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p. 13-28

Influence of Utilization of High-Volumes of Class F Fly Ash on the Abrasion Resistance of Concrete

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Abstract

Utilization of large volumes of fly ash in various concrete applications is a becoming a more general practice in an efforts towards using large quantities of fly ash. Around the world, Class C or Class F or both as available have been used in high volumes in cement-based materials. In India, majority of fly generated is of Class F type as per ASTM C 618. Yearly fly ash generation in India is approximately 95 million tonnes. Out of which around 15-20% is utilized in cement production and cement/concrete related activities. In order to increase its percentage utilization, an investigation was carried out to use it in concrete.

In this paper, abrasion resistance of high volume fly ash (HVFA) concretes made with 35, 45, 55, and 65% of cement replacement was evaluated in terms of its relation with compressive strength. Comparison was made between ordinary Portland cement and fly ash concrete. Test results indicated that abrasion resistance of concrete having cement replacement up to 35 percent was comparable to the normal concrete mix with out fly ash. Beyond 35% cement replacement, fly ash concretes exhibited slightly lower resistance to abrasion relative to non-fly ash concretes. Test results further indicated that abrasion resistance of concrete is closely related with compressive strength, and had a very good correlation between abrasion resistance and compressive strength (R^2 value between 0.9018 and 0.9859 depending upon age.

Keywords
Abrasion resistance; Compressive strength; Concretes; Fly ash; High-volume fly ash concrete

Introduction

High volume fly ash concrete (HVFA Concrete)

Cement is one of the most cost and energy intensive components of concrete. Across the world, significant environmental problems result from the manufacture of Portland cement. The principal ingredients of concrete are gravel, sand, water, and Portland cement. Although the cement only comprises 10-15% of concrete by weight, its production is responsible for most of concrete's environmental impacts. The cement composed of lime and silica (sourced from limestone, clay, and sand), is fired in a rotary kiln at 1400°C, consuming enormous quantities of fossil fuels and thereby producing high amounts of CO2. In addition, the chemical reaction that creates Portland cement produces CO_2 as a by-product. Worldwide, the manufacture of Portland cement accounts for 6-7% of the total carbon dioxide (CO_2) produced by humans, adding the greenhouse gas equivalent of 330 million cars driving 12,500 miles per year.

Fly ash, a by-product from thermal power plants, can be substituted for large portions of Portland cement, significantly improving concrete's environmental characteristics. Fly ash, consisting mostly of silica, alumina, and iron, forms a compound similar to Portland cement when mixed with lime and water. Fly ash is a non-combusted by-product of coal-fired power plants. It has been successfully used in cement based materials like concrete and controlled low-strength materials besides still being land-filled due to its large volume generation. However, when high volumes (more than 35% of cement replacement) are used in concrete and CLSM, it is called High Volume Fly Ash Concrete. It creates a stronger, more durable product and reduces concrete's environmental impact considerably. Due to its strength and lower water content, cracking is reduced. Two types of fly ash are available: Class C fly ash, which is typically light or tan colored and is produced from burning lignite or sub-bituminous coal, and Class F fly ash, which is dark grey and is produced from burning anthracite or bituminous coal. By displacing a large percentage of the cement in concrete, fly ash significantly reduces the associated environmental impacts of CO_2 production and air pollution.

Advantages of utilization HVFA concrete

- Less energy intensive manufacture
- Higher ultimate strength
- More durable
- Requires less water
- Uses a waste by-product
- Creates fewer global warming gases

Abrasion resistance (Wear) of concrete

Abrasion of concrete occurs due to scraping, rubbing, skidding or sliding of objects on its surface. Abrasion resistance of concrete is influenced by number of factors such as compressive strength, surfacing finish, aggregate properties, types of hardeners, and curing. A number of previous studies [1-5] have indicated that abrasion resistance of concrete is primarily dependent on the compressive strength of concrete. Therefore, air-entrainment, water-cement ratio, and types of aggregates and their properties, which have influence on compressive strength of concrete, should also have their effect on the abrasion resistance of concrete. In general, hardened paste has low abrasion resistance. To develop concrete for high abrasion resistance, it is important to use hard surface aggregates, surface materials, and paste having low porosity and high strength [2].

Research significance of present investigation

This research was carried out to evaluate the performance of Class F fly ash in concrete with respect to abrasion resistance and strength. Concrete strength and abrasion resistance was determined at various percentages of cement replacement with Class-F fly ash. The findings of this investigation would be useful in establishing mix proportions, and understanding the behavior of such concretes under abrasion.

Literature review

It has been well established that cement content, water-cement ratio, air content, workability, type of finish, and curing conditions have influence on characteristics of concrete surface. Studies [3-5] have shown that compressive strength is the most important factor governing the abrasion resistance of concrete. Abrasion resistance of concrete is strongly influenced by the relative abrasion of its constituent's materials, such as coarse aggregates and mortar [3]. Hadchti and Carrasquillo [4] evaluated the abrasion resistance of concrete as a function of finishing, curing and fly ash inclusion. Concrete cured at high temperature and low humidity exhibited decreased resistance to abrasion. Witte and Backstrom [5] have reported that for same strengths, abrasion resistance of air-entrained concrete is similar to that of non-air-entrained concrete.

Investigators [6-9] have shown that types of curing and surface finish have a strong influence on the abrasion resistance of concrete. Gebler and Klieger [10] have investigated the abrasion resistance of concrete incorporating Class C and Class F fly ashes from ten different sources. Concrete mixes were designed to have 25 percent fly ash by weight of total cementitious materials. Nanni [11] investigated the abrasion resistance of roller-compacted concrete using both laboratory and field specimens. Mixes were made by replacing cement with 50 percent Class C fly Ash. The test results showed that: (i) testing under air-dry conditions produces 30 to 50 percent less wear than under wet conditions; addition of steel or synthetic fibers does not cause any appreciable change in the abrasion resistance of concrete; and (iii) improper moist-curing conditions produce more negative effects on the surface quality than the compressive strength of concrete. Liu [12] compared the abrasion resistance of non-fly ash concrete with a fly ash concrete having 25 percent cement replacement. Abrasion of concrete with or without fly ash was similar up to 36 hours of abrasion testing. However, after 72 hours of testing, the fly ash concrete lost about 25 percent more weight than the concrete without fly ash.

Tikalsky [13] reported that the concrete containing Class C fly ash performed better (in abrasion resistance) than both concrete without fly ash and concretes containing Class F fly ash. Langan et al. [14] reported that the presence of fly ash at high levels of cement replacement increased the weight loss due to abrasion at all ages relative to concrete with out fly ash. Bilodeau and Malhotra [15] investigated the abrasion resistance of concrete incorporating high volumes of Class F fly ash. Superplasticized mixtures were developed with

55 to 60 percent fly ash of total cementitious materials. Test results showed that fly ash concrete have poorer abrasion resistance than concrete with out fly ash. Ukita et al. [16] studied the abrasion resistance of concrete incorporating a low-calcium fly ash in the range of 0 to 35 percent of cement by volume. They reported that at 15 percent cement replacement with fly ash, abrasion increased with fineness of fly ash. However, at fly ash content of 30 percent, the abrasion resistance of concrete was lower than that of concrete with out fly ash. Carette et al. [17] reported the results of the abrasion resistance of air-entrained, superplasticized, high-volume Class F fly ash concrete. The quantity of fly ash varied from 55 to 60 percent. They reported that some concretes exhibited significantly lower abrasion resistance than other concretes of similar or even lower compressive strength. Naik et al. [18] conducted research to establish fly ash concrete mixture proportions for highway paving work. Concrete mixes were proportioned to replace 20 and 50 percent cement with a Class C, and 40 percent with a Class F fly ash. They reported that both the high-volume mixtures (40 percent Class F and 50 percent Class C) showed better results, and should be an excellent alternative to conventional paving material. Naik et al. [19] evaluated the abrasion resistance of concrete proportioned to have five levels of cement replacements (15, 30, 40, 50, and 70 percent) with one source of Class C fly ash. Reference concrete without fly ash was proportioned to have a 28-day compressive strength of 41 MPa. Test results showed that abrasion resistance of concrete having cement replacement up to 30 percent was comparable to the reference concrete with out fly ash. Beyond 30 percent cement replacement, fly ash concrete exhibited slightly lower resistance to abrasion relative to non-fly ash concrete. Ghafoori and Diawara [20] evaluated the abrasion resistance of concrete proportioned to have four levels of fine aggregate replacement (5, 10, 15, and 20 percent) with silica fume. Test results showed that the resistance to wear of concrete containing silica fume, as a fine aggregate replacement was consistently better with increasing amounts of silica fume up to 10 percent. Naik et al. [21] reported that strength and durability properties including abrasion resistance for the 40% fly ash mixture were either comparable or superior to the no-fly ash concrete.

Experimental Procedure

Materials

Ordinary portland (43 grade) cement was used, and its properties are given in Table 1.

Table 1. Physical properties of portland cement

Physical test	Results obtained	IS: 8112-1989 Specifications
Fineness (retained on 90 μm sieve	7.1	10 max
Fineness: specific surface (air permeability test) (m^2/kg)	310	225 min
Normal consistency	32%	-
Vicat time of setting (minutes)		
Initial	115	30 min
Final	205	600 max
Compressive strength (MPa)		
3-day	24.2	22.0 min
7 -day 28-day	36.1 46.8	33.0 min 43.0 min
Specific Gravity	3.13	-

It met the requirements of Indian Standard Specifications IS: 8112-1989 [22]. Class F fly ash obtained from thermal power plant at Ropar 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 2. Chemical composition of Class F flies ash

Chemical analysis	Class F fly ash (%)	ASTM requirement C 618 (%)
Silicon Dioxide, SiO_2	56.8	-
Aluminum Oxide, Al_2O_3	26.10	-
Ferric Oxide, Fe_2O_3	5.0	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	87.9	70.0 min
Calcium Oxide, CaO	3.8	--
Magnesium Oxide, MgO	2.3	5.0 max
Titanium Oxide, TiO_2	1.4	--
Potassium Oxide, K_2O	0.6	--
Sodium Oxide, Na_2O	0.4	1.5 max
Sulfur trioxide, SO_3	1.6	5.0 max
LOI (1000^{o}C),	1.9	6.0 max
Moisture	0.3	3.0 max

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 [23], and its physical properties and sieve analysis results are shown in Table 3 and 4 respectively. Coarse aggregate used in this study were 12.5 mm nominal size, and were tested as per Indian Standard Specifications IS: 383-1970 [23], and the its physical properties and sieve analysis results are shown in Table 3 and 4 respectively. A commercially available melamine based superplasticizer was used in all mixes.

Table 3. Physical properties of aggregates

Property	Fine aggregate	Coarse aggregate
Specific gravity	2.64	2.59
Fineness modulus	2.32	6.63
SSD absorption (%)	0.81	1.05
Void (%)	34.2	41.2
Unit weight (kg/m^3)	1685	1640

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	98.6	90-100	12.5 mm	95	90-100
2.36 mm	94.1	85-100	10 mm	70	40-85
1.18 mm	78.2	75-100	4.75 mm	8	0-10
600 μm	60.9	60-79			
300 μm	36.2	12-40			
150 μm	7.0	0-10			

Mix proportions

Five different mixes were made. First was control mix (with out fly ash), and the remaining three mixes contained Class F fly ash. Cement was replaced with fly ash by weight. The proportions of portland cement replaced ranged from 35 to 65%. Mix proportions are given in Table 5. The control mix with out fly ash was proportioned as per Indian Standard Specifications IS: 10262-1982 [24] to have a 28-day cube compressive strength of 43.5 MPa. Mixture proportions are given in Table 5.

Preparation and casting of specimens

150-mm cubes were cast for compressive strength in accordance with the Indian Standard Specifications IS: 516-1959 [25], and concrete specimens of size 65 x 65 x 60 mm were cast for determination of abrasion resistance in accordance with Indian Standard Specifications IS: 1237-1980 [26]. Abrasion test specimens were cast using an external vibrator. After casting, all 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 temperatures of about 23 degree Celsius in the casting room. They were demolded after 24 hours. They were then put into a water-curing tank for the test periods.

Table 5. Mixture proportions

Mixture No.	M-1	M-2	M-3	M-4	M-5
Cement (kg/m^3)	450	293	248	203	158
Fly ash (%)	0	35	45	55	65
Fly ash (kg/m^3)	0	157	202	247	292
Water (kg/m^3)	162	162	162	162	162
W/(Cement + Fly ash)	0.36	0.36	0.36	0.36	0.36
Sand SSD (kg/m^3)	535	535	535	535	535
Coarse aggregate (kg/m^3)	1225	1225	1225	1225	1225
Superplasticizer (l/m^3)	3.8	4.3	4.4	4.6	4.7
Slump (mm)	75	85	90	85	90
Air content (%)	2.8	2.9	2.9	3.1	3.2
Density (kg/m^3)	2375	2374	2374	2375	2376

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 [27]. The results are presented in Table 5.

Testing of specimens

150-mm concrete cubes were tested for compressive strength at the ages of 7, 28, 91, and 365 days per Indian Standard Specifications IS: 516-1959 [25]. Abrasion resistance test was performed at the ages of 28, 91 and 365 days. All specimens were tested at dry conditions per Indian Standard Specifications IS 1237-1980 [26]. Each specimen was weighed accurately on a digital balance. After initial drying and weighing, thickness of the specimens was measured at five points (i.e. one at the center and four corners with micrometer). The grinding path of the disc of the abrasion-testing machine was evenly distributed with 20-gram abrasive powder (aluminum powder). The specimens were fixed in the holding device of the abrasion machine, and a load of 300 N was applied. The grinding machine was then put on motion at a speed of 30 revolutions per minute, and the abrasive powder was continuously fed back in to the grinding path so that it remained uniformly distributed in the track corresponding to the width of the test specimen. Each specimen was abraded for 60 minutes. The tests were performed for the specified time periods, and the readings were taken at every 5 minutes interval. When the abrasion test was over, specimens were weighed again to calculate the loss of weight. The thickness of the specimens was again measured at five points. The extent of abrasion was determined from the difference in values of thickness measured before and after the abrasion test. The results were also confirmed with the calculated average loss in thickness of the specimens using the following formula:

$$T = \{(W_1 - W_2) \cdot V_1\}/(W_1 \cdot A)$$

where, T is average loss in thickness in mm; W_1 is the initial weight of the specimen in gram; W_2 is the mass of the specimen after abrasion in gram; V_1 is the initial volume of the specimens in mm^3, A is the surface area of the specimens in mm^2.

Hardened concrete properties

150-mm concrete cubes were tested for compressive strength at 7, 28, 91, and 365 days, according to Indian Standard Specifications IS: 516-1959 [25]. The test results are reported in Table 6. Abrasion resistance tests were performed at 28, 91 and 365 days. All specimens were tested at dry conditions according to Indian Standard Specifications IS 1237-1980 [26].

Results and Discussion

Compressive strength

Compressive strength of concrete mixtures made with and without fly ash was determined at the ages of 7, 28, 91 and 365 days, and results are shown in Fig. 1. Fig. 1 shows the variation of compressive strength with cement replacements at various ages. Form the test results, it can be seen that the compressive strength of high-volume fly ash concrete mixtures with 35, 45, 55, and 65% cement replacement was lower than the Control Mixture (M-1) at all ages. At 7 days, compressive strength of Control Mixture M-1 was 27.5 MPa whereas it was 18.3 MPa for Mixture M-2 (35% fly ash), 15 MPa for Mixture M-3 (45% fly ash), 13.6 MPa for Mixture M-4 (55% fly ash), and 11.5 MPa for Mixture M-5 (65% fly ash). At 28 days, compressive strength of Control Mixture M-1 was 43.5 MPa, whereas it was 30.5 MPa for

Mixture M-2 (35% fly ash), 25.4 MPa for Mixture M-3 (45% fly ash), 22.5 MPa for Mixture M-4 (55% fly ash), and 17 MPa for Mixture M-5 (65% fly ash).

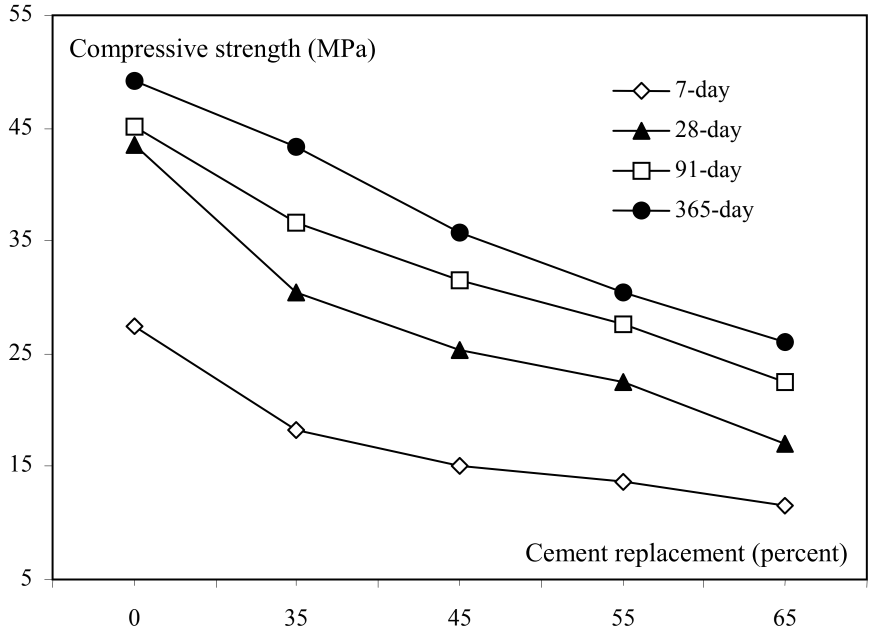

Figure 1. Compressive strength versus percentage of cement replacement with fly ash

At 91 days, compressive strength of Control Mixture M-1 was 45.1 MPa whereas it was 36.2 MPa for Mixture M-2 (35% fly ash), 31.5 MPa for Mixture M-3 (45% fly ash), 27.6 MPa for Mixture M-4 (55% fly ash), and 22.55 MPa for Mixture M-5 (65% fly ash). At 365 days, compressive strength of Control Mixture M-1 was 49.2 MPa, whereas it was 43.4 MPa for Mixture M-2 (35% fly ash), 35.8 MPa for Mixture M-3 (45% fly ash), 30.4 for Mixture M-4 (55% fly ash), and 26 MPa for Mixture M-5 (65% fly ash).

Fig. 2 shows the ratio of compressive strength at 28, 91 and 365 days with respect to 7 days strength. It is evident from this figure that there was reduction in the compressive strength of concrete mixtures with the increase in the replacement levels of cement with fly ash at all ages. But all fly ash concrete mixtures indicated significant increase in compressive strength with age, and this is definitely due to the pozzolanic action of the fly ash.

Abrasion resistance

The abrasion tests were performed at the ages of 28, 91 and 365 days for all mixes. Fig. 3 to 5 presents the abrasion resistance of all concrete mixes. In general, abrasion wear decreased (i.e. abrasion resistance increased) with the increase in age. Fig. 3 presented the

Issue 10, January-June 2007
p. 13-28

variation of abrasion resistance with cement replacements at different ages at 60 minutes of abrasion.

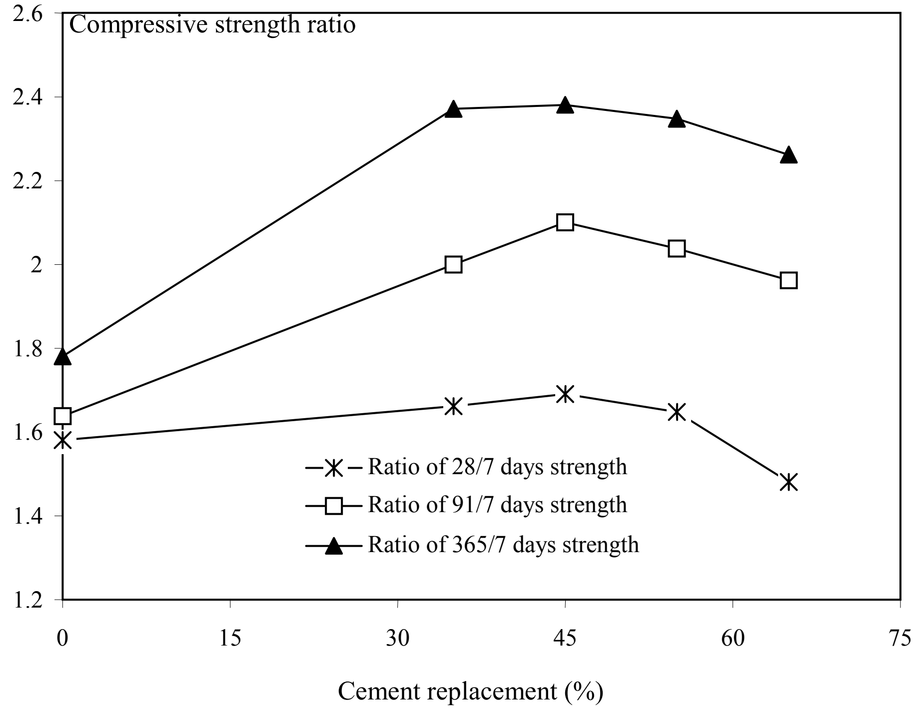

Figure 2. Ratio of compressive strength versus percentage of cement replacement with fly ash

At 60 minutes of abrasion, depth of wear for Control Mixture M-1 (0% fly ash) was 1.81 mm at 28-day, 1.72 mm at 91-day, and 1.34 mm at 365-day, whereas depth of wear was 1.94 mm at 28-day, 1.83 mm at 91-day and 1.67 mm at 365-day for Mixture M-2 (35% fly ash); 2.34 mm at 28-day, 2.23 mm at 91-day, and 2.0 mm at 365-day for Mixture M-3 (45% fly ash); 2.62 mm at 28-day; 2.48 mm at 91-day and 2.25 mm at 365-day for Mixture M-4 (55% fly ash); and 3.24 mm at 28-day, 2.93 mm at 91-day, and 2.55 mm at 365-day for Mixture M-6 (65% fly ash). This indicated that for a particular percentage of cement replacements, depth of wear decreased with increase in age, which means that abrasion resistance of concrete mixtures increased with age. This is possibly due to the increase in compressive strength resulting from increased maturity of concrete with age, and densification of the concrete matrix.

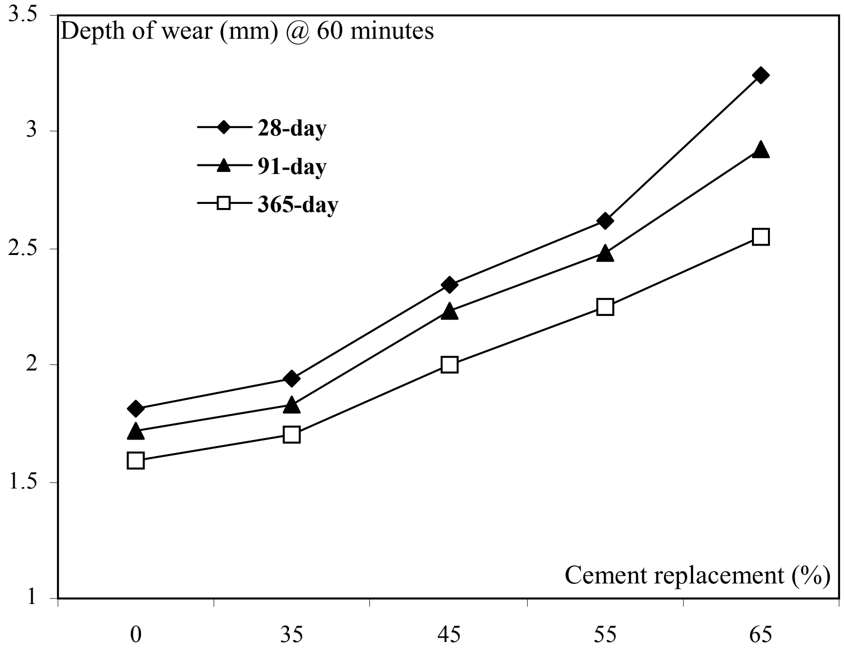

Figure 3. Abrasion resistance (depth of wear versus cement replacement with fly ash)

These results are similar to that reported by others [3-5]. From the Fig., it can be seen that abrasion resistance of mixes M-2, M-3, M-4 and M-5 containing 35, 45, 55 and 65% fly ash, was lower than that of the control mix M-1. However, abrasion resistance of mix M-2 (containing 35% fly ash) was comparable with that of control mix, but beyond, 35% cement replacement, it decreased primarily because of its lower compressive strength.

Figures 4 and 5 represent the variation of abrasion resistance with abrasion time for all mixes at 28 and 365 days respectively. From these figures, it can be seen that depth of wear increased with increase in abrasion time for all mixes, and also depth of wear decreased with the increase in age of mixes. Abrasion test results indicate that the compressive strength was an important factor affecting the abrasion resistance of concrete.

Figure 6 shows the relationship between compressive strength and abrasion resistance (depth of wear) of concrete mixtures. It is abundantly clear from this figure that abrasion resistance of concrete is closely related with compressive strength, and in this case, correlation (value of R^2) was very good (0.9018 at 28 days), and got even better at later ages (0.9847 at 91 days and 0.9859 at 365 days). Though the abrasion resistance of concrete mixtures decreased with increase in fly ash content, the abrasion resistance of Mixture M-2 (35% fly ash) was comparable with that of Control mixture M-1 (0% fly ash), but beyond, 35% cement replacement, it decreased primarily because of its lower compressive strength.

Issue 10, January-June 2007
p. 13-28

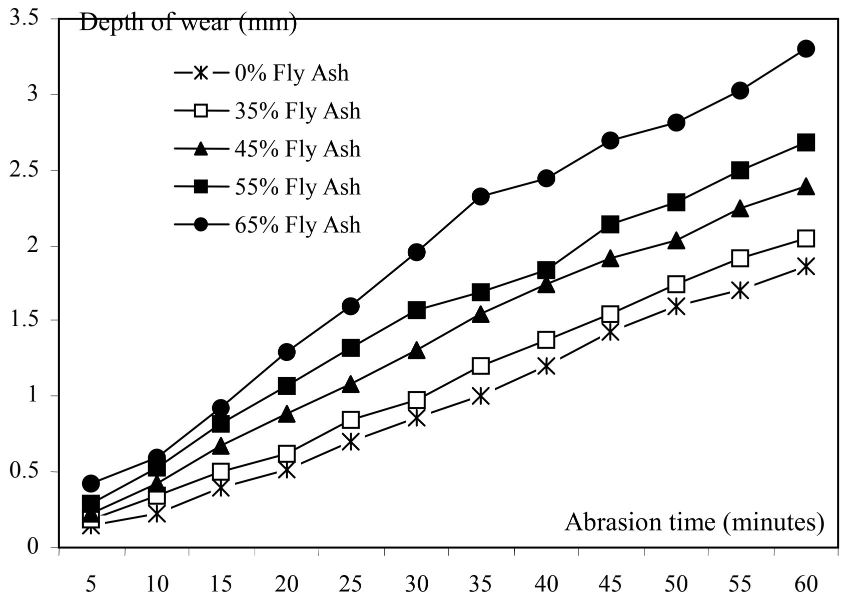

Figure 4. Depth of wear versus abrasion time at 28 days

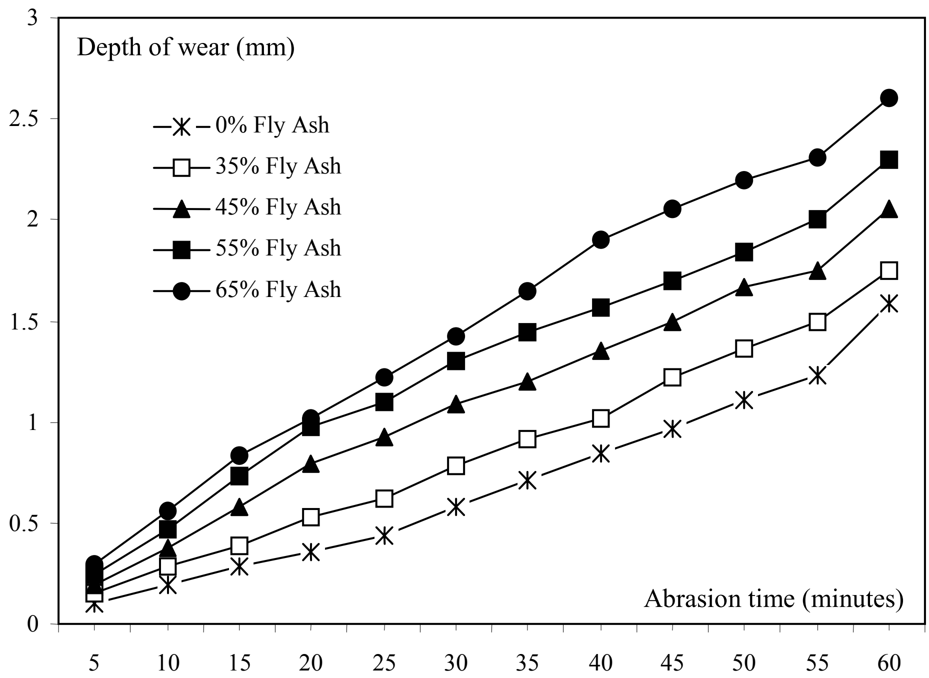

Figure 5. Depth of wear versus abrasion time at 365 days

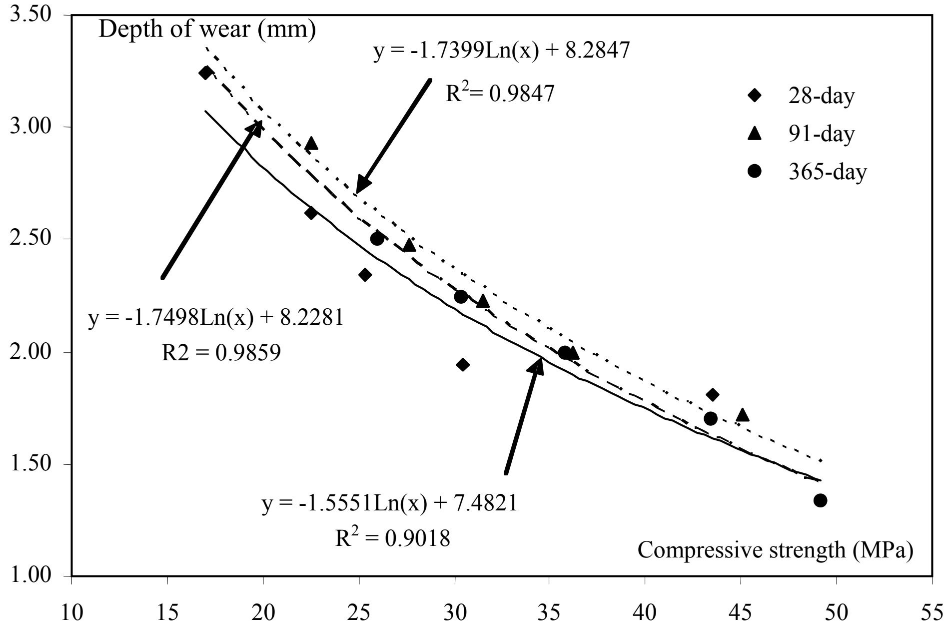

Figure 6. Relationship between compressive strength and depth of wear

Conclusions

Following conclusions can be drawn from the present investigation:

1. Compressive strength of concrete decreased with the increase in fly ash content at all ages. However, at each replacement level of cement with fly ash, an increase in strength was observed with the increase in age due to the pozzolanic reaction of fly ash.
2. Compressive strength of fly ash concrete containing up to 45% cement replacement could be useful in most structural applications.
3. Abrasion resistance was found to increase with the increase in age for all mixtures. Depth of wear was found to be maximum at 60 minutes of abrasion time for all mixtures.
4. Abrasion resistance of concrete was strongly influenced by its compressive strength, irrespective of fly ash content, and had a very good correlation (value of R^2 between 0.9018 and 0.9859).
5. Fly ash concrete mixture containing up to 35% cement replacement exhibited abrasion resistance similar to Control mixture at the ages of 28, and 365 days.

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