. During that period, lime produced form cement hydration remains within the hydration product. Generally, this lime reacts with fly ash and imparts more strength. For this reason, mortar made with fly ash will have slightly lower strength than cement mortar up to 28 days and substantially higher s trength within 90 days. Fly ash retards the hydration of C_3S in the early stages but accelerates it at later stages [17]. Conversely in cement mortar, this lime would remain intact and with time it would be susceptible to the effects of weathering and loss of strength and durability. Yamato and Sugita [18] found that the later age strength of fly ash concrete was higher than that of the control and that the modulus of elasticity was comparable to that of concrete made with moderate heat Portland cement.

4.2. Tensile Strength

The tensile strength of mortar mixes made with and with out fly ash were determined at the ages of 3, 7, 14, 28, 60 and 90 days. Figure-3 shows the variation of tensile strength with age for different fly ash mortars. These values are also presented in Table-5. Also for the ease of comparison, the relative tensile strength is plotted in Figure-4.

TABLE 5 : TENSILE STRENGTH (MPa) OF CEMENT : FLY ASH MORTARS FOR VARIOUS REPLACEMENT LEVEL

Replacement Level	**Ce:FA**	**Ce:FA**	**Ce:FA**	**Ce:FA**	**Ce:FA**	**Ce:FA**	**Ce:FA**
Curing Period (days)	**100:0**	**90:10**	**80:20**	**70:30**	**60:40**	**50:50**	**40:60**
3	2.7	2.6	2.4	2.4	2.3	1.9	1.3
7	3.2	3.1	2.9	2.9	2.8	2.6	2.0
14	3.4	3.3	3.1	3.1	3.1	3.0	2.5
28	3.7	3.6	3.4	3.5	3.6	3.5	3.1
60	4.0	3.9	4.0	4.1	4.2	4.1	3.7
90	4.3	4.3	4.4	4.6	4.7	4.6	4.1

Ce : Cement ; FA: Fly Ash

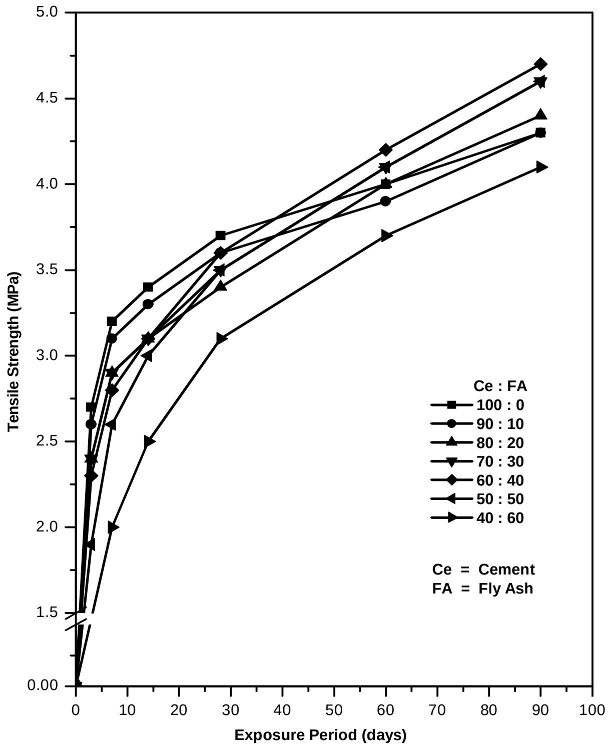


Figure 3: Tensile strength- exposure time relation for cement:fly ash mortars

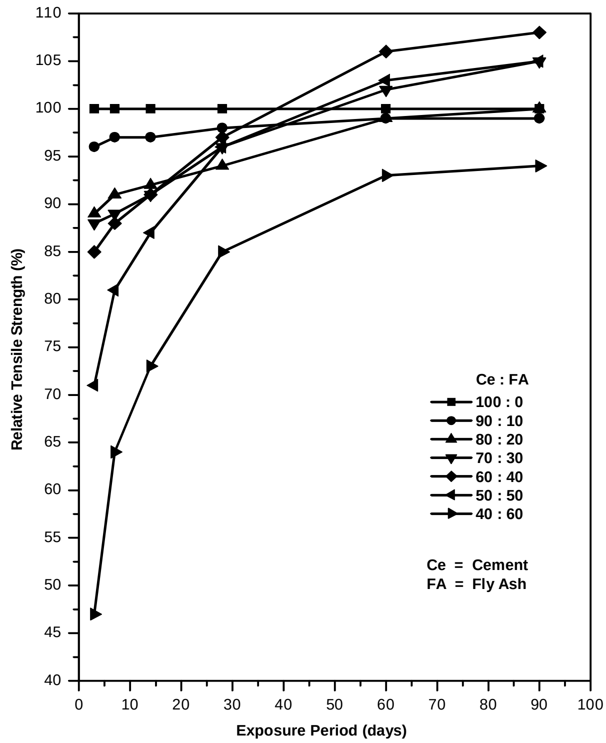


Figure 4: Relative tensile strength-exposure time relation for cement:fly ash mortars

The tensile strength of the specimens is seen to increase with age. At early ages of curing (3 days and 7 days) the tensile strength decreases with increase in fly ash content in concrete. However the rate of decrease diminished with increasing age of curing. The fly ash mortar specimens shows that tensile strength results are almost identical with that of reference mortar up to cement replacement of 50% at 28 days. Tensile strength values are 98%, 94%, 96%, 97% and 96% for fly ash mortar of replacement level of 10%, 20%, 30%, 40% and 50% for the curing age of 28 days. 60% replaced fly ash mortar achieved about 85% strength of OPC mortar.

After 60 days, maximum tensile strength of 4.1 MPa was achieved for the fly ash mortar of 40% replacement level, with an increase of 6% higher than the no fly ash mortar. Even 30%, and 50% fly ash mortar showed higher tensile strength of 2% and 3% respectively than OPC mortar. After 90 days, maximum tensile strength of 4.7 MPa was also achieved for 40% replacement mortar, which is 8% higher than the reference mortar. Even 30% and 50% fly ash replaced mortar showed higher strength. This may be due to the fact that fly ash is a pozzolanic material. The reactive silica of pozzolan and calcium hydroxide producing form the hydration of cement react together and produce calcium silicate hydrate. This imparts strength for cement mortar. As it takes time to produce $Ca(OH)_2$ by hydration of cement, strength gaining rate slows down at initial ages of curing but increases for later age of curing. However, 60% fly ash mortar provides a decrease in strength of about 6%. Korac and Ukraincik [19] found that the early-age strengths upto 50% fly ash concretes were lower than for the controls; after long curing period the strengths were comparable.

4.3. Heat of Hydration

The hydration of cement is an exothermic reaction. High amount of heat is generally developed during this reaction. The generated heat causes the rise in temperature and accelerates the setting time and strength gain of mortar. In many structures, the rapid heat gain of cement increases the chances of thermal cracking, leading to reduce concrete strength and durability. The applications of replacing cement by high percentage of fly ash can reduce the damaging effects of thermal cracking. The cumulative heat of hydration evolved from paste containing fly ash remained less than that form ordinary Portland cement paste [20].

The rate of formation of C-S-H in the fly ash-water mixture is normally slower than that in a cement-water mixture. Thus, at ages greater than 60 days, fly ash-cement-water continues to gain strength, while the cement water pastes do not show significant gain in strength. In the present study, for both compressive strength and tensile strength, the gain in strength for fly ash mortar is slower at early ages indicating lesser amount of heat generation. Hence, cement fly ash mix mortar is suitable for mass concreting works.

5. Conclusions

Based on the results of the investigation conducted on different fly ash mortars made with various level of cement replacement and cured for various curing period up to 90 days, the following conclusions can be drawn:

(1) The rate of gain in strength of fly ash mortar specimens is observed to be lower than the corresponding OPC mortar.
(2) Fly ash mortar provides satisfactory or higher strength as compared with OPC mortar.

(3) Fly ash mortar mix having various cement replacement level up to 50% exhibited satisfactory results for both compressive and tensile strength.

(4) The optimum fly ash content is observed to be 40% of cement. Fly ash mortars with 40% cement replacement shows around 14% higher compressive strength than OPC mortar after 90 days curing. The corresponding increase in tensile strength is reported to be around 8%.

(5) Use of high volume fly ash in any construction work as a replacement of cement, provides lower impact on environment (reduce CO_2 emission) and judicious use of resources (energy conservation, use of by-product)

(6) Use of fly ash reduces the amount of cement content as well as heat of hydration in a mortar mix. Thus, the construction work with fly ash concrete becomes environmentally safe and also economical.

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