

Optimization of Cement Replacement by Fly Ash in Compressive Strength of Portland Cement Concrete

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Abstract

The production of cement has been known for its additive role in environmental pollution. As a measure of abatement of pollution effort, scientist have evoked the concept of diluting cement with various pozzolanic additive like fly ash, blast furnace slag etc. Many of these additives were found to be acceptable for cement replacement, but their exact role and efficacy remains elusive. In the present study, fly ash was added as a partial replacement of cement, followed by the measurement of compressive strength after curing for periods of 7, 14, 21, 28 and 56 days. The above experiment was conducted after determining the compressive strength of concrete (without fly ash) for periods of 7, 14, 21, 28 and 56 days for comparison purpose. The main findings of the work are: The 28 day compressive strength of concrete up to 30% replacement level (with fly ash) is higher than OPC concrete. However, the compressive strength of concrete above 30% replacement level is lower than OPC concrete. The seven-day compressive strength of concrete at all replacement levels has been found to be lower as compared to concrete without any replacement.

Keywords: Cement, concrete, fly ash, compressive strength, water-cement ratio

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INTRODUCTION

Concrete is the versatile, durable, sustainable, indispensable, economical and most widely used construction material, of which, cement is an integral constituent. Concrete is a composite material that could be used either alone or reinforced with some other materials like steel, depending on the design of the structure.

Environmental pollution due to industries and industrial waste has become a knocking problem in recent years as it is potentially detrimental to environment and human health. The emerging trends in environmental regulations related to disposal of wastes such as fly ash (FA), granulated blast furnace slag (GBFS) or silica fume (SF) have opened the door of growing interest in using these wastes as construction materials partially replacing Portland cement in concrete [1]. Furthermore, energy saving, high cost of cement and pressure of environmental scientist strengthen the use of by-product cementitious materials, such as fly ash, granulated blast furnace slag

silica fume to replace cement in concrete [2]. Research concerning the use of mineral admixtures, especially fly ash (FA) and silica fume (SF), to augment the properties of concrete has been going on for many years [3]. Many mineral admixtures are obtained as by-products from other industries, and these waste by-products can be used to reduce the amount of cement required, and thus the cost of concrete.

Fly ash is a pozzolanic material. It is a finely-divided amorphous alumino-silicate with varying amounts of calcium, which when mixed with Portland cement and water, will react with the calcium hydroxide released by the hydration of Portland cement to produce various calcium-silicate hydrates (C-S-H) and calcium-aluminate hydrates. Some fly ashes with higher amounts of calcium will also display cementitious behaviour by reacting with water to produce hydrates in the absence of a source of calcium hydroxide. These pozzolanic reactions are beneficial to the concrete in that they increase the quantity of

the cementitious binder phase (C-S-H) and, to a lesser extent, calcium-aluminate hydrates, improving the long term strength and reducing the permeability of the system. Both of these mechanisms enhance the durability of the concrete [4].

The hydration reaction of cement is exothermic in nature and the rise in temperature of concrete mass exerts temperature stresses which can lead to micro cracks. When fly ash is used as part of cementitious material, the liberated heat is low which staggers through pozzolanic reaction path. This has the effect to reduce micro-cracking and improve soundness of concrete mass, which may in turn help increasing the compressive strength of concrete [5].

Fly ash has negative effects on the strength of concrete at early ages [6], however FA concretes may have better strength performance when prepared at lower water to binder ratios. While fly ash reacts (undergoes hydration) at a relatively slower rate at the beginning, which leads to lower compressive strength during in the initial days after mixing, the higher strength is achieved in later ages [7, 8]. The particle size of fly ash plays an important role in the strength development. It has been observed that in the long-term, the strength of concrete increases with increase in the fly ash content but the strength value starts decreasing with the addition of higher amount of fly ash [7].

It has been found that the hydration reaction, packing effect and pozzolanic reaction affect the compressive strengths of mortars with fly ash replacement. It was concluded that at early ages, the strength of fly ash mortar due to packing effect is more than that due to pozzolanic reaction [9]. It has been widely reported that the fly ash fineness plays an important role on the strength development [9, 10]. Various treatments that can be used to modify the properties of fly ash include sieving, magnetic extraction, grinding, mechanical separation etc. These modifications improve the compressive strength and microstructural properties of fly ash mortars [11–13]. Several studies have shown that the compressive and flexural strengths of mortars and cement pastes are higher when cured at

higher temperature [14]. Strength development has also been found to be sensitive to relative humidity [15].

In this work, the influence of fly ash as a cement replacement on the compressive strength of M 20 concrete after different curing periods (7, 14, 21, 28 and 56 days) was studied keeping water-cement ratio constant at 0.45. The results were compared with the OPC concrete without any fly ash. The effect of water-cement ratio on the compressive strength of concrete was also studied.

EXPERIMENTAL

Raw Materials

The raw materials used in the study of the influence of water-cement ratio and fly ash on the compressive strength of concrete are: fly ash, cement, fine aggregate (sand) and coarse aggregate (gravel).

Fly Ash

Fly ash (Figure 1), was procured from Tata Power Co. Ltd, Jojobera, Jamshedpur, India. According to ASTM C618-12a, the fly ash is mostly divided in to two distinct categories i.e. low calcium fly ash (Class F, $\text{CaO} < 10\%$) and high calcium fly ash (Class C, $\text{CaO} > 10\%$) [16]. In the present study, low calcium fly ash (Class F) was used. The chemical composition of fly ash (FA) is given in Table 1, and the physical properties of FA are shown in Table 2. The particle size distribution of FA is shown in Figure 2.

Table 1: Chemical Composition of Fly Ash.

Chemical Constituents	Percentage
SiO_2	51.11
Al_2O_3	29.73
Fe_2O_3	9.60
CaO	2.19
MgO	0.74
Na_2O	0.57
K_2O	0.40
P_2O_5	-
MnO	-

Table 2: Physical Properties of Fly Ash.

Physical Properties	Fly Ash
Colour	Gray
Form	Powder
Plasticity	Non plastic
Apparent Specific Gravity	1.97



Fig. 1: Fly Ash.

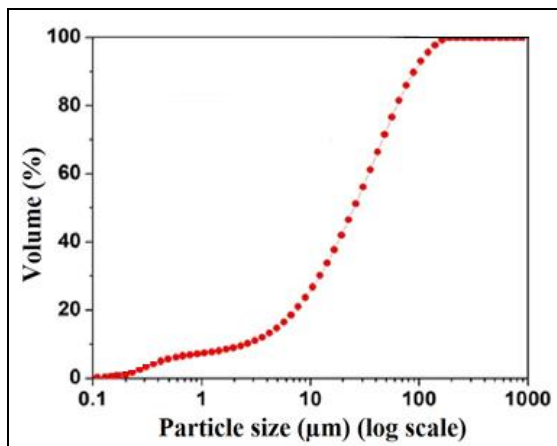


Fig. 2: Particle Size Distribution of Fly Ash.

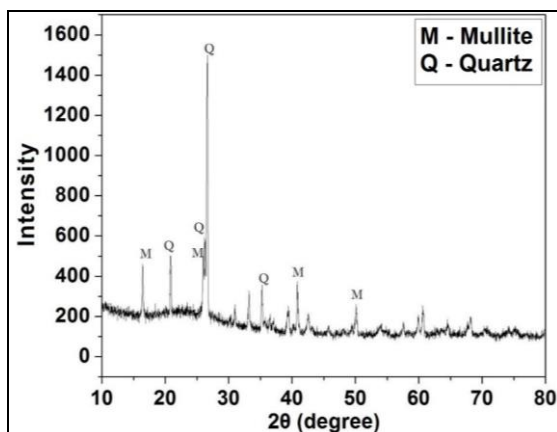


Fig. 3: X-Ray Diffraction of Fly Ash.

The mineralogical composition of fly ash as determined by XRD is shown in Figure 3. The XRD result shows the presence of mullite, quartz, magnesium silicate and iron oxide.

Cement

Ordinary Portland cement (OPC) IS 8112:1989- grade conforming to type I ASTM C150 M-16e1, was used in this study [17]. The physical properties of the cement are given in Table 3.

Table 3: Physical Properties of Ordinary Portland Cement (OPC).

Characteristics	Values
Specific Gravity	3.13
Standard Consistency (%)	32
Initial Setting Time (min)	105
Final Setting Time (min)	260

Fine Aggregate (Sand)

Washed and oven dried local river sand, (sieve analysis, grading zone II) was used as fine aggregate. The specific gravity and fineness modulus of fine aggregate was found to be 2.61 and 2.849 respectively. The sieve analysis of fine aggregate is given in Table 4 and Figure 4.

Coarse Aggregate

Locally available crushed, angular, graded coarse aggregate of nominal maximum size 20 mm was used for this study. The aggregates were thoroughly washed with water and oven dried before being used in concrete making. The specific gravity and fineness modulus of coarse aggregate were found to be 2.63 and 7.207 respectively. The sieve analysis of coarse aggregate is given in Table 5 and Figure 5.

Slump Test

One method of evaluating workability of concrete is slump test (ASTM C143M-15a) [18]. This test was carried out with M 20 (1:1.5:3) grade concrete having varying water-cement ratio (0.45, 0.50, 0.55, 0.60, 0.65, 0.70 and 0.80). The workability includes mixability, placeability, mobility, compactability and finishability [19]. It is also an indirect measurement of concrete consistency or stiffness, which indicates how much water has been used in the mix.

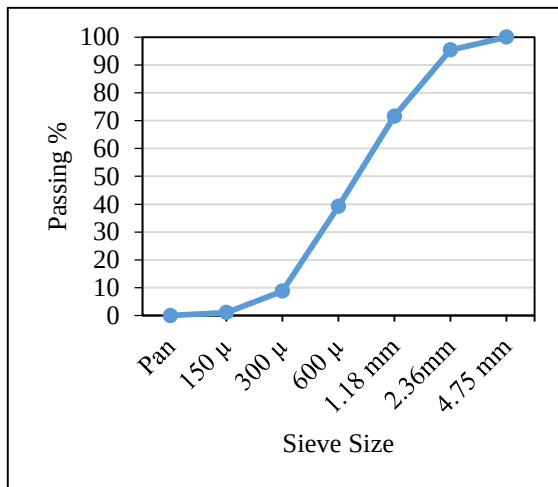
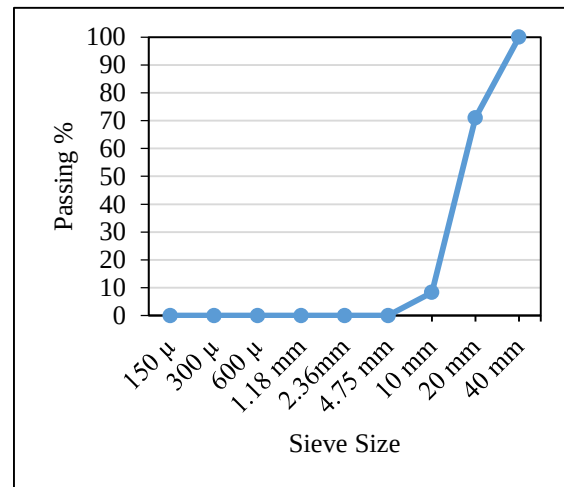
Preparation of Concrete and Test Specimens

A mix ratio of 1:1.5:3 (M 20 grade) was prepared with different water-cement ratio (0.45, 0.50, 0.55, 0.55, 0.60, 0.65, 0.70 and 0.80). The purpose of using different w/c ratio was to study the effect of w/c ratio on the compressive strength of concrete. The mixed concrete was then placed in properly cleaned

Table 4: Sieve Analysis of Fine Aggregate.

Sieve Size	Weight Retained (g)	Cumulative Weight Retained	Cumulative % Weight Retained	Passing %	Standard % Weight Passing for Zone II
4.75 mm	-	-	-	100	100
2.36 mm	48	48	4.8	95.2	75–100
1.18 mm	238	286	28.6	71.4	55–90
600 μ	324	610	61.0	39.0	35–59
300 μ	304	914	91.4	8.6	8–30
150 μ	77	991	99.1	0.9	0–10
Pan	9	1000	100	0	0

Fineness Modulus = 284.9/100=2.849

**Fig. 4: Sieve Analysis of Fine Aggregate.****Fig. 5: Sieve Analysis of Coarse Aggregate.****Table 5: Sieve Analysis of Coarse Aggregate.**

Sieve Size	Weight Retained (g)	Cumulative Weight Retained	Cumulative % Weight Retained	Passing %
40 mm	-	-	-	100
20 mm	1450	1450	29	71
10 mm	3136	4586	91.7	8.3
4.75 mm	414	5000	100	0
2.36 mm	0	5000	100	-
1.18 mm	0	5000	100	-
600 μ	0	5000	100	-
300 μ	0	5000	100	-
150 μ	0	5000	100	-

Fineness Modulus = 720.7/100=7.207

and oiled (on interior faces) cast iron cubic mould of dimension 150 mmx150 mmx150 mm and was casted as per BS: 1881-102 [20]. It was then properly compacted on vibrating machine for about two minutes. After compaction, the top surface of the concrete was finished using hand towel. The concrete cubes were then left undisturbed for 24 h to set

and harden. Finally, the concrete cube specimens were stripped off the moulds and placed in curing environment.

In another experiment, the standard concrete mix ratio of 1:1.5:3 (M 20 grade) was prepared by partial replacement of cement with fly ash (class F) (10, 20, 30, 40, 50 and 60%), keeping

water-binder ratio at 0.45. The prepared concrete mix was then placed in cleaned and oiled cast iron cubic moulds of dimension 150 mmx150 mmx150 mm, and the concrete specimens were cast as discussed above. After de-moulding, the concrete cubes (specimens) were subjected to water submerge curing (WSC) for specified number of days (7, 14, 21, 28 and 56 days).

Compressive Strength Test

The compressive strengths of molded concrete specimens of different w/c ratio (0.45, 0.50, 0.55, 0.55, 0.60, 0.65, 0.70 and 0.80), were carried out after curing under water for 7, 14, 21, 28 and 56 days. The concrete test specimens having w/c ratio 0.45 prepared by the partial replacement of cement with fly ash (10, 20, 30, 40, 50 and 60%) were also subjected to compressive strength test.

The compressive strength of the specimen was tested by compression testing machine (CTM) (Figure 6) of load capacity 1000 kN. The loading rate was 140 kg/cm²/min [20].



Fig. 6: Compression Testing Machine.

RESULT AND DISCUSSION

Effect of Water-Cement (w/c) Ratio on the Slump (Workability) of Concrete

Figure 7 shows the slump value of concrete specimens with different water-cement (w/c) ratio. The result shows that with increase in water-cement ratio the slump value is significantly increased. The increase in slump value is indicative of the increased workability. This is due to the fact that increasing the amount of water in the mix results in a more fluid concrete which is very

easy to mix and hence offers better workability. However, a detrimental effect to this would be 'bleeding' which will result in honeycombing and weaker concrete [21]. Therefore a water-cement ratio of 0.45 was chosen for further studies, in order to avoid possible honeycombing.

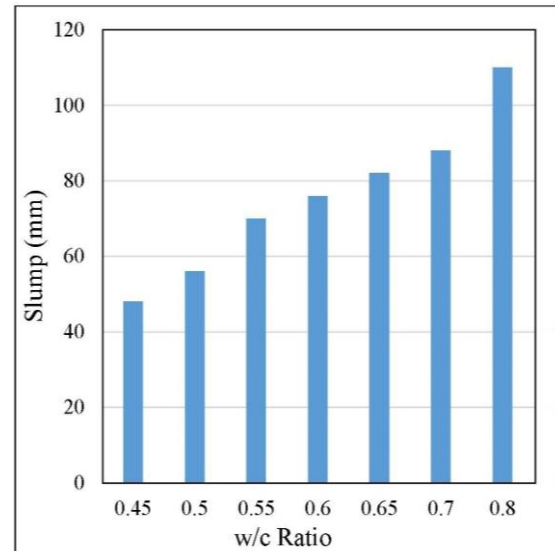


Fig. 7: Effect of Water-Cement Ratio on Slump of Concrete.

Effect of Water-Cement (w/c) Ratio on the Compressive Strength

The variation of the compressive strength of concrete cubes (grade M20; 1:1.5:3) with water-cement ratio in the range 0.45 to 0.80, within 7 to 56 days of curing after casting, were experimentally investigated in this work. The experiment was carried out at 27°C. Table 6 shows the variation of compressive strength of concrete cubes both with w/c ratio and curing age.

The compressive strengths of concrete cubes were found to increase with curing time (Figure 8). However, the compressive strengths were found to decrease with increase in water-cement ratio (Figure 9).

Figure 8 shows that for all types of w/c ratio, the compressive strength of concrete cubes increases with curing age but the strength-gain is comparatively slow after 28 days. Further, the compressive strength of concrete cubes having w/c ratio 0.45 is highest (24.41 N/mm² after 28 days of curing) as compared to concrete cubes having other w/c ratios.

Table 6: Variation of Compressive Strength of Concrete Cubes with Different w/c Ratio.

w/c Ratio	Compressive Strength (N/mm ²) after				
	7 Days Curing	14 Days Curing	21 Days Curing	28 Days Curing	56 Days Curing
0.45	14.03	17.67	21.34	24.41	25.91
0.50	13.68	17.14	21.03	24.13	25.58
0.55	13.06	16.86	20.65	23.74	25.11
0.60	12.72	16.47	20.16	22.99	24.63
0.65	12.41	16.02	19.73	22.54	24.07
0.70	10.99	14.38	17.88	20.71	22.34
0.80	10.65	13.97	17.27	20.28	22.15

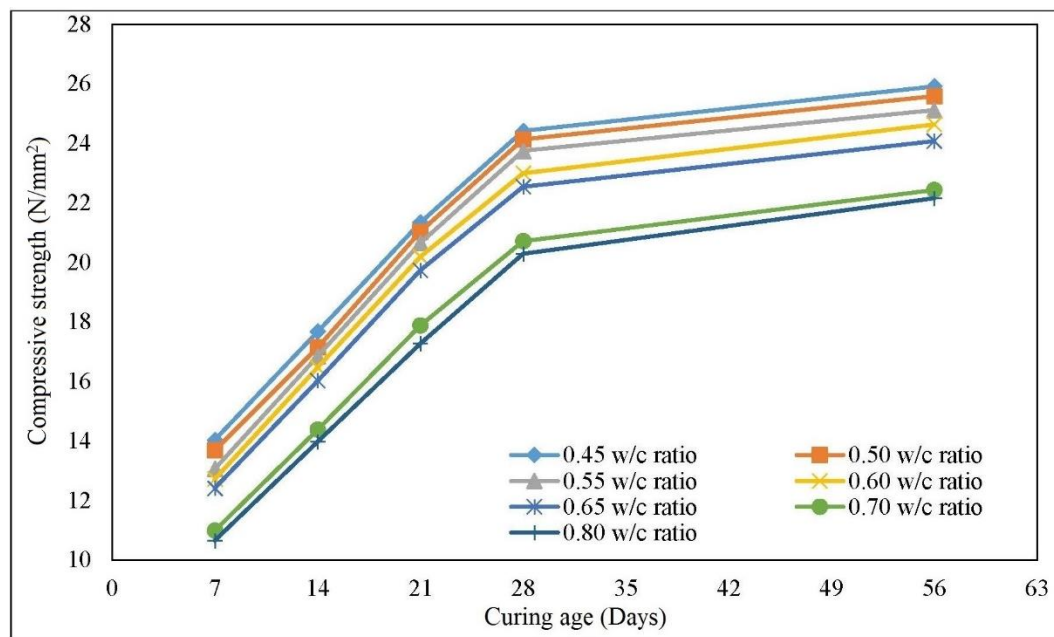
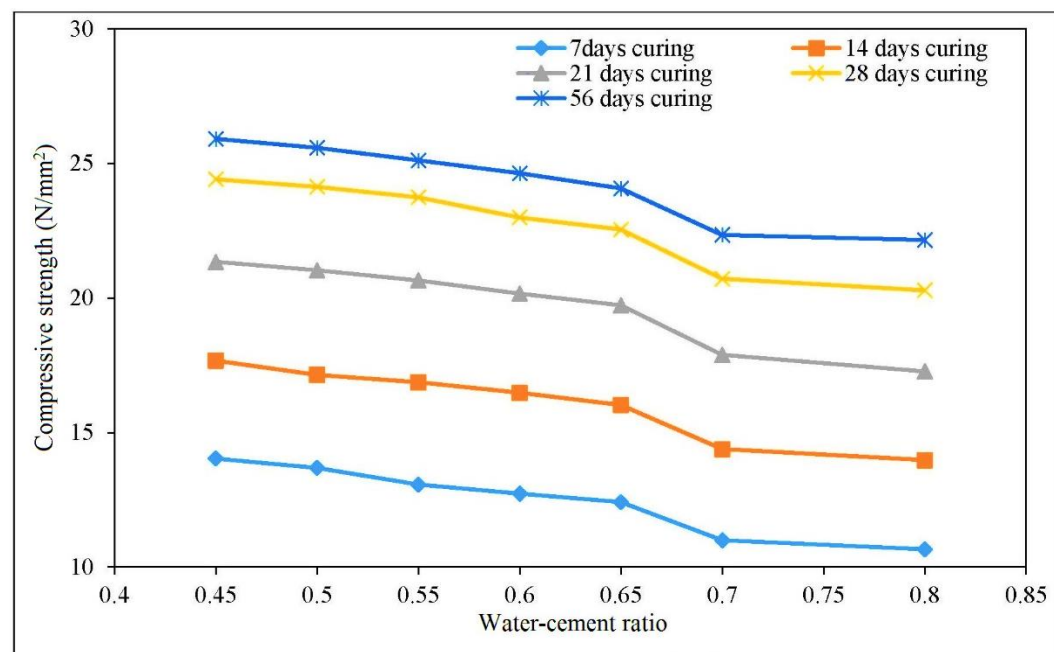
**Fig. 8:** Compressive Strength of M 20 Concrete with Curing Age.**Fig. 9:** Compressive Strength of M 20 Concrete with Different w/c Ratio.

Figure 9 shows that for all curing periods, the compressive strength of concrete cubes showed a consistent decrease with increase in w/c ratio. However, the decrease in compressive strength is particularly significant above w/c ratio 0.65.

The ratio of the volume of water to the volume of cement is critical in the hydration process of cement that causes concrete to stiffen, harden and develop strength. Only about 20% water (by mass) chemically combines with cement during hydration [22]. However, for a given volume of cement to hydrate completely, there must be an amount of original mixing water-filled space equal to 1.2 times the solid volume of the cement. This is because the hydration product has about 30% pore space that must be present, and water must be available to fill it [22]. If the amount of original mixing water-filled space is less than 40% by mass of the cement, all the cement may not hydrate, even though only half of the water is required for chemical combination. It is thus expected that total amount of water needed for hydration of cement to form calcium silicate hydrate (C-S-H) and for filling up the gel pores is around 40% by mass of the cement [22].

Some other studies have also shown that an approximate water-cement ratio of 0.40 was necessary for complete hydration of the cement [23, 24].

In concrete, the hardened cement paste is porous ensemble and the concentration of solid products of hydration in the total space (the original water and hydrated cement) is an index of porosity. Thus it appears that the

water-cement ratio (which governs the compressive strength) is an expression of concentration of hydration products in the total volume at a particular age for the resultant degree of hydration [25].

Thus, it is evident that a higher water-cement ratio will provide greater initial spacing between the grains of cement. This also provides greater volume of residual voids (those not filled by hydration products). In this situation, it is expected that the compressive strength of the concrete will be lower, as reported in the present investigation. Along with this, the workability of the concrete is reduced if the water-cement ratio is reduced. However, if the workability becomes too low, it becomes difficult to compact the concrete and the strength reduces. For a given set of materials and environment conditions, the strength at any age depends only on the water-cement ratio, provided the full compaction is achieved [26]. This is another reason why 0.45 water-cement ratio was selected for the present study.

Effect of Fly Ash (FA) on the Compressive Strength of Concrete

The variation of the compressive strength of concrete-mix (grade M20; 1:1.5:3) was determined with different percentage of cement replaced with fly ash (class F) having water-binder ratio 0.45, within 7 to 56 days of curing after casting. The experiments were carried out at 27°C (room temperature). Table 7 shows the variation of compressive strength of concrete cubes both, with percentage of cement replaced with fly ash and curing age.

Table 7: Variation of Compressive Strength of Concrete Cubes with Different % of Fly Ash.

% Replacement of Cement with Fly Ash	Compressive Strength (N/mm ²) after				
	7 Days Curing	14 Days Curing	21 Days Curing	28 Days Curing	56 Days Curing
0	14.03	17.67	21.34	24.41	25.91
10	13.81	18.78	22.32	25.61	27.54
20	12.44	19.17	23.45	27.17	29.63
30	11.18	21.72	26.56	29.36	31.43
40	9.43	20.15	22.23	23.98	25.17
50	8.15	17.89	19.38	21.43	22.72
60	6.25	15.32	16.41	17.64	18.93

The compressive strength of concrete cubes (cement partially replaced with fly ash) were found to increase with curing time at all replacement (10–60%) level with fly ash (Figure 10).

This can be attributed to continuously increasing hydration of cement and fly ash with curing time. This (hydration) resulted more and more C-S-H gel formation, which offers stronger binding of aggregates.

The compressive strengths of concrete cubes were found to increase up to 30% replacement of cement with fly ash (Figure 11). Above 30% replacement (with fly ash), the compressive strength of concrete decreases as shown in Figure 11.

The changes in compressive strength of concrete cubes (cement partially replaced with fly ash) with percentage of OPC replaced are shown in Table 8.

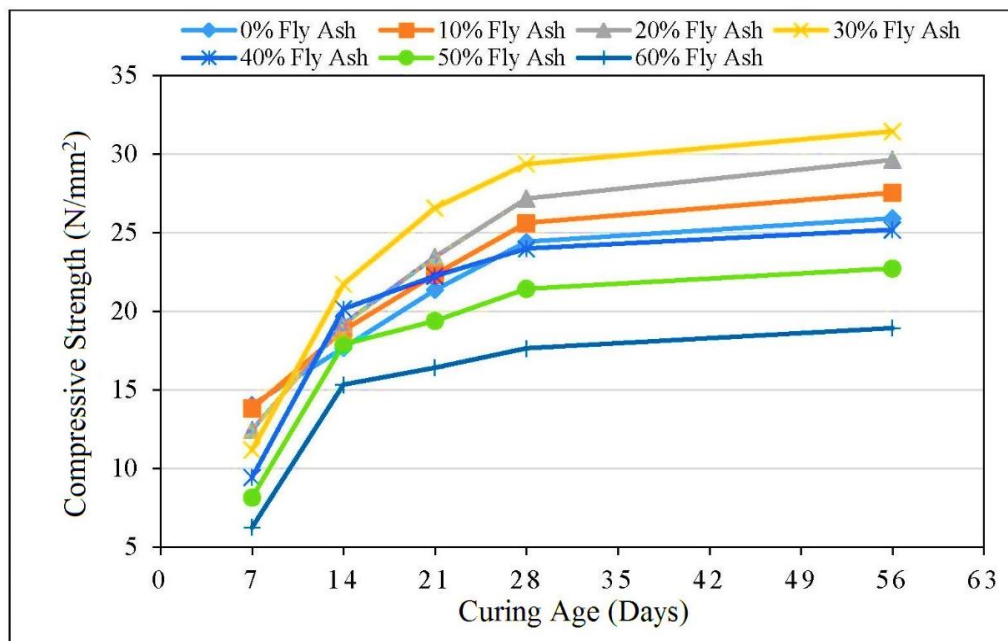


Fig. 10: Compressive Strength of M 20 Concrete (Cement Partially Replaced with Different % of Fly Ash) with Curing Age.

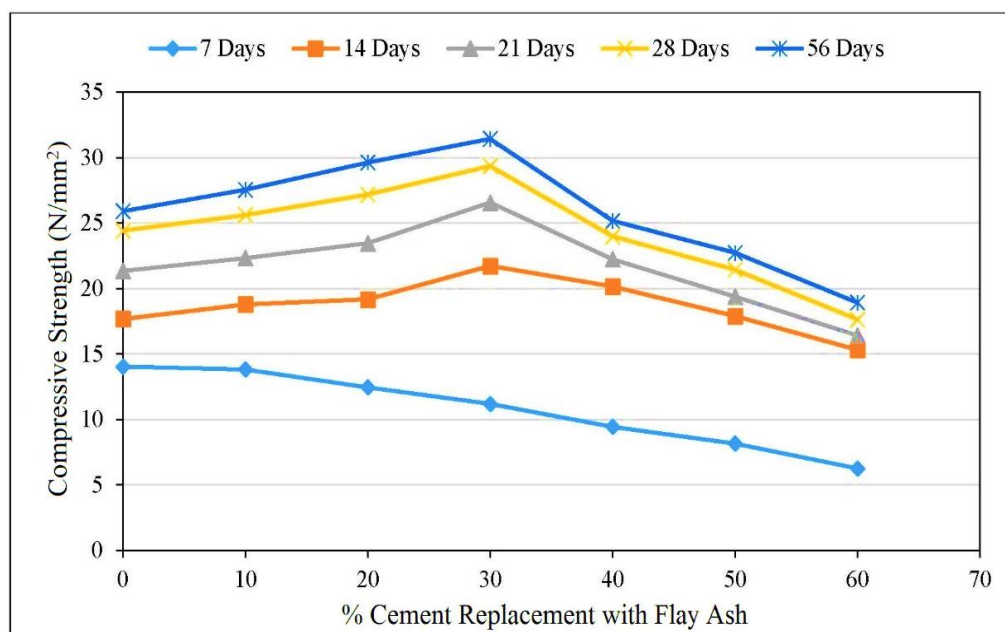
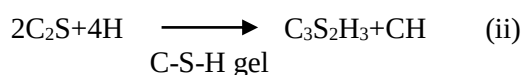
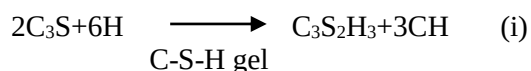


Fig. 11: Compressive Strength of M 20 Concrete with % of Cement Replaced with Fly Ash.

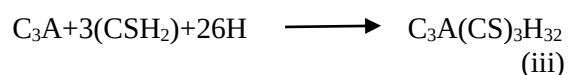
Table 8: Variations in Compressive Strength of Concrete Cubes as Compared to OPC Concrete with No Fly Ash.

% Replacement of Cement with Fly Ash	Increase 'I' or Decrease 'D' in Compressive Strength (N/mm ²) as Compared to OPC Concrete after	
	28 Days Curing	56 Days Curing
10	04.91% I	06.29% I
20	11.30% I	14.35% I
30	20.27% I	21.30% I
40	01.76% D	02.85% D
50	12.20% D	12.31% D
60	27.73% D	26.93% D

Ordinary Portland cement (OPC) contains four principal mineralogical phases, which are tricalcium silicate-C₃S (3CaO.SiO), dicalcium silicate-C₂S (2CaO.SiO), tricalcium aluminate-C₃A (3CaO.AlO) and tetracalcium aluminoferrite-C₄AF (4CaO.Al₂O₃.Fe₂O₃). The setting and hardening of the OPC is due to the hydration of these principal compounds. Tricalcium silicate and dicalcium silicate 'react with water' immediately after mixing [27]. Upon hydration, these tricalcium silicate and dicalcium silicate form calcium silicate hydrate (C-S-H) gel (a durable binder) and calcium hydroxide (a nondurable binder), as shown below [28–31]:



Tricalcium aluminate reacts with water in presence of sulphate ions supplied by gypsum present in OPC as given below:



The hydration product of tetracalcium aluminoferrite is similar to those of C₃A, with iron substituting partially for alumina in the crystal structures of ettringite and monosulpho-aluminate hydrate [32, 33].

The above reactions [(i) and (ii)] indicate that the lime is released during the hydration process of cement and remains as surplus in the hydrated cement. This surplus lime renders deleterious effect to concrete such as to make

the concrete porous, giving chance to the development of micro-cracks, weakening the bond with aggregates and thus affect the durability of concrete. This surplus lime becomes the source of pozzolanic reaction with fly ash present in the concrete [34]. The smaller particle size of fly ash with a higher surface area and glassy phase content also improved the pozzolanic reaction and forms additional C-S-H gel having similar binding properties [35, 36]. Further, the unreactive part of fly ash acts as micro-aggregates and fills up the matrix rendering a packing effect. The small and spherical fly ash particles filled the voids or airspaces and increased the density [37, 38]. Therefore, the fly ash can make the concrete more homogeneous and result in an increased strength. Thus the concrete containing fly ash has higher compressive strength as compared to OPC concrete, as observed in the present study (Figure 10).

It was also observed that with the addition of fly ash, the seven-day compressive strength of concrete decreased by 1.6 for 10% replacement (with fly ash), 11.33 for 20% replacement, 20.31 for 30% replacement, 32.78 for 40% replacement, 41.91 for 50% replacement and 55.45 for 60% replacement, as compared to the ordinary Portland cement (OPC) concrete without any fly ash. This can be attributed to the fact that the decrease in seven-day compressive strength at all replacement levels may be due to slow hydration process, since fly ash is slow reactive pozzolans which delays the hydration process [39, 40].

Figure 11 shows the decrease in compressive strength of concrete cubes containing more

than 30% fly ash (as partial replacement of OPC) for all curing periods. This can be attributed to the fact that with increasing percentage of fly ash, the voids are filled up with finer particles of fly ash which prevents the water transport/absorption to the pores, thereby hindering hydration process and decrease in strength [40–44].

CONCLUSION

In the present study, main objective was to find the role of partial replacement of cement by fly ash and to note the resultant effect on the mechanical strength of the concrete in a study extended for a period of 56 days.

The behaviour of fly ash in concrete as observed in the present study can be summarized as:

- (i) The seven-day compressive strength decreases for all replacement levels.
- (ii) Percentage increase in fly ash content, results in continuous decrease in seven-day compressive strength.
- (iii) Addition of fly ash causes increase in compressive strength with curing time, for all replacements studied.
- (iv) The rate of strength gain is higher up to 28 days and afterwards the rate of strength gain becomes less (flat).
- (v) Up to 30% replacement level, the 28 day compressive strength increases. But beyond 30% replacement level, the 28 day compressive strength decreases.
- (vi) At about 40% fly ash, the strength falls almost up to the level of OPC concrete.

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REFERENCES

1. Han SH, Kim JK, Park YD. Prediction of Compressive Strength of Fly Ash Concrete by New Apparent Activation Energy Function. *Cem Concr Res.* 2003; 33: 965–971p.
2. Atis CD. Strength Properties of High-Volume Fly Ash Roller Compacted and Workable Concrete and Influence of Curing Condition. *Cem Concr Res.* 2005; 35(6): 1112–1121p.
3. Toutanji H, Dalette N, Aggoun S, *et al.* Effect of supplementary Cementitious Materials on the Compressive Strength and Durability of short Term Cured Concrete. *Cem Concr Res.* 2004; 34: 311–319p.
4. Helmuth R. *Fly Ash in Cement and Concrete.* Skokie, IL, USA: SP040, Portland Cement Association; 1987; 203p.
5. Thomas MDA, Mukherjee PK, Sato JA, *et al.* Effect of fly Ash Composition on Thermal Cracking in Concrete. *Proceedings of the Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, ACI SP-153,* American Concrete Institute, Detroit, MI. 1995.
6. Babu KG, Rao GSN. Early Strength of FA Concrete. *Cement and Concrete Research.* 1994; 24: 277–284p.
7. Cyr M, Lawrence P, Ringot E. Efficiency of Mineral Admixtures in Mortars: Quantification of the Physical and Chemical Effects of Fine Admixtures in Relation with Compressive Strength. *Cem Concr Res.* 2006; 36(2): 264–277p.
8. Guerrero A, Gon S, Macõ A, *et al.* Effect of the Starting Fly Ash on the Microstructure and Mechanical Properties of Fly Ash ± Belite Cement Mortars. *Cem Concr Res.* 2000; 30: 553–559p.
9. Tangpagasit J, Cheerarot R, Jaturapitakkul C, *et al.* Packing Effect and Pozzolanic Reaction of Fly Ash in Mortar. *Cem Concr Res.* 2005; 35: 1145–1151p.
10. Çelik Ö, Damcı E, Pi S. Characterization of Fly Ash and its Effect on the Compressive Strength Properties of Portland Cement. *Indian J Eng Mater Sci.* 2008; 15: 433–440p.
11. Payá J, Monzó J, Borrachero MV, *et al.* Mechanical Treatment of Fly Ashes Part II: Particle Morphologies in Ground fly Ashes (GFA) and Workability of GFA-Cement Mortars. *Cem Concr Res.* 1996; 26(2): 225–235p.
12. Payá J, Monzó J, Borrachero MV, *et al.* Mechanical Treatments of Fly Ashes. Part III: Studies on Strength Development of Ground Fly Ashes (GFA)-Cement Mortars. *Cem Concr Res.* 1997; 27(9): 1365–1377p.

13. Payá J, Monzó J, Borrachero MV, *et al.* Mechanical Treatment of Fly Ashes. Part IV. Strength Development of Ground Fly Ash-cement Mortars Cured at Different Temperatures. *Cem Concr Res.* 2000; 30: 543–551p.
14. Un H, Baradan B. The Effect of Curing Temperature and Relative Humidity on the Strength Development of Portland Cement Mortar. *Sci Res Essays.* 2011; 6(12): 2504–2511p.
15. Shafiq N, Nuruddin MF. Degree of Hydration of OPC and OPC/FA Dried in Different Relative Humidity. *Concrete Research Letters (CRL).* 2010; 1(3): 81–89p.
16. ASTM C618-15. *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.* West Conshohocken, PA: ASTM International; 2015.
17. ASTM C 150/C150M-16e1. *Standard Specification for Portland Cement.* West Conshohocken, PA: ASTM International; 2016.
18. ASTM C143M-15a. *Standard Test Method for Slump of Hydraulic-Cement Concrete.* West Conshohocken, PA: ASTM International; 2015.
19. American Concrete Institute. Cement and Concrete Terminology (Reapproved 2005). ACI 116R-00, ACI Manual of Concrete Practice, Part 1, Farmington Hills, MI. 1990b.
20. BS: 1881-102. Testing Concrete. Method for Determination of Compressive Strength of Concrete Cubes. 1983.
21. Anacta ET. The Effect of Quantity of Cement and Mixing Water on Strength and Durability of Concrete. *International Journal of Science and Engineering Investigations (IJSEI).* 2013; 2(21): 110–0113p.
22. Mather B, Hime WG. Amount of Water Required for Complete Hydration of Portland Cement. *American Concrete Institute (ACI).* 2002; 24(6): 56–58p.
23. Powers TC. A Discussion of Cement Hydration in Relation to the Curing of Concrete. *Research Department Bulletin RX025*, Portland Cement Association, Chicago, USA. 1948.
24. Powers TC. The Non-evaporable Water Content of Hardened Portland Cement Paste: Its Significance for Concrete Research and Its Method of Determination. *Research Department Bulletin RX029*, Portland Cement Association, Chicago, USA. 1949.
25. Lamond JF, Pielert JH, editors. Significance of Tests and Properties of Concrete and Concrete-Making Materials. USA: ASTM International; 2006.
26. Amsterdam EV. *Construction Materials for Civil Engineering.* USA: Juta and Company Ltd.; 2000.
27. Kjellsen KO, Justnes H. Revisiting the Microstructure of Hydrated Tricalcium Silicate: A Comparison to Portland Cement. *Cem Concr Compos.* 2004; 26(8): 947–956p.
28. Feng X, Garboczi EJ, Bentz DP, *et al.* Estimation of the Degree of Hydration of Blended Cement Pastes by a Scanning electron Microscopy Point-Counting Procedure by Cement and Concrete. *Mater Sci.* 2004; 34(10): 1787–1793p.
29. Bullard JW, Jennings HM, Livingston RA, *et al.* Mechanisms of Cement Hydration. *Cem Concr Res.* 2011; 41(12): 1208–1223p.
30. Stark J. Recent Advances in the Field of Cement Hydration and Microstructure Analysis. *Cem Concr Res.* 2011; 41(7): 666–678p.
31. Bergold ST, Goetz-Neunhoeffler F, Neubauer J. Quantitative Analysis of C-S-H in Hydrating Alite Pastes by *in-situ* XRD. *Cem Concr Res.* 2013; 53: 119–126p.
32. Brown PW. Kinetics of Tricalcium Aluminate and Tetracalcium Aluminoferrite Hydration in the Presence of Calcium Sulfate. *J Am Ceram Soc.* 1993; 76(12): 2971–2976p.
33. Brown P, *et al.* Hydration of Tricalcium Aluminate and Tetracalcium Aluminoferrite in the Presence of Calcium Sulfate. *Mater Struct.* 1986; 110: 137–147p.
34. Lothenbach B, Scrivener K, Hooton RD. Supplementary Cementitious Materials. *Cem Concr Res*, Elsevier Ltd. 2011; 41(12): 1244–1256p.

35. Slanicka S. The Influence of Fly Ash Fineness on the Strength of Concrete. *Cem Concr Res.* 1991; 21(2/3): 285–296p.
36. Chindaprasirt P, Ruangsiriyakul S, Cao HT, *et al.* Influence of Mae Moh Fly Ash Fineness on Characteristics, Strength and Drying Shrinkage Development of Blended Cement Mortars. In: *The Eighth East Asia-Pacific Conference on Structural Engineering and Construction*, Singapore, Paper No. 1191. 2001.
37. Gopalan MK. Nucleation and Pozzolanic Factors in Strength Development of Class F Fly Ash Concrete. *ACI Mater J.* 1993; 90-M12: 117–121p.
38. Isaia GC, Gastaldini ALG, Moraes R. Physical and Pozzolanic Action of Mineral Additions on the Mechanical Strength of High Performance Concrete. *Cem Concr Compos.* 2003; 25(1): 69–76p.
39. Chatterjee AK. Indian Fly Ashes: Their Characteristics and Potential for Mechanochemical Activation for Enhanced Usability. *J Mater Civ Eng.* 2011; 23(6): 783–788p.
40. Cyr M, Lawrence P, Ringot E. Efficiency of Mineral Admixtures in Mortars: Quantification of the Physical and Chemical Effects of Fine Admixtures in Relation with Compressive Strength. *Cem Concr Res.* 2006; 36(2): 264–277p.
41. Prinya Chindaprasirt, Chai Jaturapitakkul, Theerawat Sinsiri. Effect of Fly Ash Fineness on Microstructure of Blended Cement Paste. *Constr Build Mater.* 2007; 21: 1534–1541p.
42. Guerrero A, Gon S, Macõ A, *et al.* Effect of the Starting Fly Ash on the Microstructure and Mechanical Properties of Fly Ash ± Belite Cement Mortars. *Cem Concr Res.* 2000; 30: 553–559p.
43. Çelik Ö, Damcı E, Pi S. Characterization of Fly Ash and its Effects on the Compressive Strength Properties of Portland Cement. *Indian J Eng Mater Sci.* 2008; 15: 433–440p.
44. Tangpagasit J, Cheerarot R, Jaturapitakkul C, *et al.* Packing Effect and Pozzolanic Reaction of Fly Ash in Mortar. *Cem Concr Res.* 2005; 35: 1145–1151p.

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