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Performance characteristics of high-volume Class F fly ash concrete

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Abstract

More than 88 million tonnes of fly ash is generated in India each year. Most of the fly ash is of Class F type. The percentage utilization is around 10 to 15%. To increase its percentage utilization, an extensive investigation was carried out to use it in concrete. This article presents the results of an experimental investigation dealing with concrete incorporating high volumes of Class F fly ash. Portland cement was replaced with three percentages (40%, 45%, and 50%) of Class F fly ash. Tests were performed for fresh concrete properties: slump, air content, unit weight, and temperature. Compressive, splitting tensile, and flexural strengths, modulus of elasticity, and abrasion resistance were determined up to 365 days of testing.

Test results indicated that the use of high volumes of Class F fly ash as a partial replacement of cement in concrete decreased its 28-day compressive, splitting tensile, and flexural strengths, modulus of elasticity, and abrasion resistance of the concrete. However, all these strength properties and abrasion resistance showed continuous and significant improvement at the ages of 91 and 365 days, which was most probably due to the pozzolanic reaction of fly ash. Based on the test results, it was concluded that Class F fly ash can be suitably used up to 50% level of cement replacement in concrete for use in precast elements and reinforced cement concrete construction.

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

1. Introduction

Cement is the most cost- and energy-intensive component of concrete. The unit cost of concrete can be reduced by partial replacement of cement with fly ash. Fly ash is the byproduct of the combustion of pulverized coal and is collected by mechanical and electrostatic separators from the fuel gases of power plants where coal is used as a fuel. The disposal of fly ash is one of the major issues for environmentalists as dumping of fly ash as a waste material may cause severe environmental problems/hazards. The utilization of fly ash instead of dumping it as a waste material can be partly used on economic grounds as pozzolana for partial replacement of cement and partly because of its beneficial effects such as lower water demand for similar workability, reduced bleeding, and lower evolution of heat. It has been used particularly in mass concrete applications and large volume placement to control expansion due to heat of hydration and also helps in reducing cracking at early ages.

High-volume fly ash concrete has emerged as construction material in its own right. This type of concrete normally contains more than 50% fly ash by mass of total cementitious materials. Many researchers have used high volumes of Class C and Class F fly ashes in concrete. In this article, an effort has been made to present the results of an investigation carried out to study the effect of replacement of cement with high volumes of Class F fly ash on the properties of concrete.

2. Literature review

Ravina and Mehta [1] reported that by replacing 35–50% of cement with fly ash, there was 5–7% reduction in the water requirement for obtaining the designated slump, and the rate and volume of the bleeding water was either higher or about the same compared with the control mixture.

Malhotra and colleagues [2–8] have reported extensively on high-volume fly ash concrete. Concrete containing high volumes of Class F fly ash exhibited excellent mechanical properties, good durability with regard to repeated freezing and thawing, very low permeability to chloride ions [2–4],

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Table 1
Physical properties of portland cement

Physical test	Results obtained	Requirement IS: 8112-1989
Fineness (retained on 90-μm sieve)	7.5	10 max
Fineness: specific surface (air permeability test) (m^2/kg)	268	225 min
Normal consistency (%)	30	–
Vicat time of setting (min)		
Initial	108	30 min
Final	195	600 max
Compressive strength (MPa)		
3 days	23.8	22.0 min
7 days	35.8	33.0 min
28 days	46.2	43.0 min
Specific gravity	3.15	–

and showed no adverse expansion when reactive aggregates were incorporated into concrete [4]. Results up to 275 days of testing have indicated that high replacement levels of cement with fly ash were highly effective in inhibiting alkali–silica reaction [5]. Superplasticized high-volume fly ash concrete containing up to 60% of fly ash of total cementitious materials had poorer abrasion resistance than concrete without fly ash [6]. Air-entrained high-volume fly ash concrete exhibited excellent characteristics regardless of the type of fly ash (eight fly ashes from the United States) and cements (two portland cements from the United States) [7]. For concrete blocks containing high volumes of low-calcium (ASTM Class F) fly ash, ratio of the 42-day core compressive strength to the 28-day laboratory-cured compressive strength ranged from 78% for the control concrete to 120% for the high-volume fly ash concrete. At 365 days, these ratios were 78% and 92%, and at 730 days, the respective ratios were 88% and 98% [8].

Addition of fly ash as an admixture increased the early-age compressive strength and long-term corrosion-resisting characteristics of concrete [9]. Abrasion resistance of concrete made with Class C fly ash was better than both concrete without fly ash and concretes containing Class F fly ash [10]. High volumes of Class C and Class F fly ash can be used to produce high-quality pavements in concrete with excellent performance [11]. Blending of Class C fly ash with Class F fly ash showed either comparable or better results than either of the control mixture without fly ash or the unblended Class C fly ash [12].

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 were determined. Test results showed that rheological constants increased with higher replacement level of fly ash and that, when water-to-cement ratio was maintained, the strength development and carbonation properties were improved. Papadakis [14] proposed a model for performance prediction of concrete made with low-calcium fly ash as an additive. Twenty-eight-day compressive strength of 80 MPa could be obtained with a water-to-binder ratio of 0.24, with a fly ash content of 45% [15].

Table 2
Chemical composition of fly ash

Chemical parameter	Class F fly ash (%)	Requirement ASTM 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
Loss on ignition (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 details

3.1. Materials

Ordinary portland (43-grade) cement was used. It conformed to the requirements of Indian Standard Specifications IS: 8112-1989 [16], and results are given in Table 1. The cement used was similar to Type I cement (ASTM C 150). Class F fly ash (specific gravity 2.72) was used in the investigation. It was tested for its chemical composition per ASTM C 311, and results are given in Table 2. The fine aggregate used was natural sand having a 4.75-mm nominal maximum size. The coarse aggregate used was 12.5 mm

Table 4
Sieve analysis of aggregates

Fine aggregates			Coarse aggregates		
Sieve no.	Percent passing	Requirement IS: 383-1970	Sieve size	Percent passing	Requirement IS: 383-1970
4.75 mm	96.4	90–100	12.5 mm	96	95–100
2.36 mm	92.8	85–100	10 mm	68	40–85
1.18 mm	76.0	75–100	4.75 mm	6	0–10
600 μm	61.4	60–79			
300 μm	34.6	12–40			
150 μm	5.8	0–10			

Table 5
Concrete mixture proportions

Mixture number	M-1	M-2	M-3	M-4
Fly ash (%)	0	40	45	50
Cement, C (kg/m^3)	400	240	220	200
Fly ash, FA (kg/m^3)	0	160	180	200
Water, W (kg/m^3)	164	160	164	160
W/(C + FA)	0.41	0.40	0.41	0.40
SSD sand (kg/m^3)	616	614	610	616
Coarse aggregate (kg/m^3)	1228	1224	1226	1225
Superplasticizer (l/m^3)	2.2	2.5	2.6	2.7
Slump (mm)	65	85	90	100
Air content (%)	3.2	3.4	3.3	3.4
Air temperature (°C)	27	24	25	26
Concrete temperature (°C)	28	26	27	27
Concrete density (kg/m^3)	2406	2398	2400	2401

nominal maximum gravel. Both aggregates were tested per Indian Standard Specifications IS: 383-1970 [17], and their physical properties and sieve analysis are given in Tables 3 and 4, respectively. A commercially available melamine-based superplasticizer was used.

3.2. Mixture proportions

In this work, one control mixture M-1 was designed per Indian Standard Specifications IS: 10262-1982 [18] to have 28-day compressive strength of 37.2 MPa. The other three concrete mixtures were made by replacing cement with 40%, 45%, and 50% of Class F fly ash by mass. In doing so, water-to-cementitious materials ratio was kept almost same to investigate the effects of replacing cement with high volumes of Class F fly ash when other parameters were almost kept same. Mixture proportions are given in Table 5.

3.3. Preparation and casting of test specimens

Concrete cubes, 150 mm in size were cast for compressive strength, 150 × 300-mm cylinders for splitting tensile strength, 101.4 × 101.4 × 508-mm beams for flexural strength, 150 × 300-mm cylinders for modulus of elasticity, and specimens of size 65 × 65 × 60 mm for abrasion resistance. All the specimens were prepared in accordance with Indian Standard Specifications IS: 516-1959 [20]. After casting, test specimens were covered with plastic sheets and left in the casting room for 24 h at a temperature of about 24 ± 1 °C. They were demolded after 24 h and were put into a water-curing room until the time of the test.

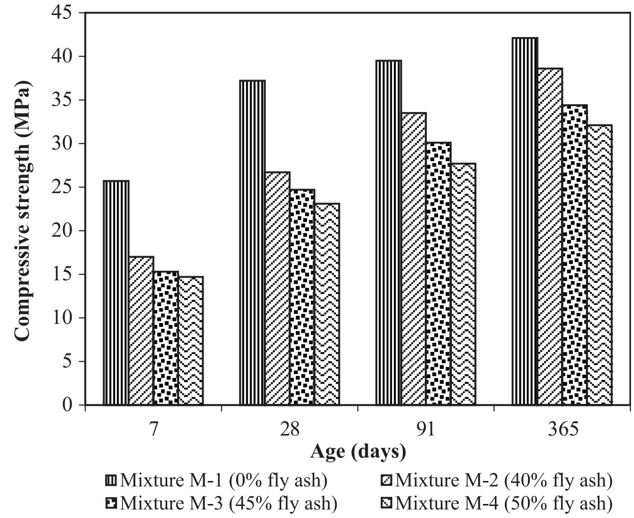

Fig. 1. Compressive strength versus age.

3.4. Fresh concrete properties

Fresh concrete properties, such as slump, unit weight, temperature, and air content, were determined per Indian Standard Specifications IS: 1199-1959 [19]. The results are presented in Table 5.

3.5. Testing of specimens

Concrete cubes, 150 mm in size were tested 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 per Indian Standard Specifications IS: 516-1959 [20]. Abrasion test on specimens of size 65 × 65 × 60 mm was performed in accordance with Indian Standard Specifications IS: 1237-1980 [21].

4. Results and discussion

4.1. Compressive strength

Compressive strength of concrete mixtures was determined at the ages of 7, 28, 91, and 365 days. Results are given in Table 6 and shown in Fig. 1. At 28 days, control mixture M-1 (0% fly ash) achieved compressive strength of

Table 6
Compressive strength results

Mixture number	Compressive strength (MPa)			
	7 days	28 days	91 days	365 days
M-1 (0% fly ash)	25.7	37.2	39.5	42.1
M-2 (40% fly ash)	17.0	26.7	33.5	38.6
M-3 (45% fly ash)	15.3	24.7	30.1	34.4
M-4 (50% fly ash)	14.7	23.1	27.7	32.1

Table 7
Splitting tensile strength results

Mixture number	Splitting tensile strength (MPa)			
	7 days	28 days	91 days	365 days
M-1 (0% fly ash)	2.8	4.1	4.2	4.3
M-2 (40% fly ash)	1.8	3.0	3.8	4.3
M-3 (45% fly ash)	1.6	2.6	3.3	3.8
M-4 (50% fly ash)	1.5	2.2	2.6	3.0

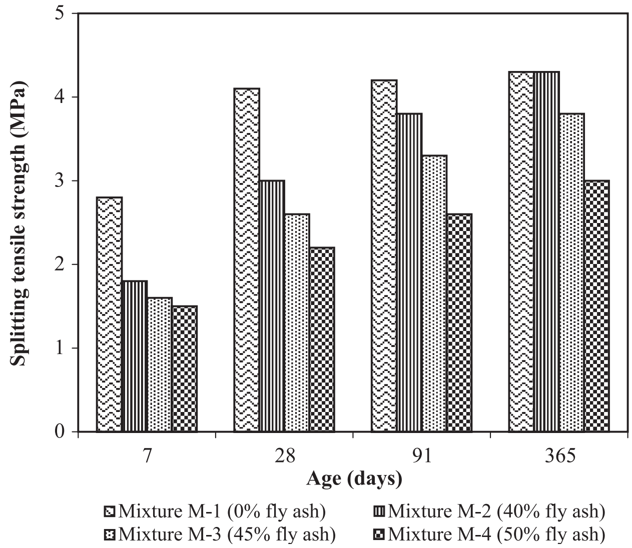

Fig. 2. Splitting tensile strength versus age.

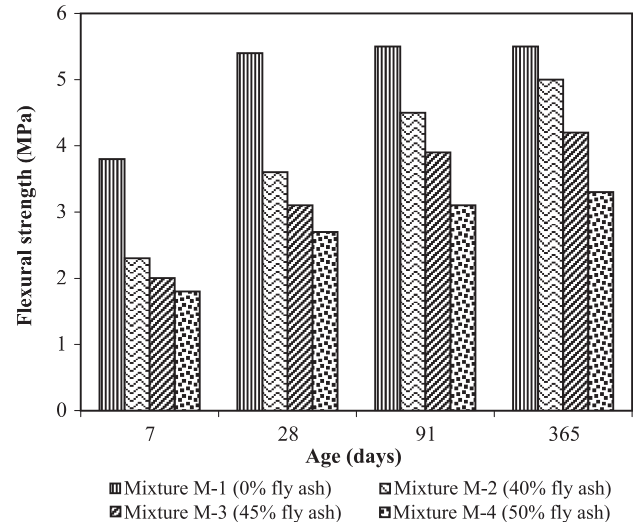

Fig. 3. Flexural strength versus age.

37.2 MPa, whereas mixtures M-2 (40% fly ash), M-3 (45% fly ash), M-4 (50% fly ash) achieved compressive strength of 26.7, 24.7, and 23.1 MPa, respectively; a reduction of 28%, 34%, and 38%, respectively, in comparison with the strength of the control mixture M-1 (0% fly ash). The results at 91 and 365 days indicated that there was continuous and significant improvement in strength beyond the age of 28 days. The increase in strength from 28 to 91 days was between 20% and 26%, whereas increase in strength from 28 to 365 days was between 39% and 45%. The increase in strength is, of course, due to the cement that continued to hydrate. The significant increase in strength of high-volume fly ash concrete is due to pozzolanic reaction of fly ash. Although at 28 days, the replacement of cement with fly ash decreased the compressive strength of concrete, but, even then, compressive strength result indicated that even mixture M-4 (50% fly ash) could be used for general concrete construction, and other mixtures M-2 (40% fly ash) and M-3 (45% fly ash) could very well be used for structural concrete.

4.2. Splitting tensile strength

Splitting tensile strength of concrete mixtures was determined at the ages of 7, 28, 91, and 365 days. Results are given in Table 7 and shown in Fig. 2. The variation in splitting tensile strength with fly ash content was similar to that observed in case of compressive strength. Splitting tensile strength decreased with the increase in fly ash content. At 28 days, splitting tensile strength of control mixture M-1 (0% fly ash) was 4.1 MPa, whereas mixtures M-2 (40% fly ash), M-3 (45% fly ash), and M-4 (50% fly ash) achieved splitting tensile strength of 3.0, 2.6, and 2.2 MPa, respectively; a reduction of 27%, 37%, and 46%, respectively, in comparison with the strength of the control mixture M-1 (0% fly ash). However, splitting tensile strength was found to increase with age. At 91 days, mixtures M-1 (0% fly ash), M-2 (40% fly ash), M-3 (45% fly ash), and M-4 (50% fly ash) achieved splitting tensile strength of 4.2, 3.8, 3.3, and 2.6 MPa, respectively; an increase of 2%, 26%, 27%, and 18%, respectively, for mixtures M-1 (0% fly ash), M-2 (40% fly ash), M-3 (45% fly ash), and M-4 (50% fly ash) in comparison with 28 days strength. Similar trend was also observed with 365 days splitting tensile strength results. Percentage increase in the strength for the mixtures M-1 (0% fly ash), M-2 (40% fly ash), M-3 (45% fly ash), and M-4 (50% fly ash) was 5%, 43%, 46%, and 36%, respectively, in comparison with 28-day strength. It can be seen from these results that percentage increase in strength at 91 and 365 days with respect to 28-day strength was much more for fly ash concrete mixtures

Table 8
Flexural strength results

Mixture number	Flexural strength (MPa)			
	7 days	28 days	91 days	365 days
M-1 (0% fly ash)	3.8	5.4	5.5	5.5
M-2 (40% fly ash)	2.3	3.6	4.5	5.0
M-3 (45% fly ash)	2.0	3.1	3.9	4.2
M-4 (50% fly ash)	1.8	2.7	3.1	3.3

Table 9
Modulus of elasticity results

Mixture number	Modulus of elasticity (GPa)		
	28 days	91 days	365 days
M-1 (0% fly ash)	29.9	31.0	31.0
M-2 (40% fly ash)	20.9	22.1	24.3
M-3 (45% fly ash)	19.8	20.9	22.2
M-4 (50% fly ash)	19.0	19.2	20.9

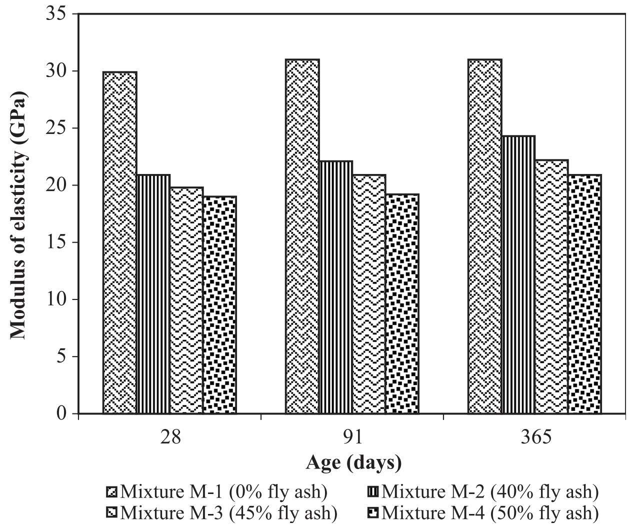

Fig. 4. Modulus of elasticity versus age.

and control mixture M-1. This could be attributed to the pozzolanic action due to fly ash.

4.3. Flexural strength

Flexural strength of concrete mixtures was determined at the ages of 7, 28, 91, and 365 days. Results are given in Table 8, and shown in Fig. 3. Like compressive and splitting tensile strength results, flexural strength of concrete mixtures also increased with age. Control mixture M-1 (0% fly ash) achieved flexural strength of 5.4 MPa at 28 days, 5.5 MPa at 91 days, and 5.5 MPa at 365 days. Mixture M-2 (40% fly ash) achieved flexural strength of 3.6 MPa at 28 days, 4.5 MPa at 91 days, and 5.0 MPa at 365 days. Mixture M-3 (45% fly ash) achieved flexural strength of 3.1 MPa at 28 days, 3.9 MPa at 91 days, and 4.2 MPa at 365 days,

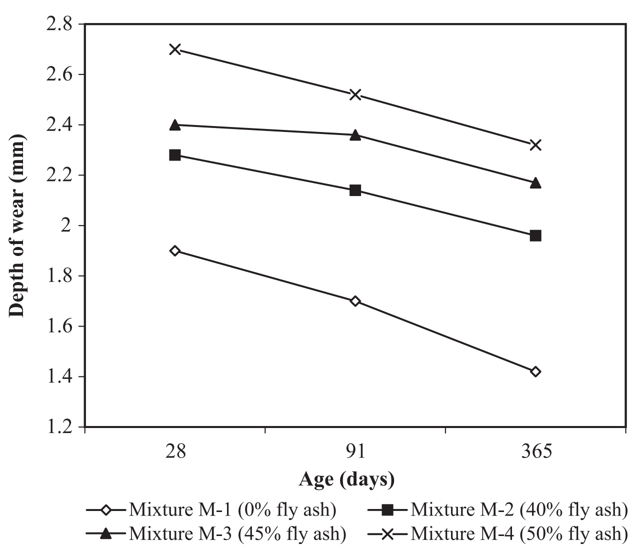

Fig. 5. Depth of wear at 60 min of abrasion.

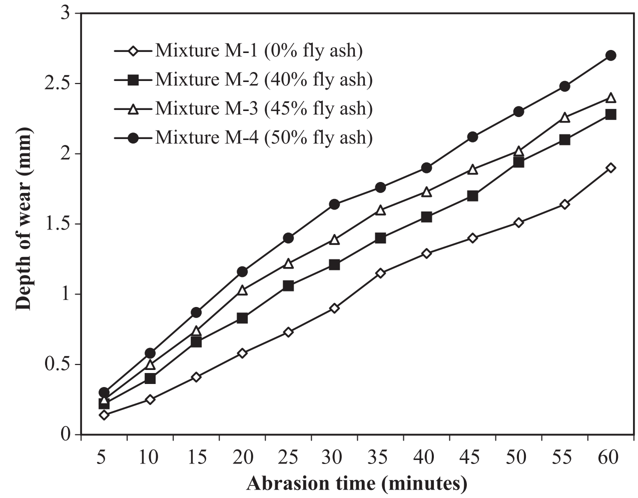

Fig. 6. Depth of wear versus abrasion time at 28 days.

whereas mixture M-4 (50% fly ash) achieved flexural strength of 2.7 MPa at 28 days, 3.1 MPa at 91 days, and 3.3 MPa at 365 days. It can be seen from these results that there was continuous strength development beyond the age of 28 days. The strength increase from 28 to 91 days was between 25% and 15%, whereas increase in strength was from 28 to 365 days is between 39% and 26%, depending upon fly ash content.

4.4. Modulus of elasticity

In this investigation, the modulus of elasticity, which is also called secant modulus, is taken as the slope of the chord from the origin to some arbitrary point on the stress–strain curve. The secant modulus calculated in this study is for 33% of the maximum stress. Modulus of elasticity of concrete mixtures was determined at the ages of 28, 91, and 365 days. Results are given in Table 9 and shown in

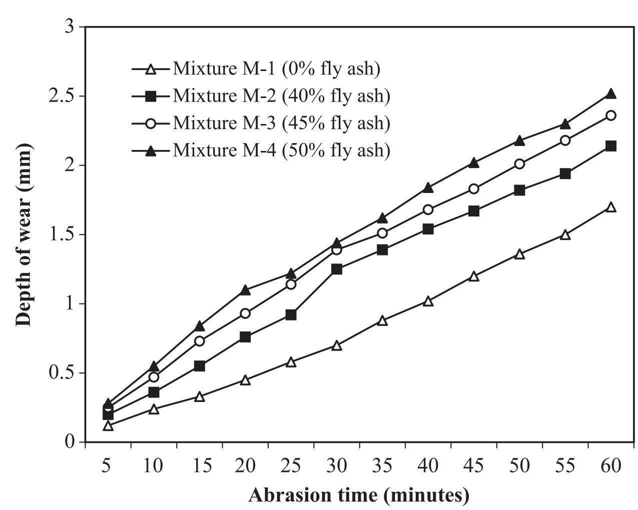

Fig. 7. Depth of wear versus abrasion time at 91 days.

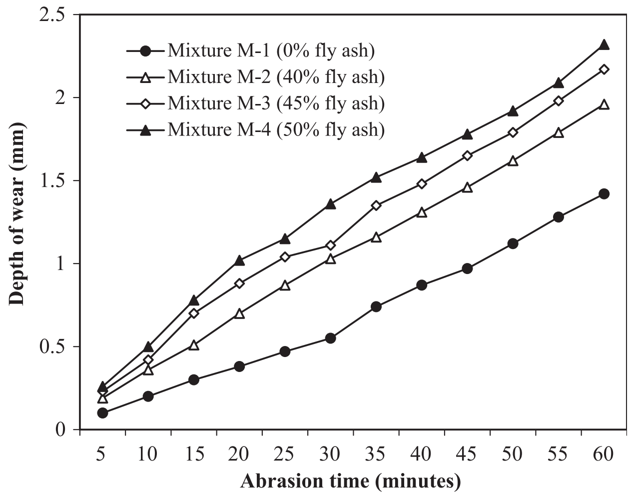

Fig. 8. Depth of wear versus abrasion time at 365 days.

Fig. 4. Test results indicated that use of large proportion of fly ash reduced the modulus of the concrete compared to that of control mixture. At 28 days, control mixture M-1 (0% fly ash) achieved modulus of elasticity of 29.9 GPa, whereas mixtures M-2 (40% fly ash), M-3 (45% fly ash), and M-4 (50% fly ash) achieved modulus of elasticity of 20.9, 19.8, and 19 GPa, respectively. However, 91 and 365 days results indicated that modulus of elasticity of concrete mixtures increased with the age.

4.5. Abrasion resistance

The abrasion resistance test was performed at the ages of 28, 91, and 365 days for all concrete mixtures. Figs. 5–8 presents the abrasion resistance of concrete mixtures. Fig. 5 represents the variation of abrasion resistance (depth of wear) with cement replacements at 60 min of abrasion at 28, 91, and 365 days of testing. From Fig. 5, it can be seen that abrasion resistance of concrete mixtures M-2 (40% fly ash), M-3 (45% fly ash), and M-4 (50% fly ash) containing 40%, 45%, and 50% fly ash was lower than that of the control mixture M-1. At 28 days, the depth of wear for mixtures M-1 (0% fly ash), M-2 (40% fly ash), M-3 (45% fly ash), and M-4 (50% fly ash) was 1.9, 2.28, 2.4, and 2.7 mm, respectively, whereas it was 1.7, 2.14, 2.36, and 2.52 mm at 91 days for mixtures M-1, M-2, M-3, and M-4, respectively. At 365 days, depth of wear was 1.42, 1.96, 2.17, and 2.32 mm for mixtures M-1, M-2, M-3, and M-4, respectively. Figs. 6–8 show the variation of abrasion resistance (depth of wear) with abrasion time for all concrete mixtures at the ages of 28, 91, and 365 days, respectively. From these figures, it can be seen that depth of wear increased with increase in abrasion time for all mixtures, and also depth of wear decreased with the increase in age for all concrete mixtures. Abrasion test results indicated that the compressive strength was an important factor affecting the abrasion resistance of concrete.

5. Conclusions

The following conclusions are drawn from this investigation:

1. The replacement of cement with three percentages of fly ash content reduced the compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of concrete at the age of 28 days, but there was a continuous and significant improvement of strength properties beyond 28 days.
2. The strength of concrete with 40%, 45%, and 50% fly ash content, even at 28 days is sufficient enough for use in reinforced cement concrete construction.
3. Abrasion resistance of concrete was strongly influenced by its compressive strength, irrespective of fly ash content.
4. Abrasion resistance was found to increase with the increase in age for all concrete mixtures. Depth of wear was found to be maximum at 60 min of abrasion time for all mixtures.

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