Wear Resistance of High-Volume Fly Ash Concrete

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Abstract

Wear resistance of high-volume fly ash concrete (HVFA) intended for pavement applications is presented in this paper. In India, yearly production of fly ash is more than 100 million tons. Majority of fly ash is of Class F type. Out of which 20-25% is being utilized in cement-based materials. In order to increase its percentage utilization, an investigation was carried out for its large scale utilization. Concrete mixtures were prepared by replacing cement with 40, 50, and 60% of fly ash. Experiments were conducted for fresh concrete properties, compressive strength and wear resistance. Test results indicated that wear resistance of concrete having cement replacement up to 40% was comparable to the normal concrete. Beyond 40% fly ash content, concretes exhibited slightly lower resistance to wear in relation non-fly ash concretes. There is very good correlation between wear resistance and compressive strength (R^2 value between 0.8482 and 0.9787) depending upon age.

Keywords

Wear resistance; Compressive strength; Concretes; Fly ash; High-volume fly ash concrete (HVFA)

Introduction

The principal ingredients of concrete are gravel, sand, water, and Portland cement. Amongst them, cement is one of the most cost and energy intensive components of concrete.

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 CO_2. 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. Fly ash, consisting mostly of silica, alumina, and iron, forms a compound similar to Portland cement when mixed with lime and water. 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 30-40% 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. 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.

Wear Resistance of Concrete

Wear of concrete occurs due to scraping, rubbing, skidding or sliding of objects on its surface. Wear 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 wear 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 wear resistance of concrete. In general, hardened paste has low wear resistance. To develop concrete for high wear resistance, it is important to use hard surface aggregates, surface materials, and paste having low porosity and high strength [3].

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. Investigations by Witte and Backstrom [1], Hadchti and Carrasquillo [4], Laplante et al. [5] have shown that compressive strength is the most important factor governing the wear resistance of concrete. Wear resistance of concrete is strongly influenced by the relative wear of its constituent's materials, such as coarse aggregates and mortar [5] Hadchti and Carrasquillo [4] evaluated the wear 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 wear. Witte and Witte and Backstrom [1] have reported that for same strengths, wear 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 wear resistance of concrete. Gebler and Klieger [10] have investigated the wear 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 [8] investigated the wear 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 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 wear resistance of concrete and improper moist-curing conditions produce more negative effects on the surface quality than the compressive strength of concrete. Liu [11] compared the wear resistance of non-fly ash concrete with a fly ash concrete having 25 percent cement replacement. Wear of concrete with or without fly ash was similar up to 36 hours of wear testing. However, after 72 hours of testing, the fly ash concrete lost about 25 percent more weight than the concrete without fly ash.

Tikalsky [12] reported that the concrete containing Class C fly ash performed better (in wear resistance) than both concrete without fly ash and concretes containing Class F fly ash. Langan et al. [13] reported that the presence of fly ash at high levels of cement replacement increased the weight loss due to wear at all ages relative to concrete with out fly ash. Bilodeau and Malhotra [14] investigated the wear 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 wear resistance than concrete with out fly ash. Ukita et al. [15] studied the wear 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, wear increased with fineness of fly ash. However, at fly ash content of 30 percent, the wear resistance of concrete was lower than that of concrete with out fly ash. Carette et al. [16] reported the results of the wear 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 wear resistance than other concretes of similar or even lower compressive strength. Naik et al. [17] 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. [17] evaluated the wear 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 wear 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 wear relative to non-fly ash concrete. Ghafoori and Diawara [18] evaluated the wear 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 [19] reported that strength and durability properties including wear resistance for the 40% fly ash mixture were either comparable or superior to the no-fly ash concrete.

Siddique [20] investigated the influence of fine aggregate replacement (10, 20, 30, and 40%) with Class F fly ash on the wear resistance and compressive strength of concrete up to the age of 365 days. Test results indicated that wear resistance and compressive strength of concrete mixtures increased with the increase in percentage of fine aggregate replacement with fly ash. Wear resistance of concrete was improved approximately by 40% over control mixture with 40% replacement of fine aggregate with fly ash.

Sebök and Stráněl [21] studied the wear resistance of mortar and concrete samples untreated and impregnated with solutions of epoxide resin. Based on the results obtained, they concluded that compressive strength has a decisive influence on the wear of untreated mortar and concrete samples. The wear resistance of impregnated samples with low compressive strength markedly increased. The hardener used influences the polymerization rate of the activated resin in the structure of samples, with time, and their wear is influenced also in this way.

Yazici and İnan [22] developed a relationship between mechanical properties (compressive and splitting tensile strengths) and wear resistance of high strength concretes (HSC) having compressive strength between 65 and 85MPa. They concluded that wear damage of high strength concrete can be estimated from compressive and splitting tensile strength results. The proposed equation has a sufficient reliability.

Yen et al. [23] investigated the wear–erosion resistance of high-strength concrete (HSC) mixtures in which cement was partially replaced by four kinds of replacements (15%, 20%, 25% and 30%) of class F fly ash. They concluded that wear–erosion resistances of fly ash concrete mixtures were improved by increasing compressive strength and decreasing the ratio of water-to-cementitious materials, wear–erosion resistance of concrete with cement replacement up to 15% was comparable to that of control concrete without fly ash. Beyond 15% cement replacement, fly ash concrete showed lower resistance to wear–erosion compared to non-fly ash concrete. They also established equations based on effective compressive strengths and effective water-to-cementitious materials ratios, which were modified by cement replacement and developed to predict the 28- and 91-day wear-erosion resistance of concretes with compressive strengths ranging from approximately 30 - 100 MPa. The calculation results are compared favorably with the experimental results.

Research Significance of Present Investigation

This research was carried out to evaluate the performance of Class F fly ash in concrete with respect to wear of HVFA concrete pavements. Concrete strength and wear 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 wear.

Material and Method

Materials

Ordinary Portland (43 grade) cement was used and tested as per the requirements of Indian Standard Specifications BIS: 8112 [24]. Properties of cement 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	8.3	10 max
Fineness: specific surface (air permeability test) (m^2/kg)	300	225 min
Normal consistency	31%	-
Vicat time of setting (minutes)		
Initial	100	30 min
Final	260	600 max
Compressive strength (MPa)		
3-day	24.0	22.0 min
7 -day	34.8	33.0 min
28-day	46.6	43.0 min
Specific Gravity	3.13	-

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

Natural sand with a 4.75 mm maximum size was used as a fine aggregate. It was tested as per Indian Standard Specifications BIS: 383 [25], 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 [25], 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 2. Chemical composition of Class F fly ash

Chemical analysis	Class F fly ash (%)	ASTM requirement C 618 (%)
Silicon Dioxide, SiO_2	54.4	-
Aluminum Oxide, Al_2O_3	26.5	-
Ferric Oxide, Fe_2O_3	4.8	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	85.7	70.0 min
Calcium Oxide, CaO	3.5	--
Magnesium Oxide, MgO	2.5	5.0 max
Titanium Oxide, TiO_2	1.5	--
Potassium Oxide, K_2O	0.6	--
Sodium Oxide, Na_2O	0.4	1.5 max
Sulfur trioxide, SO_3	1.7	5.0 max
LOI (1000^{o}C),	2.3	6.0 max
Moisture	0.3	3.0 max

Table 3. Physical properties of aggregates

Property	Fine aggregate	Coarse aggregate
Specific gravity	2.63	2.59
Fineness modulus	2.37	6.47
SSD absorption (%)	0.86	1.1
Void (%)	34.3	40.9
Unit weight (kg/m^3)	1686	1642

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	97.6	90-100	12.5 mm	93	90-100
2.36 mm	95.1	85-100	10 mm	72	40-85
1.18 mm	77.5	75-100	4.75 mm	7	0-10
600 μm	61.5	60-79			
300 μm	36.2	12-40			
150μm	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 40 to 60%. Mix proportions are given in Table 5. The control mix with out fly ash was proportioned as per Indian Standard Specifications BIS: 10262 [26] to have a 28-day cube compressive strength of 41.5 MPa. Mixture proportions are given in Table 5.

Table 5. Mixture proportions

Mixture No.	M-1	M-2	M-3	M-4
Cement (kg/m^3)	440	264	220	176
Fly ash (%)	0	40	50	60
Fly ash (kg/m^3)	0	176	220	264
Water (kg/m^3)	160	160	160	160
W/(Cement + Fly ash)	0.36	0.36	0.36	0.36
Sand SSD (kg/m^3)	540	540	540	540
Coarse aggregate (kg/m^3)	1230	1230	1230	1230
Superplasticizer (l/m^3)	3.7	4.2	4.3	4.5
Slump (mm)	70	80	85	80
Air content (%)	2.7	2.8	2.8	3.0
Density (kg/m^3)	2375	2374	2374	2375

Preparation and Casting of Specimens

150-mm cubes were cast for compressive strength in accordance with the Indian Standard Specifications BIS: 516 [27], and concrete specimens of size 65 × 65 × 60 mm were cast for determination of wear resistance in accordance with Indian Standard Specifications BIS: 1237 [28]. Wear 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.

Fresh Concrete Properties

Fresh concrete properties such as slump, unit weight, temperature and air-content were determined according to Indian Standard Specifications BIS: 1199 [29]. 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 BIS: 516 [27]. Wear resistance test was performed at the ages of 28, 91 and 365 days. All specimens were tested at dry conditions per Indian Standard Specifications BIS 1237 [28]. 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

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disc of the wear-testing machine was evenly distributed with 20-gram abrasive powder (aluminum powder). The specimens were fixed in the holding device of the wear 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 wear 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 wear was determined from the difference in values of thickness measured before and after the wear 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 = average loss in thickness in mm; W_1 = initial weight of the specimen in gram; W_2 = mass of the specimen after wear in gram; V_1 = initial volume of the specimens in mm^3; A = 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 BIS: 516 (1959). The test results are reported in Table 1. Wear resistance tests were performed at 28, 91 and 365 days. All specimens were tested at dry conditions according to Indian Standard Specifications BIS 1237 (1980).

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 Figure 1. It also 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 40, 50, and 60% 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 MPa whereas it was 18.2 MPa for Mixture M-2 (40% fly ash), 15 MPa for Mixture M-3 (50% fly ash), and 13.3 MPa for Mixture M-4 (60% fly ash). At 28 days, compressive strength of Control Mixture M-1 was 41.5 MPa, whereas it was 30.2 MPa for Mixture M-2 (40% fly ash), 24.8 MPa for Mixture M-3 (50% fly ash), and 22.2 MPa for Mixture M-4 (60% fly ash).

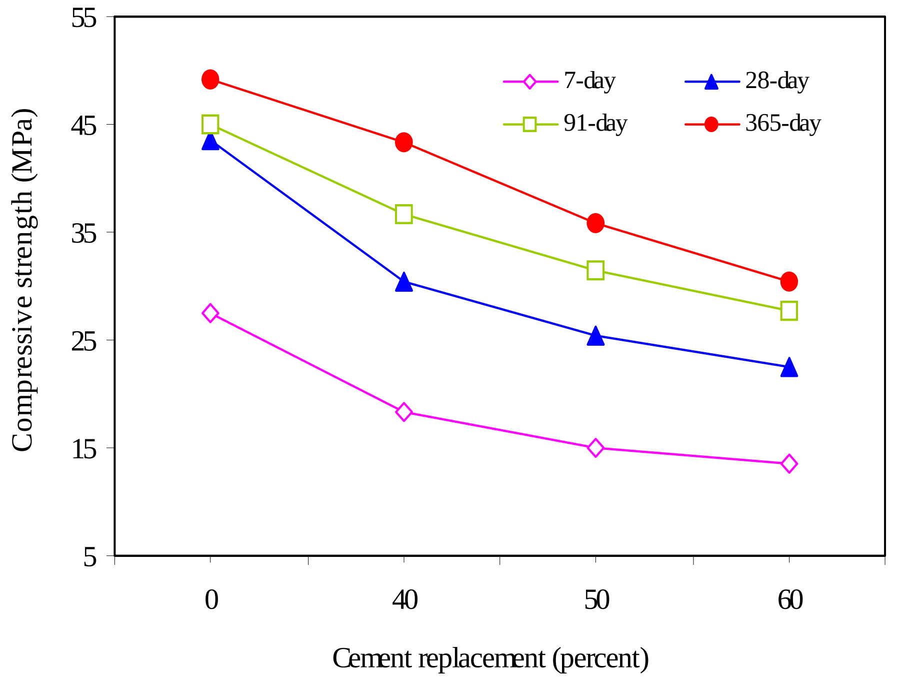

Figure 1. *Compressive strength versus percentage of cement replaced with fly ash*

At 91 days, compressive strength of Control Mixture M-1 was 44.9 MPa whereas it was 36.0 MPa for Mixture M-2 (40% fly ash), 31.2 MPa for Mixture M-3 (50% fly ash), and 27.2 MPa for Mixture M-4 (60% fly ash). At 365 days, compressive strength of Control Mixture M-1 was 48.6 MPa, whereas it was 43.0 MPa for Mixture M-2 (40% fly ash), 35.2 MPa for Mixture M-3 (50% fly ash), and 29.6 MPa for Mixture M-4 (55% fly ash).

Figure 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.

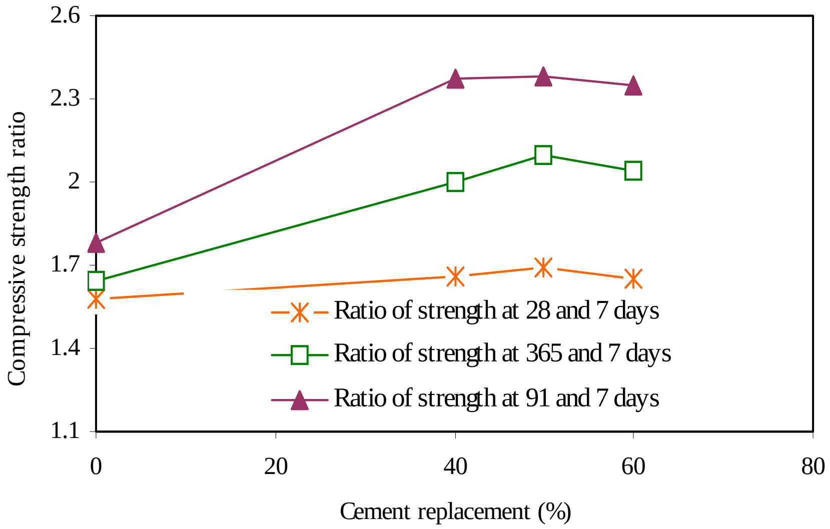

Figure 2. *Ratio of compressive strength versus percentage of cement replaced with fly ash*

Wear Resistance

The wear tests were performed at the ages of 28, 91 and 365 days for all mixes. Figure 3 to 5 presents the wear resistance of all concrete mixes. In general, wear decreased (i.e. wear resistance increased) with the increase in age. Figure 3 represents the variation of wear resistance with cement replacements at different ages at 60 minutes of wear. At 60 minutes of wear, depth of wear for Control Mixture M-1 (0% fly ash) was 1.82 mm at 28-day, 1.73 mm at 91-day, and 1.36 mm at 365-day, whereas depth of wear was 1.95 mm at 28-day, 1.85 mm at 91-day and 1.69 mm at 365-day for Mixture M-2 (40% fly ash); 2.35 mm at 28-day, 2.26 mm at 91-day, and 1.9 mm at 365-day for Mixture M-3 (50% fly ash); and 2.60 mm at 28-day; 2.50 mm at 91-day and 2.27 mm at 365-day for Mixture M-4 (60% fly ash).

This indicated that for a particular percentage of cement replacements, depth of wear decreased with increase in age, which means that wear 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. These results are similar to that reported by others [1, 4, 5]. From Figure 4 it can be seen that wear resistance of mixes M-2, M-3, and M-4 containing 40, 50 and 60% fly ash, was lower than that of the control mix M-1. However, wear resistance of mix M-2 (containing 40% fly ash) was comparable with that of control mix, but beyond, 40% cement replacement, it decreased primarily because of its lower compressive strength. Results of this investigation are in line with that of Naik et al [17].

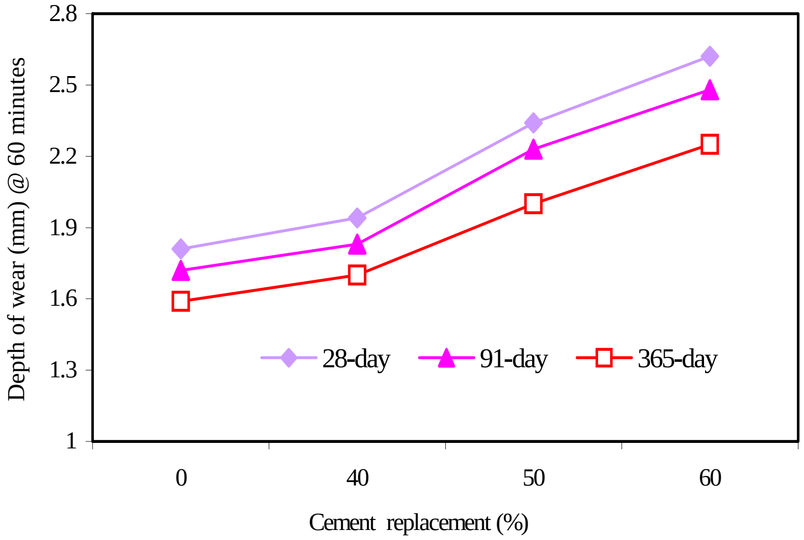

Figure 3. *Dept of wear versus cement replaced with fly ash*

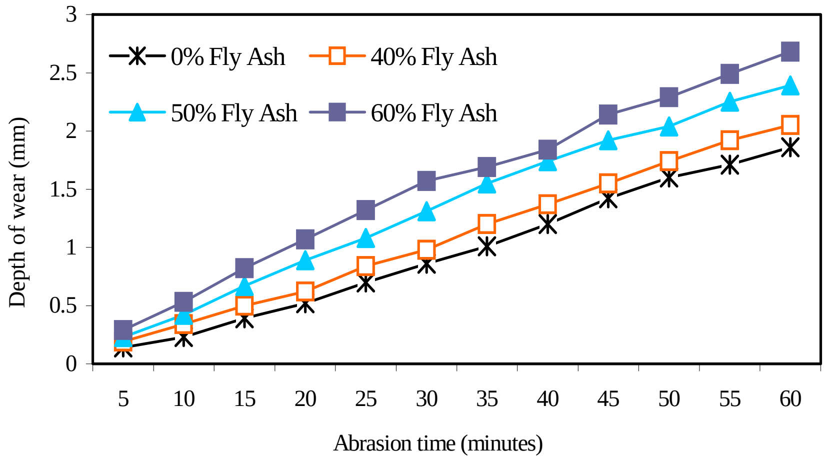

Figure 4. *Dept of wear versus abrasion time at 28 days*

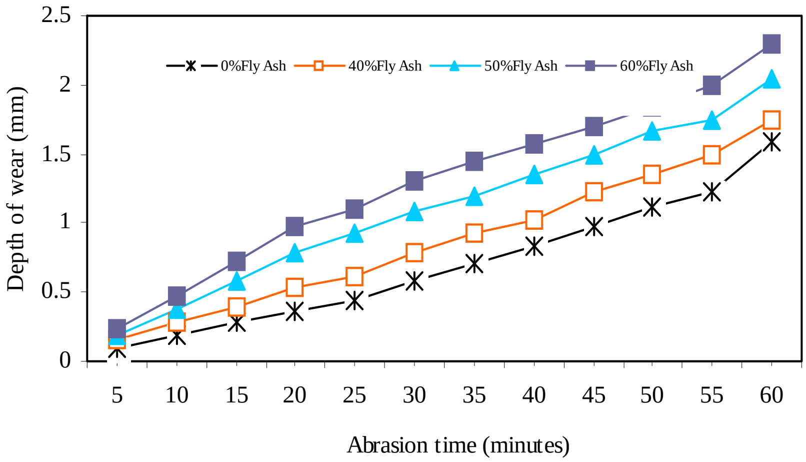

Figure 5. *Dept of wear versus abrasion time at 365 days*

Figures 4 and 5 represent the variation of wear resistance with wear 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 wear time for all mixes, and also depth of wear decreased with the increase in age of mixes. Wear test results indicate that the compressive strength was an important factor affecting the wear resistance of concrete.

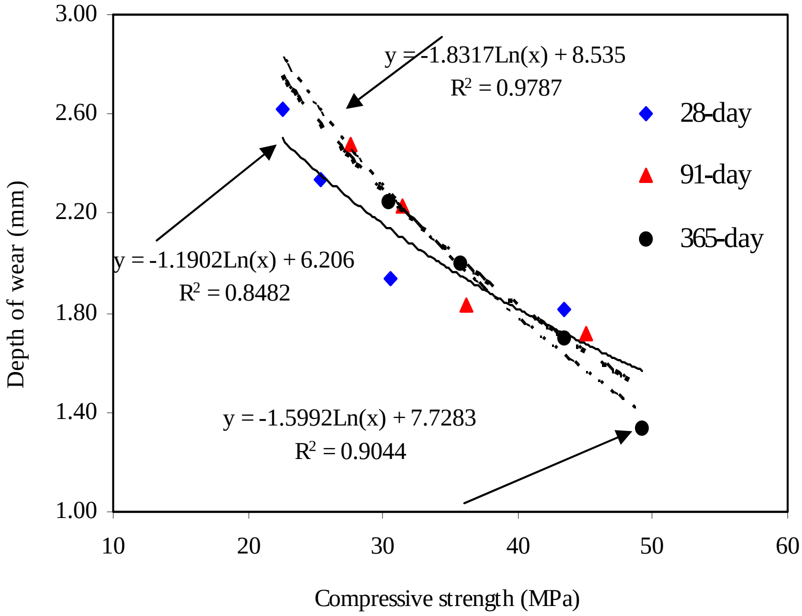

***Figure 6.** Relationship between compressive strength and depth of wear*

Figure 6 shows the relationship between compressive strength and wear resistance (depth of wear) of concrete mixtures. It is abundantly clear from this figure that wear resistance of concrete is closely related with compressive strength, and in this case, correlation (value of R^2) was very good (0..8482 at 28 days), and got even better at later ages (0.9044 at 91 days and 0.9787 at 365 days). Though the wear resistance of concrete mixtures decreased with increase in fly ash content, the wear resistance of Mixture M-2 (40% fly ash) was comparable with that of Control mixture M-1 (0% fly ash) , but beyond, 40% cement replacement, it decreased primarily because of its lower compressive strength.

Conclusions

Following conclusions can be drawn from the present investigation:

- 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.

- Compressive strength of fly ash concrete containing up to 50% cement replacement could be useful in most structural applications.
- Wear 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 wear time for all mixtures.
- Wear 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 0.8482 and 0.9787).
- Fly ash concrete mixture containing up to 40% cement replacement exhibited wear resistance similar to Control mixture at the ages of 28, and 365 days.

References

1. Witte L.P., Backstrom, J.E., *Some properties affecting the abrasion resistance of air-entrained concrete*, ASTM Proceedings, 1951, 51, p.1141-1155.
2. ACI Committee 201, *Guide to Durable Concrete* (ACI 74-53), American Concrete Institute, Detroit, USA, 1977.
3. Mehta P.K., *Concrete structure, properties and materials, Prentice-Hall International Series in Civil Engineering and Engineering Mechanics*, 3rd Edition, 1986.
4. Hadchti K. M., Carrasquillo R.L., *Abrasion resistance and scaling resistance of concrete containing fly ash,* Research Report 481-3, Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin, 1988.
5. Laplante P., Aitcin P.C., Vezna D., *Abrasion Resistance of Concrete*, ASCE Journal of Materials in Civil Engineering, 1991, 3(1), p. 19-28.
6. Ytterburg R.F., *Wear-resistant industrial floors of Portland cement concrete,* Civil engineering, ASCE, 1971, 41(1), p. 68-71.
7. Fentress B., *Slab construction practice compared by wear tests*, ACI Journal, Proceedings, 1973, 70(7), p. 486-491.

8. Nanni A., *Curing of roller-compacted concrete and strength development*, Journal of Transportation Engineering, ASCE, 1988, 114(6), p. 684-694.

9. Sadeyzadeh M., Page C.L., Kettle R.J., *Surface microstructure and abrasion resistance of concrete*, Cement and Concrete Research, 1987, 17(4), p. 581-590.

10. Gebler S.H., Klieger P., *Effect of fly ash on physical properties of concrete*, ACI Special Publication (SP-91), 1986, p. 1-50.

11. Liu T.C., 1981. *Abrasion resistance of concrete*, ACI Journal, Proceedings, 1981, 78(5), p. 341-350.

12. Tikalsky P.J., Carrasquillo P.M., Carrasquillo R.L., 1988. *Strength and durability considerations affecting mix proportions of concrete containing fly ash*, ACI Materials Journal, 1988, 85(6), p. 505-511.

13. Langan B.W., Joshi R.C., Ward M.A., *Strength and durability of concrete containing 50 percent Portland cement replacement by fly ash and other materials*, Canadian Journal of Civil Engineering, 1990, 17, p. 19-27.

14. Bilodeau A., Malhotra V.M., 1992. *Concrete incorporating high volumes of ASTM class f fly ashes: mechanical properties and resistance to deicing salt scaling and to chloride-ion penetration*, Proceedings of the CANMET/ACI Fourth International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Istanbul, Turkey, ACI SP-132, Editor V.M. Malhotra, American Concrete Institute, pp. 319-349.

15. Ukita K., Shigematsu S., Ishic M., 1989. *Improvements in the properties of concrete utilizing classified fly ash*, Proceedings of the CANMET/ACI Third International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Trondheim, Norway, pp. 219-240, 1989.

16. Carette, G.G., Bilodeau, A., Cheurier, R., and Malhotra, V.M., 1992. Mechanical properties of concrete incorporating high volumes of fly ash from sources in the U.S, Supplementary Proceedings of the CANMET/ACI Fourth International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, EPRI Report No. TR-100577, pp. 1-33.

17. Naik T.R., Singh S.S., Hossain M.M., *Abrasion resistance of high-strength concrete made with class C fly ash*, ACI Materials Journal, 1995, 92(6), p. 649-659.

18. Ghafoori N., Diawara H., 1999. *Abrasion Resistance of Fine Aggregate-Replaced Silica Fume Concrete*, ACI Materials Journal, 96(5), p. 559-567.
19. Naik T.R., Singh S.S., Ramme B.W., *Effect of source and amount of fly ash on mechanical and durability properties of concrete*, ACI Special Publication (SP-170), 1997, p. 157-188.
20. Siddique R., *Effect of fine aggregate replacement with Class F fly ash on the abrasion resistance of concrete*, Cement and Concrete Research, 2003, 33, p. 1887-1881.
21. Sebök T., Stráněl O., *Wear of polymer-impregnated mortars and concrete*, Cement and Concrete Research, 2004, 34, p. 1853-1858.
22. Yazici Ş., İnan G., *An investigation on the wear resistance of high strength concretes*, Wear, 2006, 260, p. 15-618.
23. Yen T., Hsu T. H., Liu Y. W., Chen S. H., *Influence of class F fly ash on the abrasion-erosion resistance of high-strength concrete*, Construction and Building Materials, 2007, 21, p. 458-463.
24. BIS: 8112, 1989. *Specifications for 43-grade Portland cement*, Bureau of Indian Standards, New Delhi, India
25. BIS: 383, 1970. *Specifications for coarse and fine aggregates from natural sources for concrete*, Bureau of Indian Standards, New Delhi, India.
26. BIS: 10262, 1982. *Recommended Guidelines for Concrete Mix Design*, Bureau of Indian Standards, New Delhi, India.
27. BIS: 516, 1959. *Indian standard code of practice- methods of test for strength of concrete*, Bureau of Indian Standards, New Delhi, India.
28. BIS: 1237, 1980. *Method for testing abrasion resistance of concrete*, Bureau of Indian Standards, New Delhi, India.
29. BIS: 1199, 1959. *Indian standard methods of sampling and analysis of concrete*, Bureau of Indian Standards, New Delhi, India.