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Effect of fine aggregate replacement with Class F fly ash on the abrasion resistance of concrete☆

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Abstract

This paper presents the abrasion resistance of concrete proportioned to have four levels of fine aggregate replacement (10%, 20%, 30%, and 40%) with Class F fly ash. A control mixture with ordinary Portland cement was designed to have 28 days compressive strength of 26 MPa. Specimens were subjected to abrasion testing in accordance with Indian Standard Specifications (IS: 1237). Tests were also performed for fresh concrete properties and compressive strength. Tests on compressive strength and abrasion were performed up to 365 days.

Test results indicated that abrasion resistance and compressive strength of concrete mixtures increased with the increase in percentage of fine aggregate replacement with fly ash. Abrasion resistance of concrete was improved approximately by 40% over control mixture with 40% replacement of fine aggregate with fly ash, and concrete with fine aggregate replacement could be suitably used.

Keywords: Abrasion resistance; Compressive strength; Depth of wear; Fine aggregate; Fly ash

1. Introduction

Approximately 80 million tonnes of fly ash is generated each year in India and most of it is of Class F type. Percentage utilization is around 10–15%. Generally, fly ash is used as replacement of cement, as an admixture in concrete, and in manufacturing of cement. As percentage utilization of fly ash is very low, an effort was made to increase its utilization by using it as fine aggregate replacement in concrete. Therefore, this investigation was carried out to explore the possibility of replacing part of fine aggregate with Class F fly ash as a means of incorporating significant amounts of fly ash in concrete. The aim of this work was to evaluate the effect of fine aggregate replacement with Class F fly ash on the abrasion resistance of concrete. Compressive strength and abrasion resistance were determined at various percentages of fine aggregate replacement with Class F fly ash. The result of this investigation would be helpful in understanding the behavior of such concretes under abrasion.

It has been established that compressive strength is the most important factor governing the abrasion resistance of concrete [1–3]. Other factors, which influence the surface characteristics of concrete surface, are cement content, water-to-cementitious materials ratio, workability, air-entrainment, type of finish, and curing conditions. Witte and Backstrom [1] reported that for same strengths, abrasion resistance of air-entrained concrete is similar to that of non-air-entrained concrete. It has been established that types of curing and surface finish influence the abrasion resistance of concrete [2,4,5,7]. Liu [6] compared the abrasion resistance of non-fly ash concrete with a fly ash concrete with 25% cement replacement. He concluded that abrasion of concrete with or without fly ash was similar up to 36 h of abrasion testing, but after 72 h of testing, the fly ash concrete lost about 25% more weight than the concrete without fly ash. Nanni [7] reported that abrasion resistance of concrete was strongly influenced by the relative abrasion of its constituent materials, such as coarse aggregates and mortar.

Nanni [8] investigated the abrasion resistance of roller-compacted concrete using both laboratory and field specimens made by replacing cement with 50% Class C fly ash.

☆ This work was carried out by the author at Thapar Institute of Engineering and Technology, Patiala, India, where he was Assistant Professor of Civil Engineering.

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Table 1
Physical properties of Portland cement

Physical test	Results obtained	IS: 8112-1989 specifications
Fineness (retained on 90-μm sieve)	7.5	10 max
Fineness: specific surface (air permeability test) (m^2/kg)	300	225 min
Normal consistency	31%	–
Vicat time of setting (min)		
Initial	115	30 min
Final	210	600 max
Compressive strength (MPa)		
3 days	23.5	22.0 min
7 days	36.0	33.0 min
28 days	46.5	43.0 min
Specific gravity	3.15	–

He concluded that (i) testing under air-dry conditions produced 30–50% less wear than under wet conditions; (ii) addition of steel or synthetic fibers did not cause any appreciable change in the abrasion resistance of concrete; and (iii) improper moist-curing conditions produced more negative effects on the surface quality than the compressive strength of concrete.

Tikalsky et al. [9] concluded that concrete containing Class C fly ash possessed superior abrasion resistance compared to either ordinary Portland cement concrete or concrete containing Class F fly ash. Langan et al. [10] investigated the influence of compressive strength on the durability of concrete containing 50% fly ash as replacement of cement and concluded 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 without fly ash. Bilodeau and Malhotra [11] investigated the abrasion resistance of concrete incorporating high volumes of Class F fly ash. Superplasticized mixtures were developed with 55–60% fly ash of total cementitious materials. Test results showed that fly ash concrete had poorer abrasion resistance than concrete without fly ash. Naik et al. [12] evaluated the abrasion resistance of concrete proportioned to have five levels of cement replacements (15%, 30%, 40%, 50%, and 70%) with one source of Class C fly ash. Test results showed that abrasion resistance of concrete having cement replacement up to 30% was comparable to the reference concrete with out fly ash, but beyond 30% cement replacement, fly ash concrete exhibited slightly lower resistance to abrasion relative to non-fly ash concrete.

Ghafoori and Diawara [13] investigated the abrasion resistance of concrete incorporating four percentages of fine aggregate replacement (5%, 10%, 15%, and 20%) with silica fume. They concluded 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%. Naik et al. [14] reported that blending of Class C with Class F fly ash showed either comparable or better abrasion resistance results than either the control mixture without fly ash or the unblended Class C fly ash. Naik et al. [15] investigated the effects of three sources of Class C fly ash on strength and durability properties of concrete. Three sources of Class C fly ash were used in this work. Fly ash from each source was used at three levels of cement replacements (40%, 50%, and 60%). They reported that strength and durability properties including abrasion resistance for the 40% fly ash mixture were either comparable or superior to the non-fly ash concrete.

2. Experimental details

2.1. Materials

Ordinary Portland (43 grade) cement conforming to Indian Standard Specifications IS: 8112-1989 [16] was used and its physical properties are given in Table 1. Class F fly ash was used. Its chemical analysis was done per ASTM C 311, and results are given in Table 2.

Natural sand with a 4.75-mm maximum size was used as a fine aggregate, and crushed stone with a 12.5-mm maximum size was used as coarse aggregate. Both fine and coarse aggregates were tested per Indian Standard Specifications IS: 383-1970 [17] and their physical properties and sieve analysis results are given in Tables 3 and 4, respectively. A commercially available melamine-based superplasticizer was used in all concrete mixtures.

2.2. Mixture proportions

First of all, a control mixture without Class F fly ash was designed per Indian Standard Specifications IS: 10262-1982 [18] to have a 28-day cube compressive strength of 26 MPa. Then, four levels of fine aggregate replacement (10%, 20%, 30%, and 40%) were made with Class F fly ash. Concrete mixtures were made in power-driven revolving type drum mixers of capacity 0.76 m^3. Concrete mixture proportions are given in Table 5. Fresh concrete properties such as slump, unit weight, temperature, and air content were

Table 2
Chemical composition of fly ash

Chemical analysis	Class F fly ash (%)	ASTM requirement C 618 (%)
SiO_2	55.3	–
Al_2O_3	25.7	–
Fe_2O_3	5.3	–
$SiO_2+Al_2O_3+Fe_2O_3$	85.9	70.0 min
CaO	5.6	–
MgO	2.1	5.0 max
TiO_2	1.3	–
K_2O	0.6	–
Na_2O	0.4	1.5 max
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	2.29	6.58
SSD absorption (%)	0.85	1.13
Void (%)	34.3	38.6
Unit weight (kg/m^3)	1680	1620

determined per Indian Standard Specifications IS: 1199-1959 [19]. The results are given in Table 5.

2.3. Preparation and casting of specimens

Cube specimens (150 mm) were cast for compressive strength per Indian Standard Specifications IS: 516-1959 [20], and concrete specimens of size $65 \times 65 \times 60$ mm were cast for determination of abrasion resistance per Indian Standard Specifications IS: 1237-1980 [21]. All 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 °C in the casting room. They were demolded after 24 h and then put into a water-curing tank for the test periods.

2.4. Testing of specimens

Compressive strength of concrete mixtures was determined at the ages of 7, 28, 91, and 365 days per Indian Standard Specifications IS: 516-1959 [20]. Abrasion resistance test was performed at the ages of 28, 91, and 365 days per Indian Standard Specifications IS 1237-1980 [21]. 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 at the corners with micrometer). The grinding path of the disc of the abrasion-testing machine was evenly distributed with a 20-g 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 rpm, 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 min. The tests were performed for the specified time periods, and the reading were taken at every 5-min interval. When the abrasion test was over, specimens were weighed again to calculate the loss of weight. The thicknesses of the specimens were 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:

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

where T is the average loss in thickness in millimeter; W_1 is the initial weight of the specimen in gram; W_2 is the weight of the specimen after abrasion in gram; V_1 is the initial volume of the specimens in cubic millimeter; and A is the surface area of the specimens in square millimeter.

Table 4
Sieve analysis of aggregates

Fine aggregates			Coarse aggregates		
Sieve No.	Passing (%)	Requirement IS: 383-1970	Sieve size (mm)	Passing (%)	Requirement IS: 383-1970
4.75 mm	98.2	90–100	12.5	96	90–100
2.36 mm	94.6	85–100	10	75	40–85
1.18 mm	79.2	75–100	4.75	9	0–10
600 μm	61.2	60–79			
300 μm	36.8	12–40			
150 μm	6.2	0–10			

Table 5
Concrete mixture proportions

Mixture number	M-1	M-2	M-3	M-4	M-5
Cement, C (kg/m^3)	370	370	370	370	370
Fly ash (%)	0	10	20	30	40
Fly ash (kg/m^3)	0	60	120	180	240
Water, W (kg/m^3)	175	178	179	182	185
W/C	0.47	0.48	0.48	0.49	0.50
Sand SSD (kg/m^3)	580	520	460	400	340
Coarse aggregate (kg/m^3)	1180	1180	1180	1180	1180
Superplasticizer (l/m^3)	2.6	3.4	3.5	3.6	3.7
Slump (mm)	100	85	65	40	30
Air content (%)	2.1	2.4	2.3	2.2	1.8
Air temperature (°C)	26	28	25	26	27
Concrete temperature (°C)	27	29	26	27	28
Density (kg/m^3)	2309	2311	2313	2316	2339

3. Results and discussion

3.1. Compressive strength

Compressive strength of concrete mixtures was determined at the ages of 7, 28, 91, and 365 days. The test results are shown in Fig. 1. Fig. 1 shows the variation of compressive strength with age for various percentages of fine aggregate replacement with Class F fly ash. It is evident from Fig. 1 that compressive strength of concrete mixtures with 10%, 20%, 30%, and 40% of fly ash as fine aggregate replacement was higher than the control mixture (M-1) at all ages and that the strength of all mixtures continued to increase with the age.

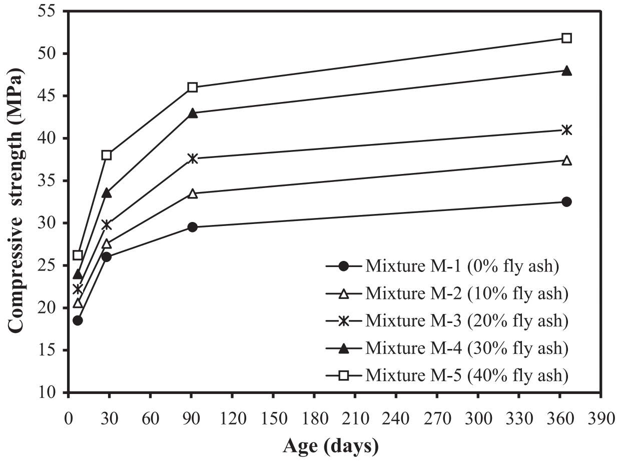

Fig. 1. Compressive strength of concrete mixtures versus age.

Fig. 2 shows the compressive strength ratio (at 91 and 365 days) with respect to 28 days compressive strength. Compressive strength at 91 days was 13%, 21%, 25%, 28%, and 21% higher than the 28 days compressive strength of mixtures M-1 (0% fly ash), M-2 (10% fly ash), M-3 (20% fly ash), M-4 (30% fly ash), and M-5 (40% fly ash), respectively. Similarly, compressive strength at 365 days was 25%, 35%, 38%, 43%, and 36% higher than 28 days compressive strength of mixtures M-1 (0% fly ash), M-2 (10% fly ash), M-3 (20% fly ash), M-4 (30% fly ash), and M-5 (40% fly ash), respectively. It can be seen from Fig. 2 that there was a decrease in compressive strength at 40% fly content with respect to the strength of concrete having 30% fly ash content. However, maximum strength at all ages occurred with 40% fine aggregate replacement. This increase in strength due to the replacement of fine aggregate with fly ash could be attributed to the pozzolanic action of fly ash, leading to the densification of the matrix.

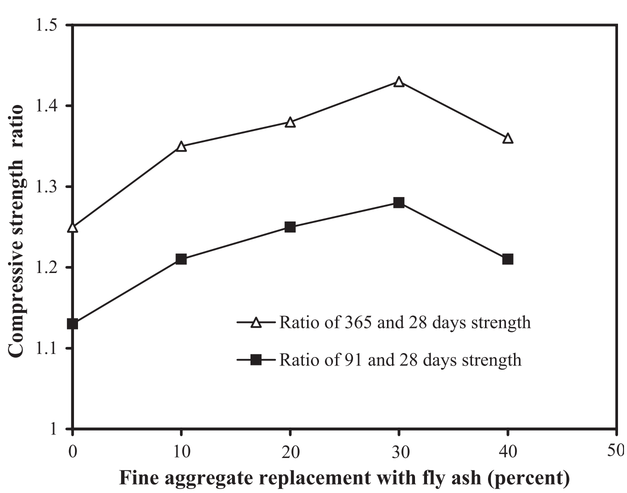

Fig. 2. Compressive strength ratio versus fine aggregate replacement with fly ash.

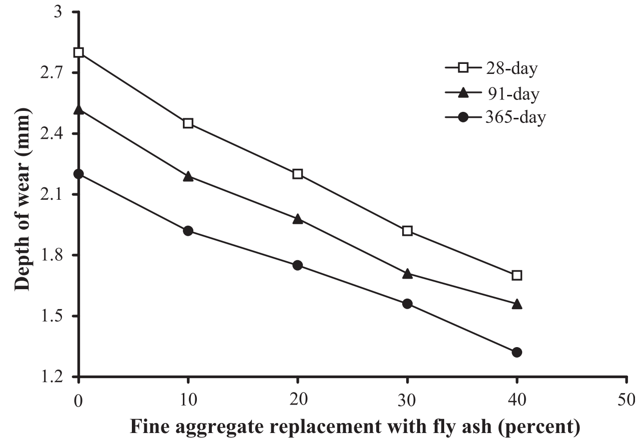

Fig. 3. Depth of wear at 60 min of abrasion versus fine aggregate replacement with fly ash.

3.2. Abrasion resistance

The abrasion resistance of concrete mixtures was determined at the ages of 28, 91, and 365 days. It was measured in term of depth of wear. It was observed that depth of wear increased with increase in abrasion time for all concrete mixtures at all ages. Fig. 3 shows the variation of depth of wear versus percentage of fine aggregate replacement with Class F fly ash at 60 min of abrasion time. It is evident from Fig. 3 that with the increase in percentage of fine aggregate replacement with fly ash, depth of wear decreased, which indicated that the abrasion resistance of concrete increased with the increase in fly ash content. After 60 min of abrasion, depth of wear for control mixture M-1 (0% fly ash) was 2.8 mm at 28 days, 2.52 mm at 91 days, and 2.3 mm at 365 days; whereas depth of wear was 2.45 mm at 28 days, 2.14 mm at 91 days, and 1.92 mm at 365 days for mixture M-2 (10% fly ash); 2.2 mm at 28 days, 1.98 mm at 91 days, and 1.75 mm at 365 days for mixture M-3 (20% fly ash); 1.92 mm at 28 days, 1.71 mm at 91 days, and 1.56 mm at 365 days for mixture M-4 (30% fly ash); and 1.7 mm at 28 days, 1.56 mm at 91 days, and 1.32 mm at 365 days for mixture M-5 (40% fly ash). This shows that for a particular percentage of fine aggregate replacement with fly ash, depth of wear decreased with increase in age, which means that abrasion resistance increased with age. This could be primarily attributed to the increase in compressive strength resulting from increased maturity of concrete with age.

Abrasion test results indicated that the compressive strength was an important factor affecting the abrasion resistance of concrete.

4. Conclusions

The following conclusions are drawn from this study:

1. Compressive strength of concrete increased with the increase in fine aggregate replacement with Class F fly

ash. However, at each replacement level of fine aggregate with fly ash, an increase in strength was observed with the increase in age.

2. Abrasion resistance of concrete was strongly influenced by its compressive strength, irrespective of fly ash content. In general, concrete abrasion resistance was proportional to the compressive strength; i.e., abrasion resistance increased with increase in compressive strength.
3. Abrasion resistance was found to increase with increase in fly ash content as replacement of fine aggregate.
4. Abrasion resistance was found to increase with the increase in age for all mixtures.
5. Class F fly ash could be suitably used as partial replacement of fine aggregate in concrete, and thereby significantly increasing the percentage utilization of Class F fly ash.

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