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Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete

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Abstract

This paper presents the results of an experimental investigation carried out to evaluate the mechanical properties of concrete mixtures in which fine aggregate (sand) was partially replaced with Class F fly ash. Fine aggregate (sand) was replaced with five percentages (10%, 20%, 30%, 40%, and 50%) of Class F fly ash by weight. Tests were performed for properties of fresh concrete. Compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity were determined at 7, 14, 28, 56, 91, and 365 days. Test results indicate significant improvement in the strength properties of plain concrete by the inclusion of fly ash as partial replacement of fine aggregate (sand), and can be effectively used in structural concrete.

Keywords: Concrete; Fly ash; Compressive strength; Tensile properties; Elastic moduli

1. Introduction

The quantity of fly ash produced from thermal power plants in India is approximately 80 million tons each year, and its percentage utilization is less than 10%. Majority of fly ash produced is of Class F type. During the last few years, some cement companies have started using fly ash in manufacturing cement, known as 'pozzolana Portland cement,' but the overall percentage utilization remains very low, and most of the fly ash are dumped at landfills. Fly ash is generally used as replacement of cement, as an admixture in concrete, and in manufacturing of cement. Whereas concrete containing fly ash as partial replacement of cement poses problems of delayed early strength development, concrete containing fly ash as partial replacement of fine aggregate will have no delayed early strength development, but rather will enhance its strength on long-term basis. This study explores the possibility of replacing part of fine aggregate with fly ash as a means of incorporating significant amounts of fly ash.

2. Literature review

Though number of significant results have been reported on the use of Class F fly ash in concrete [1–14], but there is not much literature available on the use of Class F fly ash as partial replacement of fine aggregates [10–14]. Maslehuddin et al. [10] carried out investigations to evaluate the compressive strength development and corrosion-resisting characteristics of concrete mixes in which fly ash was used as an admixture (equal quantity of sand replacement). Concrete mixtures were made with fly ash additions of 0%, 20%, and 30%, and water–cement ratios of 0.35, 0.40, 0.45, and 0.50. Based on the test results, they concluded that addition of fly ash as an admixture increases the early age compressive strength and long-term corrosion-resisting characteristics of concrete. The superior performance of these mixes compared to plain concrete mixes was attributed to the densification of the paste structure due to pozzolanic action between the fly ash and the calcium hydroxide liberated as a result of hydration of cement.

Berg and Neal [11] used municipal solid waste bottom ash (MSWBA) as a potential aggregate for concrete masonry

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Table 1
Physical properties of Portland cement

Physical test	Results obtained	IS: 8112-1989 [15] specifications
Fineness (retained on 90-μm sieve)	8.5	10 max
Fineness: specific surface (air permeability test) (m^2/kg)	285	225 min
Normal consistency	30%	–
Vicat time of setting (min)		
Initial	120	30 min
Final	215	600 max
Compressive strength (MPa)		
3 days	23.5	22.0 min
7 days	36.0	33.0 min
28 days	46.0	43.0 min
Specific gravity	3.15	–

units (CMU). The test results indicate that MSWBA could be used as an aggregate in concrete to produce CMU that meets ASTM C 90 standards when it is processed for maximum size and gradation and ferrous removal by magnetic separation.

Ghafoori et al. [12] carried out investigations on a series of laboratory-made roller compacted concretes (RCC) containing high-calcium dry bottom ash as a fine aggregate. Concrete specimens of six different proportions (cement content of 188–337 kg/m^3 and coarse aggregate content of 1042–1349 kg/m^3) were prepared at their optimum moisture content and fabricated in accordance with ASTM C 1170 Procedure A. Specimens were tested for compression, splitting tension, drying shrinkage, and resistance to abrasion and rapid freezing and thawing. Based on the test results, they concluded that good strength, stiffness, drying shrinkage and resistance to wear, and repeated freezing and thawing cycles can be obtained with compacted concretes containing bottom ash.

Hwang et al. [13] examined the effects of fine aggregate replacement on the rheology, compressive strength, and carbonation properties of fly ash and mortar. Rheological properties, compressive strength, and rate of carbonation of mortars of water to Portland cement ratio of 0.3, 0.4, and 0.5, in which the fine aggregate was replaced with fly ash at 25% and 50% levels. Test results showed that rheological constants increased with higher replacement level of fly ash and that, when water to Portland cement ratio was maintained, the strength development and carbonation properties were improved.

Bakoshi et al. [14] used bottom ash in amounts of 10–40% as replacement for fine aggregate. Test results indicate that the compressive strength and tensile strength of bottom ash concrete generally increases with the increase in replacement ratio of fine aggregate and curing age. The freezing–thawing resistance of concrete using bottom ash is lower than that of ordinary concrete and abrasion resistance of bottom ash concrete is higher than that of ordinary concrete.

Table 2
Chemical composition of fly ash

Chemical analysis	Class F fly ash (%)	ASTM requirement C 618 (%)
Silicon dioxide, SiO_2	55.3	–
Aluminum oxide, Al_2O_3	25.70	–
Ferric oxide, Fe_2O_3	5.3	–
$SiO_2+Al_2O_3+Fe_2O_3$	85.9	70.0 min
Calcium oxide, CaO	5.6	–
Magnesium oxide, MgO	2.1	5.0 max
Titanium oxide, TiO_2	1.3	–
Potassium oxide, K_2O	0.6	–
Sodium oxide, Na_2O	0.4	1.5 max
Sulfur trioxide, SO_3	1.4	5.0 max
LOI (1000 °C)	1.9	6.0 max
Moisture	0.3	3.0 max

Table 3
Physical properties of aggregates

Property	Fine aggregate	Coarse aggregate
Specific gravity	2.63	2.61
Fineness modulus	2.25	6.61
SSD absorption (%)	0.86	1.12
Void (%)	36.2	39.6
Unit weight (kg/m^3)	1690	1615

3. Experimental program

3.1. Materials

3.1.1. Cement

Ordinary Portland (43 grade) cement was used. It was tested as per Indian Standard Specifications IS: 8112-1989 [15]. Its properties are shown in Table 1.

3.1.2. Fly ash

Class F fly ash obtained from thermal power plant at Bathinda in India was used in this investigation. Chemical composition of the fly ash was determined according to ASTM C 311. The results are shown in Table 2.

Table 4
Sieve analysis of aggregates

Fine aggregates			Coarse aggregates		
Sieve no.	Percent passing	Requirement IS: 383-1970 [16]	Sieve size	Percent passing	Requirement IS: 383-1970 [16]
4.75 mm	98.4	90–100	40 mm	100	100
2.36 mm	93.8	85–100	20 mm	98	95–100
1.18 mm	73.8	75–100	10 mm	31	25–55
600 μm	61.4	60–79	4.75 mm	4	0–10
300 μm	35.8	12–40			
150 μm	6.5	0–10			

Table 5
Mixture proportions

Mixture no.	M-1	M-2	M-3	M-4	M-5	M-6
Cement (kg/m^3)	390	390	390	390	390	390
Fly ash (%)	0	10	20	30	40	50
Fly ash (kg/m^3)	0	50	110	170	220	280
Water (kg/m^3)	185	187	190	190	192	195
W/C	0.47	0.48	0.49	0.49	0.49	0.50
Sand SSD (kg/m^3)	560	510	450	390	340	280
Coarse Aggregate (kg/m^3)	1170	1170	1170	1170	1170	1170
Superplasticizer (l/m^3)	2.6	3.5	3.6	3.7	3.7	3.9
Slump (mm)	100	90	65	40	30	20
Air content (%)	5.2	4.8	4.4	4.0	3.8	3.2
Air temperature (°C)	27	26	27	26	25	26
Concrete temperature (°C)	28	26	28	27	26	27
Fresh concrete density (kg/m^3)	2308	2310	2314	2314	2316	2319

3.1.3. Fine aggregate

Natural sand with a 4.75-mm maximum size was used as a fine aggregate. It was tested as per Indian Standard Specifications IS: 383-1970 [16], and its physical properties and sieve analysis results are shown in Tables 3 and 4, respectively.

3.1.4. Coarse aggregate

Coarse aggregate used in this study were 20-mm nominal size, and were tested as per Indian Standard Specifications IS: 383-1970 [16]. Its physical properties and sieve analysis results are shown in Tables 3 and 4, respectively.

3.1.5. Superplasticizer

A commercially available melamine-based superplasticizer was used in all mixes.

3.2. Mix proportions

Six mixture proportions were made. First was control mix (with out fly ash), and the other five mixes contained Class F fly ash. Fine aggregate (sand) was replaced with fly ash by weight. The proportions of fine aggregate replaced ranged from 10% to 50%. Mix proportions are given in Table 5. The control mix with out fly ash was proportioned as per Indian Standard Specifications IS: 10262-1982 [17], to obtain a 28-day cube compressive strength of 26.4 MPa. Concrete mixes were made in power-driven revolving type drum mixers of capacity 0.76 m^3.

3.3. Preparation and casting of test specimens

The 150-mm concrete cubes were cast for compressive strength, 150 × 300 mm cylinders for splitting tensile strength, 101.4 × 101.4 × 508 mm beams for flexural strength, and 150 × 300 mm cylinders for modulus of elasticity. After casting, all the test specimens were finished with a steel towel. Immediately after finishing, the specimens were covered with plastic sheets to minimize the moisture loss from them. All the test specimens were stored at

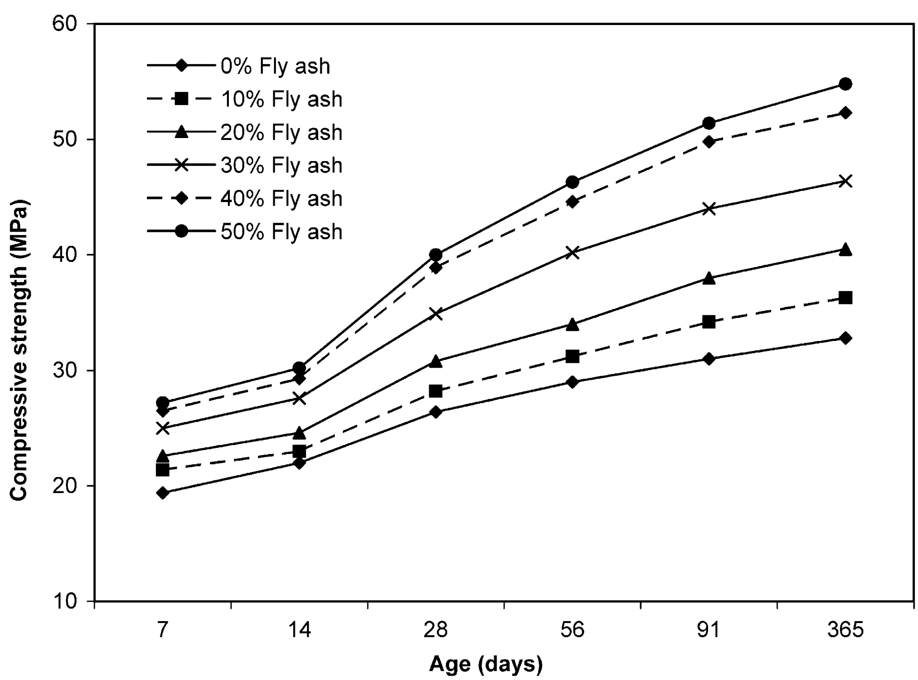

Fig. 1. Compressive strength versus age.

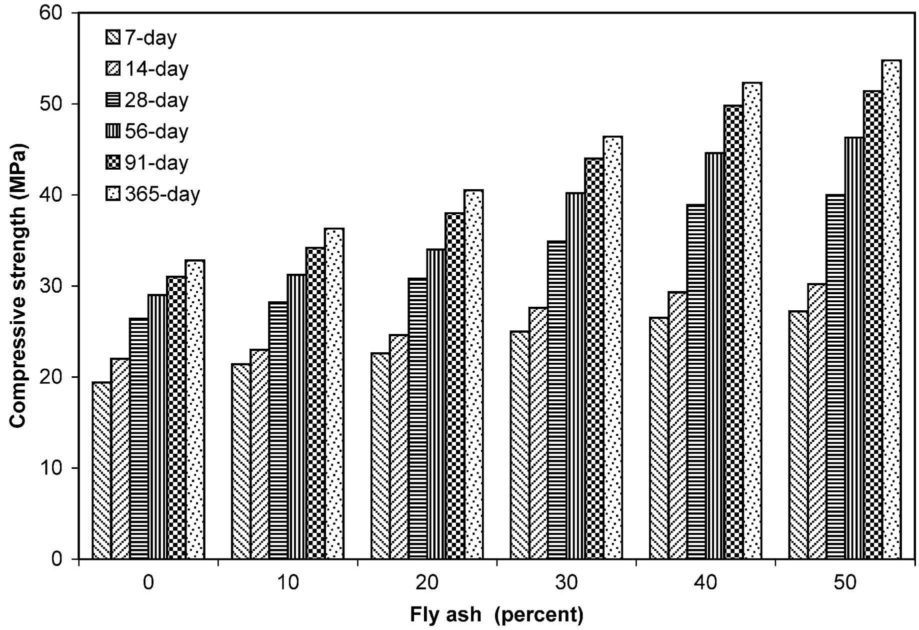

Fig. 2. Compressive strength versus fly ash percentage.

temperature of about 23 °C in the casting room. They were demolded after 24 h, and were put into a water-curing tank.

3.4. Fresh concrete properties

Fresh concrete properties such as slump, unit weight, temperature, and air-content were determined according to Indian Standard Specifications IS: 1199-1959 [18]. The results are presented in Table 5.

3.5. Hardened concrete properties

The 150-mm concrete cubes were tested for compressive strength, 150 × 300 mm cylinders for splitting tensile

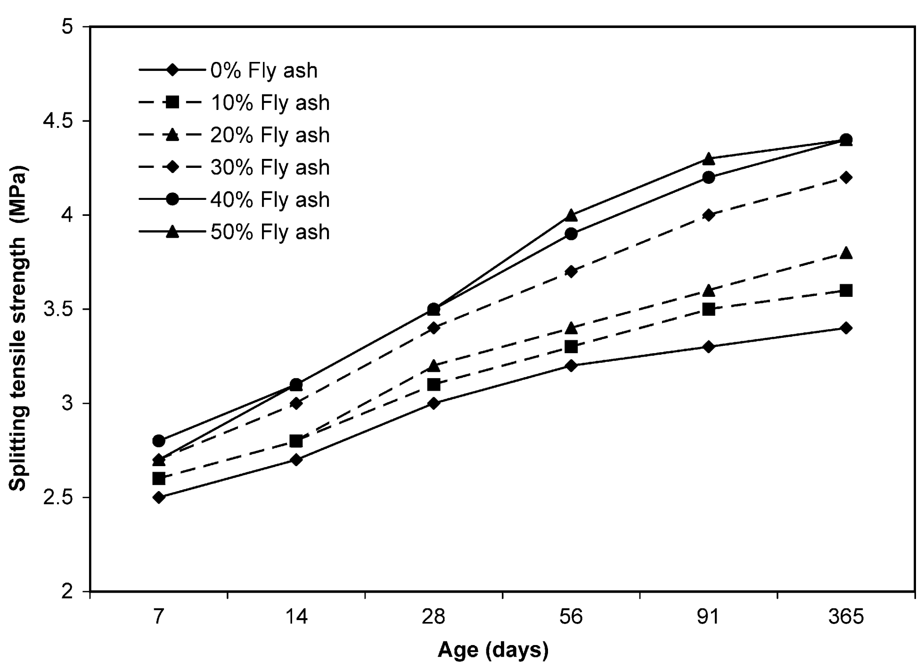

Fig. 3. Splitting tensile strength versus age.

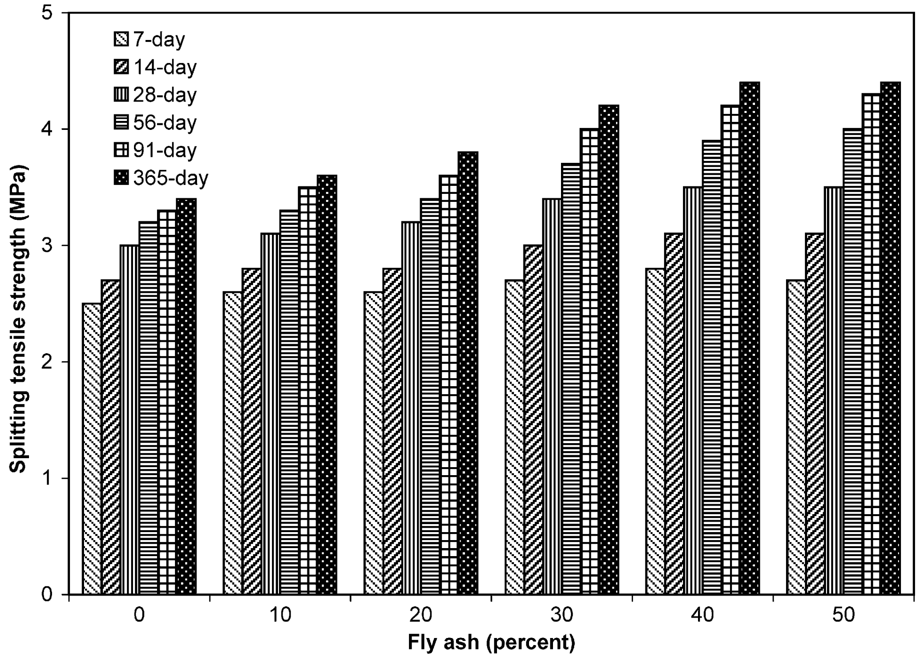

Fig. 4. Splitting tensile strength versus fly ash percentage.

strength, 101.4 × 101.4 × 508 mm beams for flexural strength, and 150 × 300 mm cylinders for modulus of elasticity. Tests were performed at 7, 14, 28, 56, 91, and 365 days in accordance with the provisions of the Indian Standard Specifications IS: 516-1959 [19]. Compressive strength results are shown in Figs. 1 and 2, splitting tensile strength in Figs. 3 and 4, flexural strength results in Figs. 5 and 6, and modulus of elasticity results in Figs. 7 and 8.

4. Results and discussion

4.1. Compressive strength

Compressive strength of concrete mixes made with and with out fly ash were determined at 7, 14, 28, 56, 91, and 365 days of curing. The test results are given in Table 6 and shown in Figs. 1 and 2. Fig. 1 shows the variation of

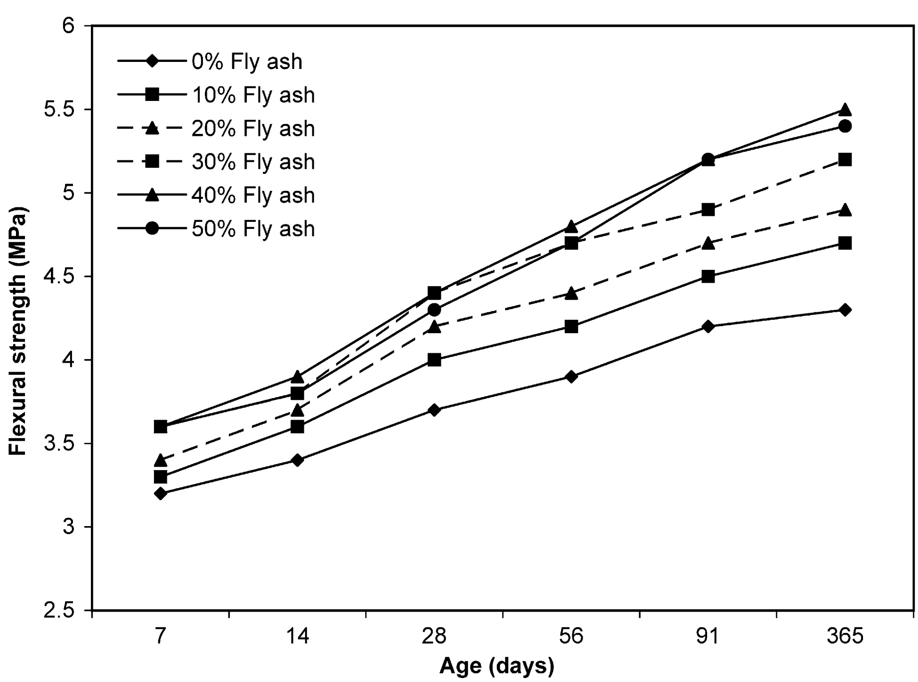

Fig. 5. Flexural strength versus age.

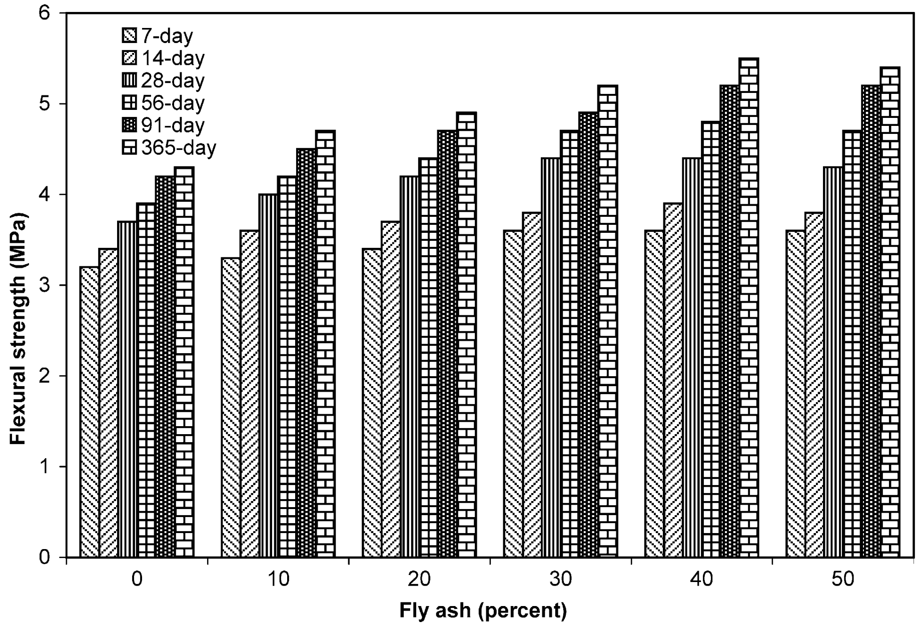

Fig. 6. Flexural strength versus fly ash percentage.

compressive strength with age for various fly ash percentages, and Fig. 2 shows the variation of compressive strength with fly ash percentages at different ages. From the test results, it can be seen that the compressive strength of fly ash concrete mixes with 10%, 20%, 30%, 40%, and 50% fine aggregate replacement with fly ash, were higher than the control mix (M-1) at all ages. It is evident from Table 6 and Fig. 1 that compressive strength of all mixes continued to increase with the increase in age.

From Fig. 2, it can be seen that there is increase in strength with the increase in fly ash percentages; however, the rate of increase of strength decreases with the increase in fly ash content. This trend is more obvious between 40% and 50% replacement level. However, maximum strength at all

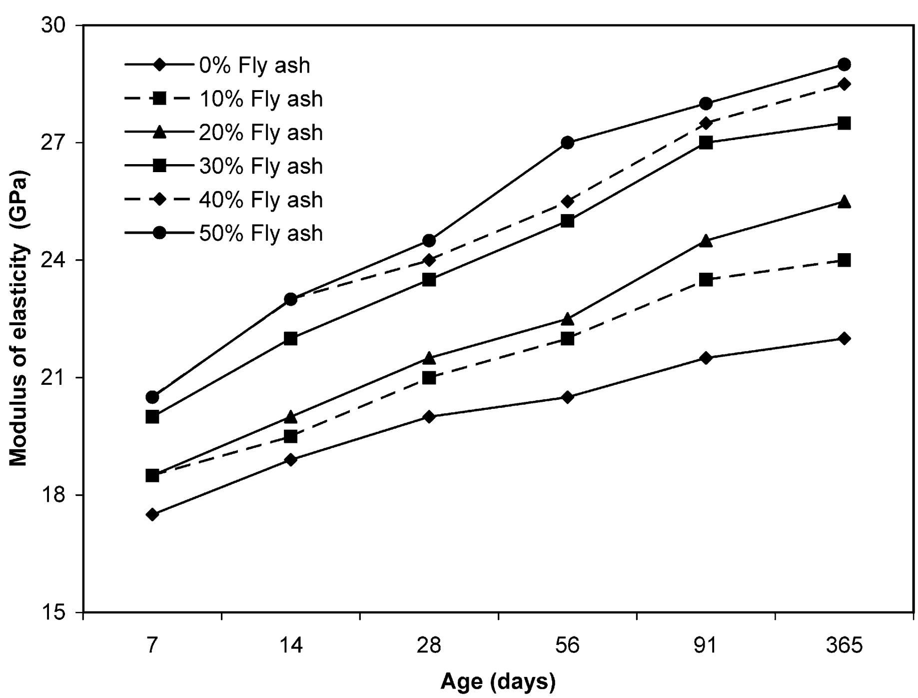

Fig. 7. Modulus of elasticity versus age.

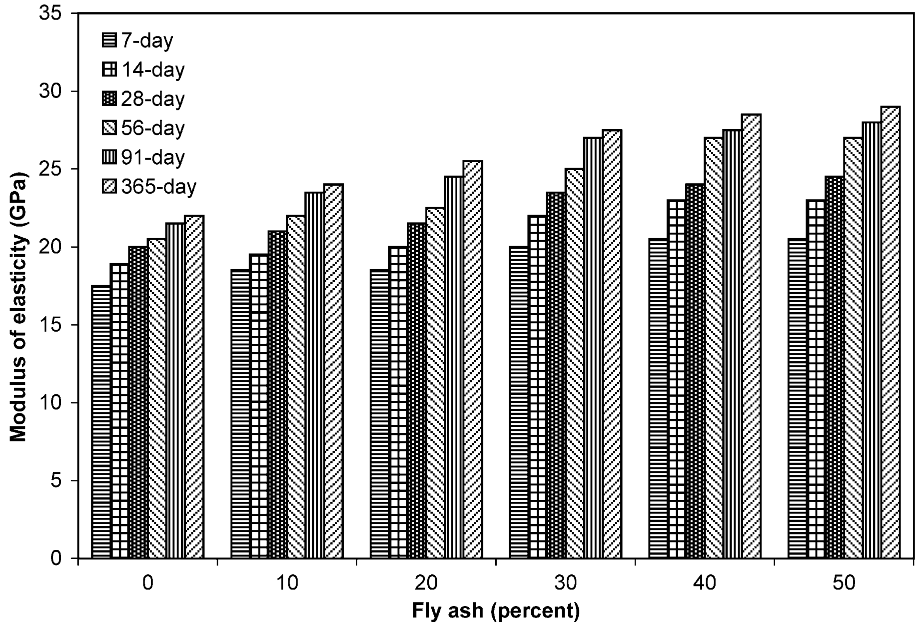

Fig. 8. Modulus of elasticity versus fly ash percentage.

ages occurs with 50% fine aggregate replacement. This increase in strength due to the replacement of fine aggregate with fly ash is attributed to the pozzolanic action of fly ash. In the beginning (early age), fly ash reacts slowly with calcium hydroxide liberated during hydration of cement and does not contribute significantly to the densification of the concrete matrix at early ages. Concrete with fly ash shows higher strength at early ages because inclusion of fly ash as partial replacement of sand starts pozzolanic action and densification of the concrete matrix, and due to this strength of fly ash concrete is higher than the strength of control mix even at early ages.

4.2. Splitting tensile strength

The splitting tensile strength of concrete mixes made with and with out fly ash were measured at the ages of 7, 14, 28, 56, 91, and 365 days. The results are given in Table 7 and shown in Figs. 3 and 4, respectively. Fig. 3 shows the variation of splitting tensile strength with age for different fly ash percentages, and Fig. 4 shows the variation of splitting tensile strength with fly ash percentages. From Table 7 and Fig. 3, it is evident that splitting tensile strength of all mixes continued to increase with the age.

From Fig. 4, it can be seen that there is increase in strength with the increase in fly ash percentages; however, the rate of increase of strength is becoming lesser with the

Table 7
Splitting tensile strength test results

Mix	M-1	M-2	M-3	M-4	M-5	M-6
Fly ash (%)	0	10	20	30	40	50
Test age (days)	Splitting tensile strength (MPa)					
7	2.5	2.6	2.6	2.7	2.8	2.7
14	2.7	2.8	2.8	3.0	3.1	3.1
28	3.0	3.1	3.2	3.4	3.5	3.5
56	3.2	3.3	3.4	3.7	3.9	4.0
91	3.3	3.5	3.6	4.0	4.2	4.3
365	3.4	3.6	3.8	4.2	4.4	4.4

Table 6
Compressive strength test results

Mix	M-1	M-2	M-3	M-4	M-5	M-6
Fly ash (%)	0	10	20	30	40	50
Test age (days)	Compressive strength (MPa)					
7	19.4	21.4	22.6	25.0	26.5	27.2
14	22.0	23.0	24.6	27.6	29.3	30.2
28	26.4	28.2	30.8	34.9	38.9	40.0
56	29.0	31.2	34.0	40.2	44.6	46.3
91	31.0	34.2	38.0	44.0	49.8	51.4
365	32.8	36.3	40.5	46.4	52.3	54.8

Table 8
Flexural strength test results

Mix	M-1	M-2	M-3	M-4	M-5	M-6
Fly ash (%)	0	10	20	30	40	50
Test age (days)	Flexural strength (MPa)					
7	3.2	3.3	3.4	3.6	3.6	3.6
14	3.4	3.6	3.7	3.8	3.9	3.8
28	3.7	4.0	4.2	4.4	4.4	4.3
56	3.9	4.2	4.4	4.7	4.8	4.7
91	4.2	4.5	4.7	4.9	5.2	5.2
365	4.3	4.7	4.9	5.2	5.5	5.4

Table 9
Modulus of elasticity test results

Mix	M-1	M-2	M-3	M-4	M-5	M-6
Fly ash (%)	0	10	20	30	40	50
Test age (days)	Modulus of elasticity (GPa)					
7	17.5	18.5	18.5	20.0	20.5	20.5
14	18.9	19.5	20.0	22.0	23.0	23.0
28	20.0	21.0	21.5	23.5	24.0	24.5
56	20.5	22.0	22.5	25.0	27.0	27.0
91	21.5	23.5	24.5	27.0	27.5	28.0
365	22.0	24.0	25.5	27.5	28.5	29.0

increase in fly ash content. This trend is more obvious between 40% and 50% replacement level. However, maximum strength at all ages occurs at 50% fine aggregate replacement. The rate of increase in strength is more prominent after 28-days. This may be attributed to the late pozzolanic reaction for forming pozzolanic C–S–H gel.

4.3. Flexural strength

The flexural strength test results of fly ash concrete are given in Table 8 and shown in Figs. 5 and 6, respectively. Fig. 5 shows the flexural strength development with age, and Fig. 6 shows the variation of flexural strength with various percentages of fly ash. It is evident from Table 8 and Fig. 5 that the flexural strength of fly ash concretes continued to increase with the age.

From Fig. 6, it can be seen that flexural strength continued to increase with the increase in fly ash percentages at all ages, and there is significant increase in strength with that of strength of control mix. This is believed to be due to the large pozzolanic reaction and improved interfacial bond between paste and aggregates.

4.4. Modulus of elasticity

Modulus of elasticity test results of fly ash concretes are given in Table 9 and shown in Figs. 7 and 8, respectively. Fig. 7 shows the variation of modulus of elasticity with age, and Fig. 8 shows the variation of modulus of elasticity with fly ash percentages. From the test results, it can be seen that the modulus of elasticity of fly ash concretes with 10%, 20%, 30%, 40%, and 50% fine aggregate (sand) replacement was higher than the control mix (M-1) at all ages. From Table 9 and Fig. 7, it can be seen that modulus of elasticity of all mixes continued to increase with age.

From Fig. 8, it can be seen that modulus of elasticity of fly ash concretes continued to increase with the increase in fly ash content. However, the rate of increase is becoming lesser with the increase in fly ash content. This trend is more obvious between 40% and 50% replacement level. However, maximum strength at all ages occurs at 50% fine aggregate replacement.

As fly ash is available free of cost in India and it may only involve transportation cost of bringing it to either laboratory or site, it does not incur any additional cost in making concrete as money will be saved on use of lesser sand.

5. Conclusions

The following conclusions can be drawn from the present investigation.

1. Compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of fine aggregate (sand) replaced fly ash concrete specimens were higher than the plain concrete (control mix) specimens at all the ages. The strength differential between the fly ash concrete specimens and plain concrete specimens became more distinct after 28 days.
2. Compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of fine aggregate (sand) replaced fly ash concrete continued to increase with age for all fly ash percentages.
3. The maximum compressive strength occurs with 50% fly ash content at all ages. It is 40.0 MPa at 28 days, 51.4 MPa at 91 days, and 54.8 MPa at 365 days.
4. At all the ages, the maximum splitting tensile strength was observed with 50% fly ash content. It is 3.5 MPa at 28 days, 4.3 MPa at 91 days, and 4.4 MPa at 365 days.
5. The maximum flexural strength has been found to occur with 50% fly ash content at all ages. It is 4.3 MPa at 28 days, 5.2 MPa at 91 days, and 5.4 MPa at 365 days.
6. At all ages, the maximum value of modulus of elasticity occurs with 50% fly ash content. It is 24.5 GPa at 28 days, 28.0 GPa at 91 days, and 29.0 GPa at 365 days.
7. Results of this investigation suggest that Class F fly ash could be very conveniently used in structural concrete.

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