

Center for By-Products Utilization

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SYNOPSIS

This paper presents the results of an investigation carried out to develop permeable base course materials using coal combustion products (CCPs) for roadways, highways, and airfield pavements. Three sources of CCPs were selected for this investigation. These include two sources of high-carbon/sulfate-bearing CCPs, which did not meet ASTM C 618 requirements for coal fly ash for use as mineral admixture in concrete, and one source of variable carbon fly ash.

These CCPs were used for no-fines/low-fines concrete as a permeable base material. Two types of mixtures were developed using each of these by-products for base course materials. In these mixtures, the amount of fines was varied for the permeable base, one with open-graded and one with an intermediate-graded structure. Tests were performed for fresh concrete properties as well as for compressive strength, splitting tensile strength, flexural strength, etc. The performance of the permeable base mixtures containing CCPs was also compared with a reference mixture without any ash.

Test results up to 181 days of testing indicate that CCPs materials can be effectively used as a permeable base course material.

Keywords: Compressive strength, flexural strength, FGD fly ash, slump, splitting-tensile strength, unit weight.

1. INTRODUCTION

Presence of excess water in the pavement structure is known to be the primary cause of pavement distress. Extended exposure to water can lead to pumping, D-cracking, faulting, frost action, shrinkage, cracking, and potholes [1]. Out of these parameters, pumping is known to be the most dominating mechanism of pavement distress. The water that infiltrates through the pavement is trapped within the pavement structure when draining capabilities of the pavement base is low. Application of high pressure to the trapped water causes erosion of the base because fines are pumped out along with the water. Consequently, a loss in pavement support occurs, leading to early failure. However, this can be avoided by using free-draining pavement base [2-8]. Permeable bases are divided into two classes: treated and untreated. A treated permeable base employs a binder, which would typically consists of either cement (119-178 kg/m³) or asphalt (2 – 5% by weight). An untreated subbase contains more small particles in order to provide stability through aggregate interlock. A permeable base must be capable of maintaining both permeability and stability. In order to improve stability, an untreated subbase should contain 100% crushed aggregate [2]. Grogan [5] reported that dense-graded subsurface pavement layers are virtually impermeable. Saturation of these layers will cause pumping, erosion, subgrade weakening, and freeze/thaw damage. Use of properly designed and constructed permeable bases reduces or practically eliminates these problems thus improving pavement performance. Hall [6] reported that factors such as cement content, truck traffic, sublayer stability, segregation, and surface irregularities are important in affecting performance of the permeable base. Kozeliski [7] reported successful application of open-graded cement treated base material in the construction of a parking lot for an office building, the driveway of a home, and a ground cover of a refinery. Kuennen [8] described construction of a high-quality, high-durability, drainable PCC pavement incorporating 18% fly ash of total cementitious materials. Naik and Ramme [9] presented the state-of-the-art information on permeable base road pavements. They reported the results from the demonstration

project, and mentioned that fly ash can be used in the manufacture of permeable base concrete pavements.

In order to meet EPA air quality standards, utilities are utilizing supplemental flue gas treatments to reduce emissions. These treatments either alter the quality of the coal combustion by-products, or generate another type of "waste" material. Two processes typically used are flue gas desulfurization (FGD) to reduce SO_x emissions and low-NO_x burners to reduce NO_x emissions. FGD by-products are high-sulfite and/or sulfate by-products, and low-NO_x burners generate high-carbon CCPs. Approximately 28 million tons of FGD by-products were generated in 2001 in the USA with a utilization rate of less than 30 percent. Consequently, most FGD by-products are landfilled at high disposal costs and potential future environmental liabilities to the producer. To avoid these, there is a need to develop beneficial uses of these by-products.

2. OBJECTIVE

This investigation was conducted to develop permeable base course materials using coal combustion products (CCPs) for highways, roadways, and airfield pavement. Three types of CCPs, two flue-gas desulfurization (FGD) by-products, and a variable-carbon fly ash, are being evaluated for no-fines or low-fines concrete as a permeable base material. Use of FGD by-products and high-carbon or variable carbon CCPs in permeable base course is expected to utilize significant quantities of these by-products. It will also help to reduce the cost of installing permeable base materials for pavement, which will lead to increased use of such permeable bases for highways, roadways, and airfield pavement. Reducing the cost of permeable base materials is expected to expand its use in many other types of pavement construction with increased pavement life and increased utilization rate of CCPs and FGD by-products.

3. EXPERIMENTAL PROCEDURE

3.1 Materials

Type I Portland cement was used. Its physical and chemical properties were determined per ASTM C 150 requirements. Both physical and chemical properties of the cement except available alkali met the ASTM standards. The cement had slightly higher available alkali content (0.9%) relative to the ASTM C 150 (0.6%) requirement.

Three sources of CCPs were used. These include two high-carbon/sulfate-bearing CCPs, designated as FGD-1 and FGD-2, and a variable carbon fly ash designated as FGD-3. Each ash source was tested for physical and chemical properties. The physical properties of CCPs are given in Table 1, and chemical analysis in Table 2. One source of concrete sand and coarse aggregate was acquired from a local concrete producer. Physical properties of the sand and coarse aggregate were determined per ASTM C 33 requirements, and both met all the ASTM C 33 requirements for fine aggregate.

3.2 Mixture Proportions

The mixture proportion for open-graded and intermediate-graded base course materials are given in Tables 3 and 4, respectively.

For open-graded base course mixtures, Mixture MO was proportioned without any ash. Three series of mixtures (MO1, MO2, and MO3) were proportioned using FGD-2 fly ash. These mixtures contained 15%, 30%, and 45% of FGD-2 fly ash, respectively as additional cementitious material (Table 3). Similarly, three series of mixtures (MO4, MO5, and MO6) were proportioned to contain 15%, 30%, and 45% of FGD-3 fly ash as a cement replacement (Table 3). Another, three series of mixtures, MO7, MO8, and MO9 (Table 3) contained 15%, 30%, and 45%, respectively, of FGD-1 ash by weight of cement; however, only half of the ash was considered to be cementitious, while the remaining half was considered to be filler, replacing sand.

For intermediate-graded base course mixtures, Mixture M2A was proportioned without any ash. Mixtures M21, M22, and M23 were proportioned using FGD-3 fly ash, to replace 15%, 30%, and 45% of cement with FGD-3 fly ash, respectively (Table 4). Three mixtures (M24, M25, and M26) were proportioned to contain 15%, 30%, and 45% of FGD-1 fly ash (Table 4). Half of the addition of FGD-1 ash was considered to be cementitious, while the remaining half was considered sand replacement. Three Series of mixtures, M27, M28, and M29, contained 15%, 30%, and 45%, respectively, of FGD-2 ash by weight of cement (Table 4).

Table 1 - Physical Properties of CCPs

TEST PARAMETER	Ash Source Number			ASTM C 618 REQUIREMENTS	
	FGD-1	FGD-2	FGD-3	CLASS C	CLASS F
Retained on No.325 sieve (%)	23.7	29.5	21.7	34 max	34 max
Strength Activity Index with Cement (% of Control)					
3-day	--	--	107.6	--	--
7-day	60.3	87.3	109.5	75 min	75 min
28-day	60.6	115.5	129.5	75 min	75 min
Water Requirement (% of Control)	107.4	112.4	92	105 max	105 max
Autoclave Expansion (%)	0.05	0.26	0.05	±0.8	±0.8
Specific Gravity	2.64	2.17	2.58	-	-
Variation from Mean (%)					
Fineness	2.3	2.0	5.3	5 max	5 max
Specific Gravity	1.1	6.0	1.9	5 max	5 max

3.3 Casting, Curing, and Testing of Specimens

All concrete mixtures were mixed in a rotating drum concrete mixer in accordance with ASTM C 192. The resulting mixture was used in making concrete specimens. Fresh concrete was tested for air content (ASTM C 138), unit weight (ASTM 138), and temperature (ASTM C 1064). Ambient air temperature was also measured and recorded.

Specimens were prepared in accordance with ASTM C 1435. Freshly mixed concrete was molded in cylindrical steel molds (4 x 8 in.) for compressive strength (ASTM C 39) and splitting tensile (ASTM 496) strength measurements; and in beam molds (3 x 4 x 16 in.) for measurements of flexural strength (ASTM C 78). For each 4 x 8 in. cylinder, concrete in the mold was compacted in two lifts (layers) with the vibratory hammer. For each lift, enough concrete was placed in the mold to fill one-half of its volume after compaction. Each layer was compacted by placing a circular tamping plate on the concrete while the hammer was operated for 20 seconds. For each 3 x 4 x 16 in. beam specimen, concrete in the mold was compacted in one lift with the vibratory hammer. For each specimen, enough concrete was placed in the mold to fill its entire volume after compaction. The concrete layer in the mold was compacted by placing a rectangular tamping plate on the concrete while the hammer was operated for about 10 seconds. All test specimens were cured in their molds for one day and then demolded. These specimens were then subjected to moist curing in accordance with ASTM C 192 until the time of test.

Table 2– Chemical Analysis of CCPs

Analysis Parameter	Ash Source Number			ASTM C-618 Requirements	
	FGD-1	FGD-2	FGD-3	Class C	Class F
SiO ₂	5.1	8.8	36.2	--	--
Al ₂ O ₃	2.5	7.8	19.4	--	--
Fe ₂ O ₃	1.2	2.5	6.2	--	--
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	8.8	19.1	61.8	50.0 Min	70.0 Min
CaO	38.3	10.1	24.0	--	--
MgO	0.9	3.5	6.4	--	--
TiO ₂	0.1	0.5	1.3	--	--
K ₂ O	0.2	0.6	0.5	--	--
Na ₂ O	0.3	7.2	2.1	--	--
SO ₃	19.9	18.1	1.3	5.0 Max	5.0 Max
LOI (1000 ^o C)	14.4	33.2	1.7	6.0 Max	6.0 Max
Moisture (%)	0.03	0	0	3.0 Max	3.0 Max
Na ₂ O, (ASTM C-311)	0.9	15.2	--	1.5 Max	1.5 Max

4. RESULTS AND DISCUSSION

4.1 Compressive Strength

Compressive strength results of permeable base course (open-graded) mixtures are shown in Figs. 1-3, and compressive strength results of permeable base course (intermediate -graded) mixtures are shown in Figs. 10-12. The compressive strength of the reference mixture for open-graded permeable base course was 970 psi at 28 days, and 1250 psi at 182 days. It is evident from Figs. 1-3 that compressive strength of mixtures containing FGD-2, FGD-3, and FGD-1 fly ash increased with increasing age. Compressive strength of mixtures with FGD-2 fly ash varied between 540 and 660 psi at 28 days, and 640 to 925 psi at 182 days. Similarly, Compressive strength of mixtures with FGD-3 fly ash ranged from 935 to 1010 psi at 28 days, and 1175 to 1570 psi at 182 days, whereas compressive strength of mixtures with FGD-1 fly ash ranged from 680 to 1135 psi at 28 days, and 955 to 1265 psi at 182 days. Compressive strength decreased with increased fly ash content.

For intermediate-graded permeable base course, compressive strength of the reference mixture varied from 1330 psi at 28 days to 1660 psi at 182 days. It can be seen from Figs.10-12 that compressive strength of mixtures containing FGD-3, FGD-1, and FGD-2 fly ash increased with increasing age. Compressive strength of mixtures with FGD-3 fly ash ranged from 1755 to 2175 psi at 28 days, and 1870 to 2355 psi at 182 days. Similarly, Compressive strength of mixtures with FGD-1 fly ash ranged from 580 to 1215 psi at 28 days, and 600 to 1490 psi at 182 days, whereas compressive strength of mixtures with FGD-2 fly ash ranged from 705 to 1030 psi at 28 days, and 1030 to 1355 psi at 182 days the compressive strength decreased with increased fly ash content. It is evident from these data that compressive strength decreased with increase in fly ash content. From Figs 1-3 and 1-12, it can be concluded that FGD fly ash contributes to the development of strength at later ages because of pozzolanic action.

Table 3 – Mixture Proportions for Permeable Base (Open-graded) Course Mixtures
Incorporating FGD-1, FGD-2 and FGD-3 Fly Ashes

Mixture No.	FGD-2 Fly Ash				FGD-3 Fly Ash			FGD-1 Fly Ash		
	MO	MO1	MO2	MO3	MO4	MO5	MO6	MO7	MO8	MO9
Ash Content, %	0	15	30	45	15	30	45	15	30	45
Cement, C, (lb/yd ³)	196	197	185	212	176	143	115	205	175	150
Fly Ash, A, (lb/yd ³)	0	30	55	95	39	77	118	30	62	90
Water, W, (lb/yd ³)	67	67	63	63	73	75	79	75	70	67
[W/(C+A)]	0.34	0.30	0.26	0.24	0.34	0.34	0.34	0.34	0.34	0.34
SSD Fine Aggregate (lb/yd ³)	--	--	--	--	--	--	--	--	--	--
SSD Coarse Aggregate (lb/yd ³)	2739	2695	2573	2900	2835	2800	2872	2865	2892	2725
Air Content (%)	2.0	4.8	2.5	4.2	1.2	2.6	4.6	1.6	2.2	1.4
Air Temperature (°F)	69	70	72	70	73	71	67	72	71	71
Concrete Temperature (°F)	70	73	74	72	70	69	66	69	72	67
Fresh Concrete Density (lb/ft ³)	117	134	126	130	116	115	118	118	119	112

Table 4 – Mixture Proportions for Permeable Base (Intermediate-graded) Course Mixtures
Incorporating FGD-1, FGD-2 and FGD-3 Fly Ashes

Mixture No.	FGD-3 Fly Ash				FGD-1 Fly Ash			FGD-2 Fly Ash		
	M2A	M21	M22	M23	M24	M25	M26	M27	M28	M29
Ash Content, %	--	15	30	55	15	30	45	15	30	45
Cement, C, (lb/yd ³)	205	184	148	198	200	181	160	205	197	200
Fly Ash, A, (lb/yd ³)	-	41	78	151	33	63	92	31	59	90
Water, W, (lb/yd ³)	70	70	78	85	74	73	70	73	77	83
[W/(C+A)]**	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.34	0.34
SSD Fine Aggregate (lb/yd ³)	600	625	605	630	610	585	545	620	580	590
SSD Coarse Aggregate (lb/yd ³)	2585	2700	2620	2725	2710	2665	2560	2665	2515	2535
Air Content (%)	3.3	3.8	3.9	4.2	4.2	4.4	4.8	4.9	4.6	4.4
Air Temperature (°F)	74	75	75	75	75	75	78	76	80	78
Concrete Temperature (°F)	72	78	73	72	77	77	81	78	84	82
Fresh Concrete Density (lb/ft ³)	128	134	131	137	134	133	127	133	127	130

4.2 Splitting-tensile Strength

Splitting-tensile strength results of permeable base course (open-graded) mixtures are shown in Figs. 4-6, and splitting-tensile strength results of permeable base course (intermediate -graded) mixtures are shown in Figs. 13-15. Splitting-tensile strength of reference mixture for open-graded permeable base course was 130 psi at 28 days, and 180 psi at 182 days. It is clear from Figs. 4-6 that splitting-tensile strength of mixtures containing FGD-2, FGD-3, and FGD-1 fly ash increased with the increase in age. Splitting-tensile strength of mixtures with FGD-2 fly ash varied between 65 and 155 psi at 28 days, and between 180 and 185 psi at 182 days. Similarly, splitting-tensile strength of mixtures with FGD-3 fly ash ranged from 110 to 145 psi at 28 days, and 145 to 185 psi at 182 days, whereas splitting-tensile strength of mixtures with FGD-1 fly ash ranged from 85 to 170 psi at 28 days, and 130 to 165 psi at 182 days. Splitting-tensile strength decreased with increased fly ash content.

For intermediate-graded permeable base course, splitting-tensile strength of the reference mixture varied from 220 psi at 28 days to 440 psi at 182 days. It can be seen from Figs.13-15 that splitting-tensile strength of mixtures containing FGD-3, FGD-1, and FGD-2 fly ash increased with increasing age. Splitting-tensile strength of mixtures with FGD-3 fly ash ranged from 220 to 410 psi at 28 days, and 250 to 365 psi at 182 days. Similarly, Splitting-tensile strength of mixtures with FGD-1 fly ash ranged from 100 to 225 psi at 28 days, and 100 to 350 psi at 182 days, whereas splitting-tensile strength of mixtures with FGD-2 fly ash ranged from 140 to 205 psi at 28 days, and 165 to 355 psi at 182 days the splitting-tensile strength decreased with increased fly ash content. It is clearly evident from these data that splitting-tensile strength decreased with increasing fly ash content. These results indicate that ,generally, the splitting-tensile strength has increased with the increase in age, as has been compressive strength due to pozzolanic action.

4.3 Flexural Strength

Flexural strength results of the permeable base course (open-graded) mixtures are shown in Figs. 6-9, and flexural strength results of permeable base course (intermediate -graded) mixtures are shown in Figs. 15-18. Flexural strength of the reference mixture for open-graded permeable base course was 140 psi at 28 days, and 2150 psi at 182 days. It is evident from Figs. 6-9 that flexural strength of mixtures containing FGD-2, FGD-3, and FGD-1 fly ash increased with increasing age. Flexural strength of mixtures with FGD-2 fly ash ranged from 55 to 135 psi at 28 days, and 80 to 190 psi at 182 days. Similarly, Flexural strength of mixtures with FGD-3 fly ash ranged from 135 to 185 psi at 28 days, and 185 to 240 psi at 182 days, whereas flexural strength of mixtures with FGD-1 fly ash ranged from 95 to 135 psi at 28 days, and 145 to 60 psi at 182 days. Flexural strength decreased with increased fly ash content.

For intermediate-graded permeable base course, flexural strength of the reference mixture varied from 290 psi at 28 days to 360 psi at 182 days. It can be seen from Figs.15-18 that flexural strength of mixtures containing FGD-3, FGD-1, and FGD-2 fly ash increased with increasing age. Flexural strength of mixtures with FGD-3 fly ash ranged from 320 to 355 psi at 28 days, and 360 to 460 psi at 182 days. Similarly, Flexural strength of mixtures with FGD-1 fly ash ranged from 95 to 160 psi at 28 days, and 100 to 380 psi at 182 days, whereas flexural strength of mixtures with FGD-2 fly ash ranged from 195 to 225 psi at 28 days, and 160 to 210 psi at 182 days the flexural strength decreased with increased fly ash content. It is clearly evident from these data that flexural strength decreased with increasing fly ash content. Flexural strength , like that of compressive and splitting tensile strength also increased with age.

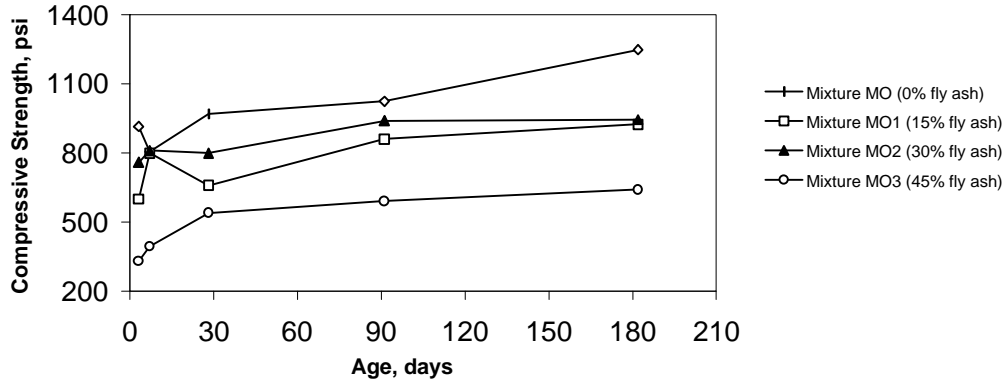


Fig. 1 Compressive Strength of Permeable Base Course (Open-graded) with FGD-2 Fly Ash

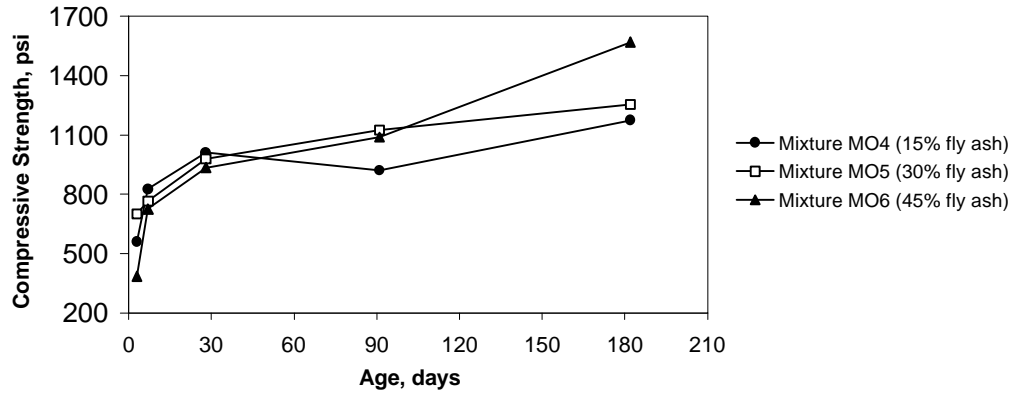


Fig. 2 Compressive Strength of Permeable Base Course (Open-graded) with FGD-3 Fly Ash

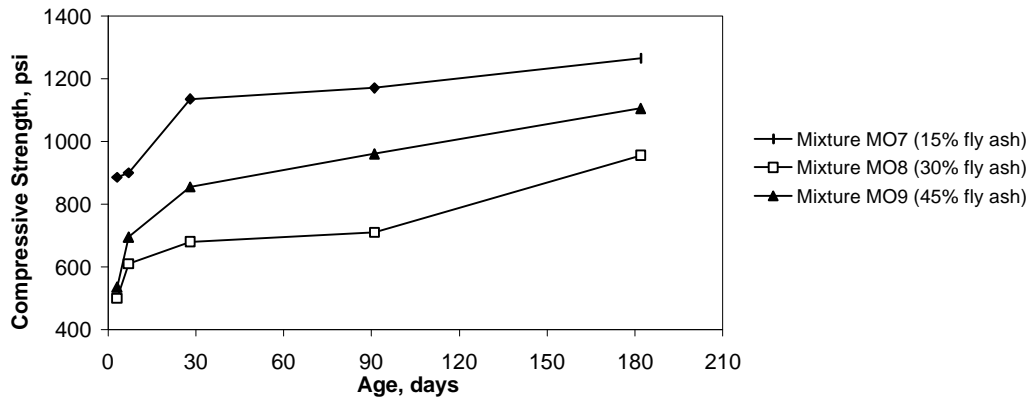


Fig. 3 Compressive Strength of Permeable Base Course (Open-graded) with FGD-1 Fly Ash

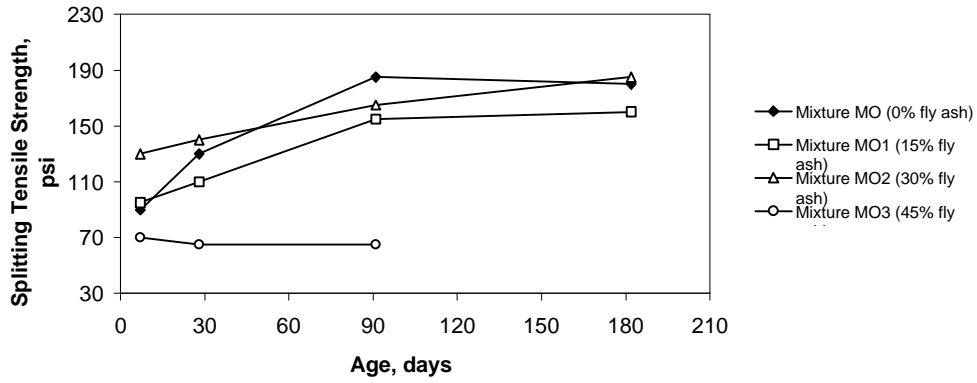


Fig. 4 Splitting Tensile Strength of Permeable Base Course (Open-graded) with FGD-2 Fly Ash

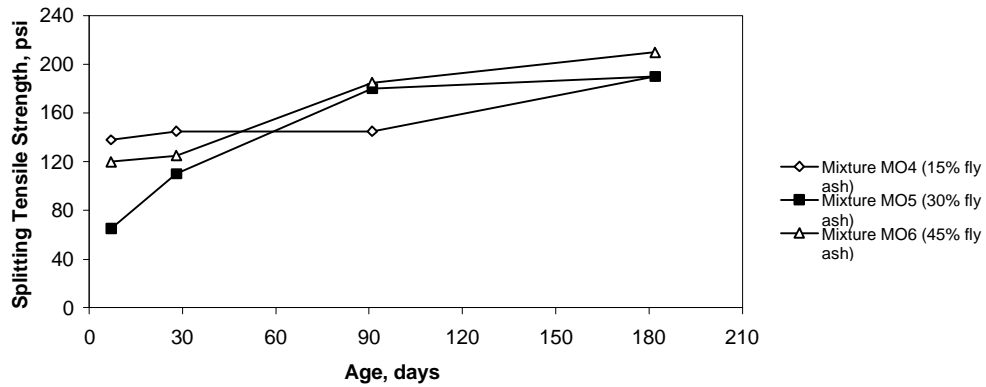


Fig. 5 Splitting Tensile Strength of Permeable Base Course (Open-graded) with FGD-3 Fly Ash

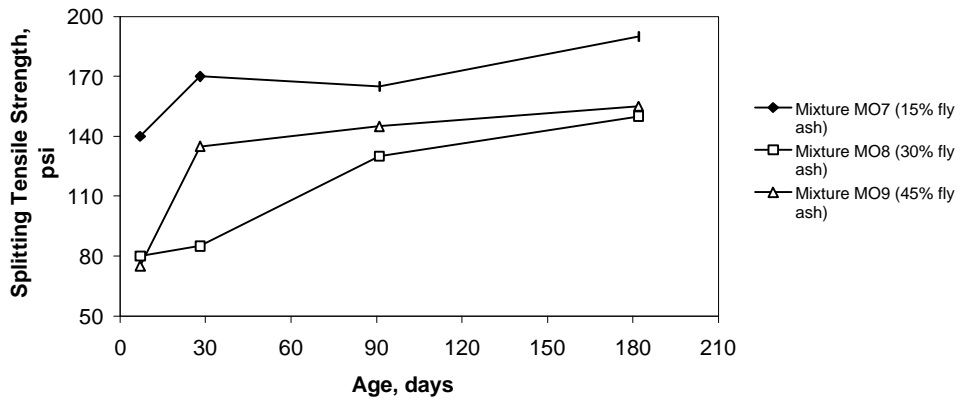


Fig. 6 Splitting Tensile Strength of Permeable Base Course (Open-graded) with FGD-1 Fly Ash

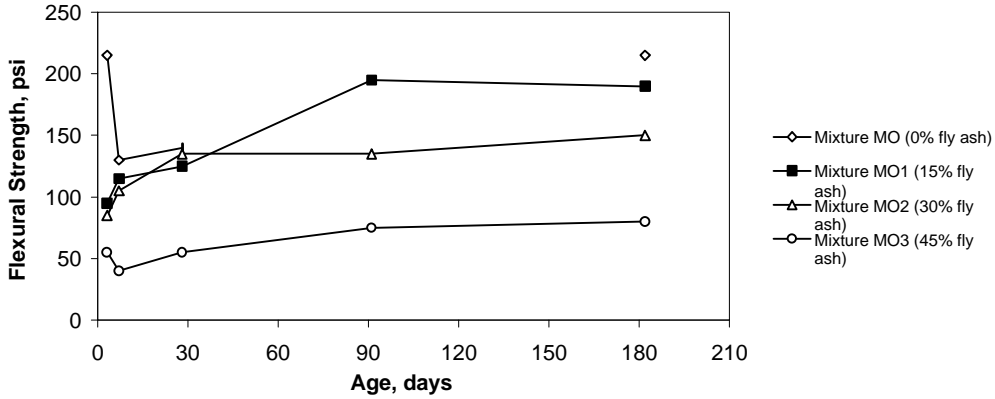


Fig. 7 Flexural Strength of Permeable Base Course (Open-graded) with FGD-2 Fly Ash

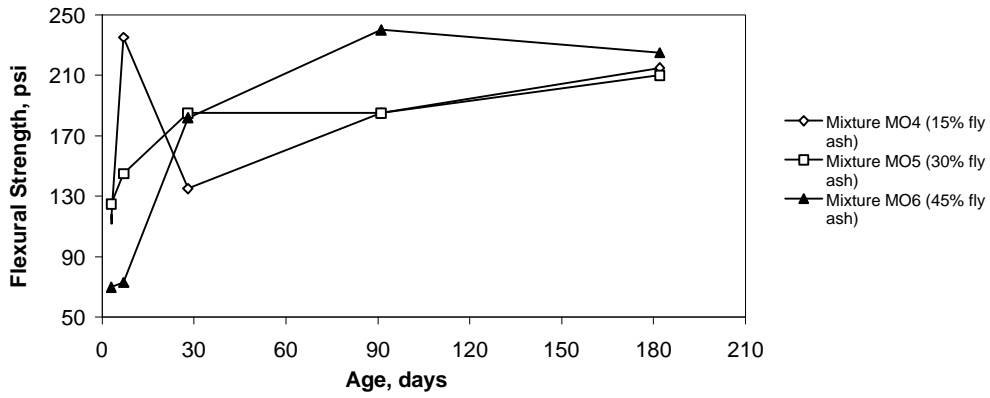


Fig. 8 Flexural Strength of Permeable Base Course (Open-graded) with FGD-3 Fly Ash

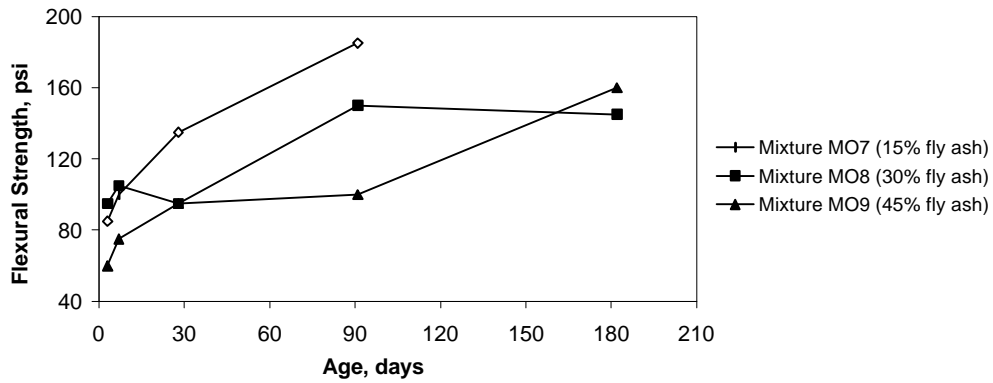


Fig. 9 Flexural Strength of Permeable Base Course (Open-graded) with FGD-1 Fly Ash

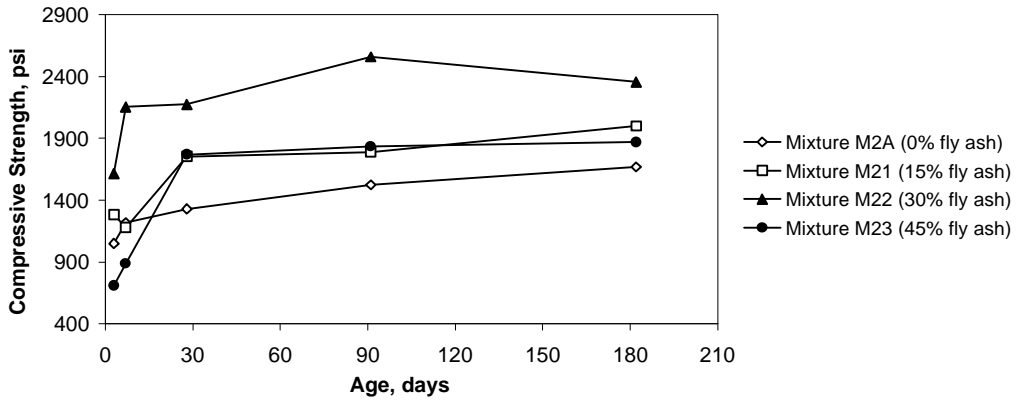


Fig. 10 Compressive Strength of Permeable Base Course (Intermediate-graded) with FGD-3 Fly Ash

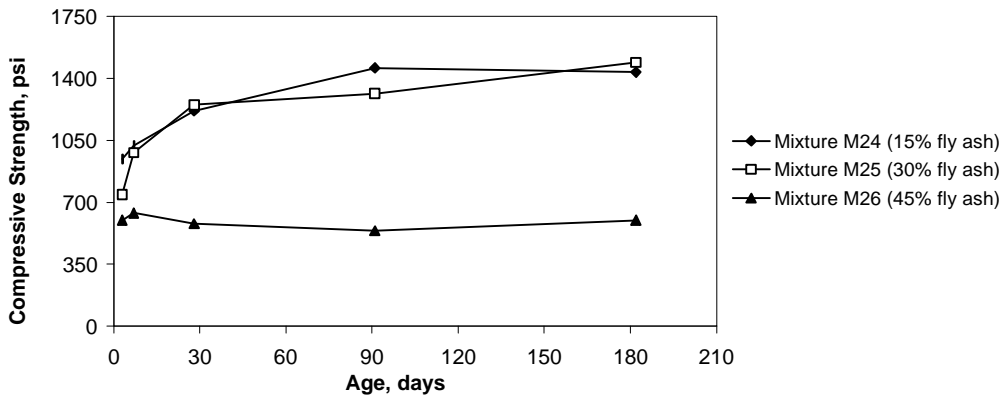


Fig. 11 Compressive Strength of Permeable Base Course (Intermediate-graded) with FGD-1 Fly Ash

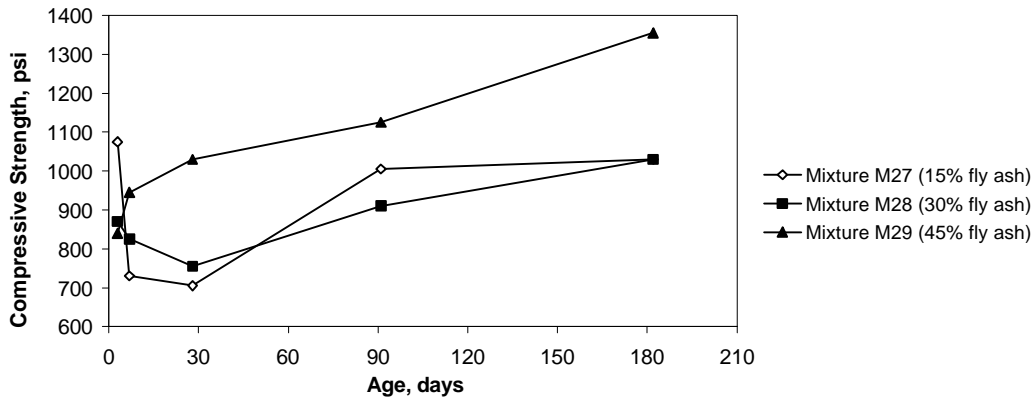


Fig. 12 Compressive Strength of Permeable Base Course (Intermediate-graded) with FGD-2 Fly Ash

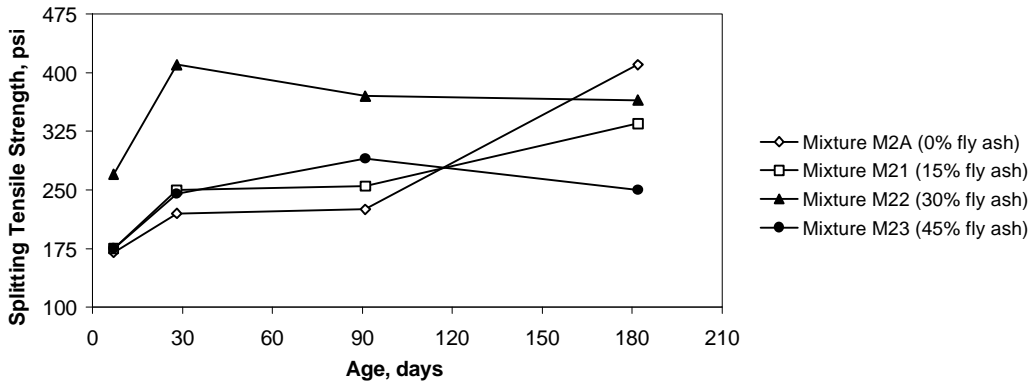


Fig. 13. Splitting Tensile Strength of Permeable Base Course (Intermediate-graded) with FGD-3 Fly Ash

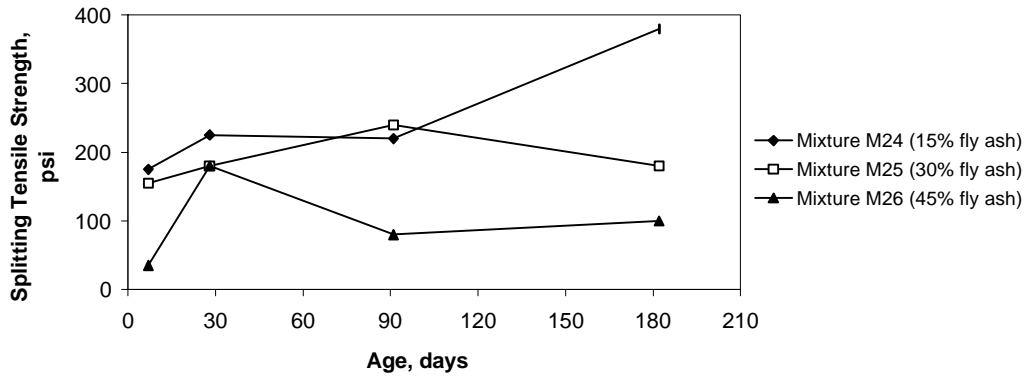


Fig. 14 Splitting Tensile Strength of Permeable Base Course (Intermediate-graded) with FGD-1 Fly Ash

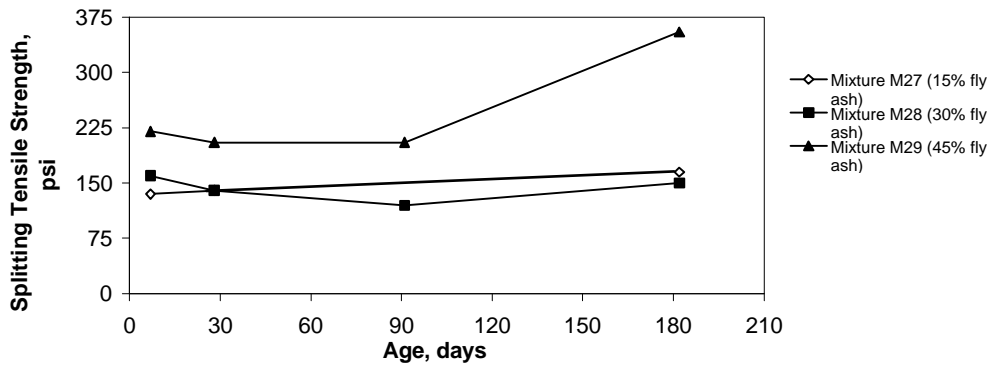


Fig. 15 Splitting Tensile Strength of Permeable Base Course (Intermediate-graded) with FGD-2 Fly Ash

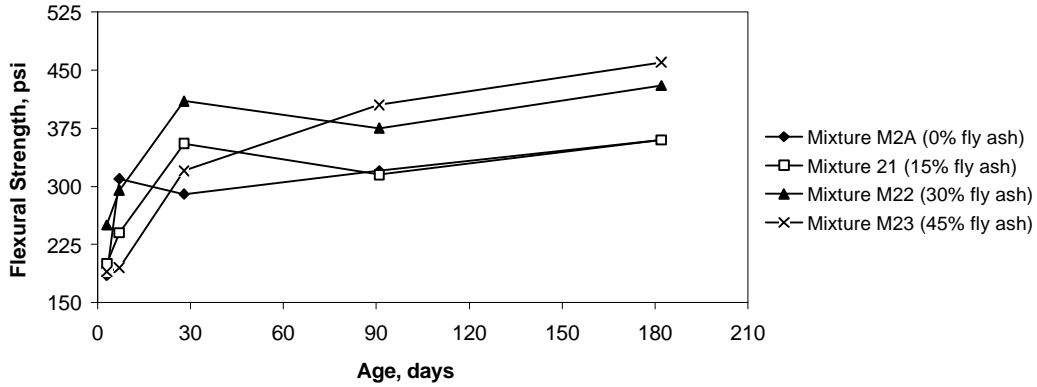


Fig. 16 Flexural Strength of Permeable Base Course (Intermediate-graded) with FGD-3 Fly Ash

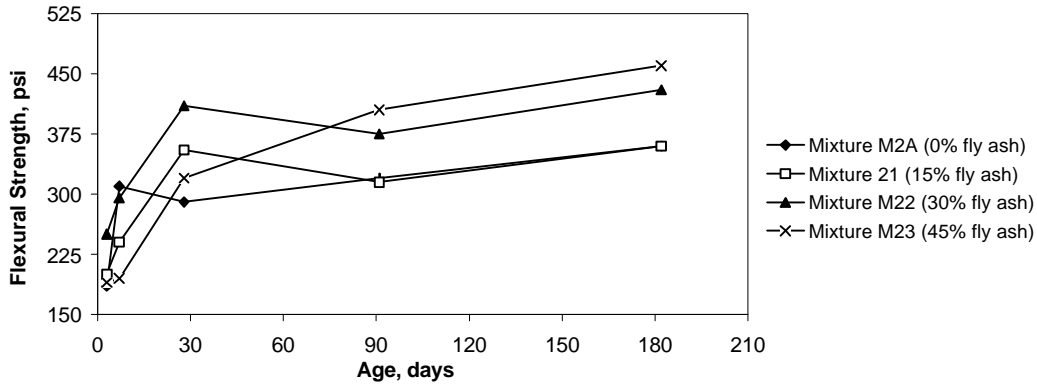


Fig. 16 Flexural Strength of Permeable Base Course (Intermediate-graded) with FGD-3 Fly Ash

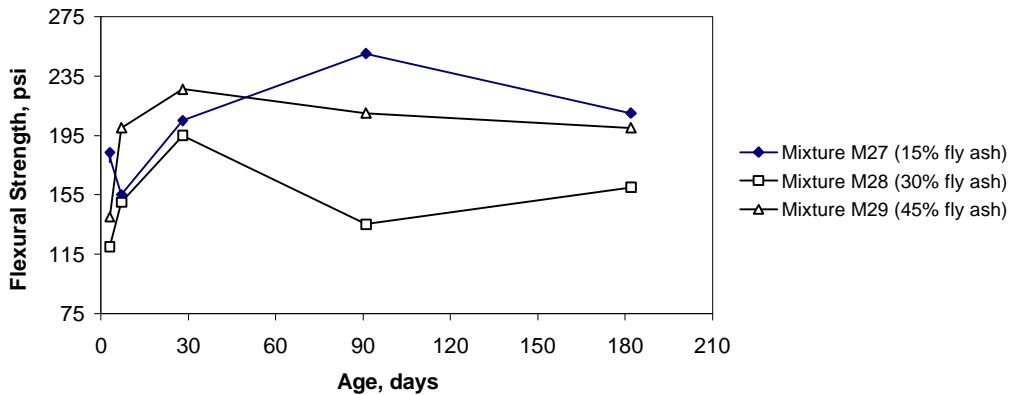


Fig. 18 Flexural Strength of Permeable Base Course (Intermediate-graded) with FGD-2 Fly Ash

5. CONCLUSIONS

Following conclusions are drawn from this investigation:

- (1) Compressive strength of open-graded permeable base concrete mixtures incorporating FGD-1, FGD-2 and FGD-3 fly ash ranged from 540 to 1135 psi at 28-days, and 640 –to 1570 psi at 182-days. The maximum compressive strength of 1135 psi was achieved at 28-days with FGD-1 fly ash.
- (2) Compressive strength of intermediate-graded permeable base concrete mixtures made with FGD-1, FGD-2 and FGD-3 fly ash varied between 580 and 2175 psi at 28-days, and between 600 and 2355 psi at 182-days. The maximum compressive strength of 2175 psi was achieved at 28-days with FGD-3 fly ash.
- (3) Splitting-tensile strength of open-graded permeable base concrete mixtures incorporating FGD-1, FGD-2 and FGD-3 fly ash ranged from 65 to 170 psi at 28-days, and 150 to 210 psi at 182-days. The maximum splitting-tensile strength of 170 psi was achieved at 28-days with FGD-1 fly ash.
- (4) Splitting-tensile strength of intermediate-graded permeable base concrete mixtures made with FGD-1, FGD-2 and FGD-3 fly ash ranged from 140 to 410 psi at 28-days, and 100 to 365 psi at 182-days. The maximum splitting-tensile strength of 410 psi was achieved at 28 days with FGD-3 fly ash.
- (5) Flexural strength of open-graded permeable base concrete mixtures incorporating FGD-1, FGD-2 and FGD-3 fly ash ranged from 75 to 185 psi at 28-days, and 80 to 225 psi at 182-days. The maximum flexural strength of 185 psi was achieved at 28-days with FGD-3 fly ash.
- (6) Flexural strength of intermediate-graded permeable base concrete mixtures incorporating FGD-1, FGD-2 and FGD-3 fly ash ranged from 95 to 410 psi at 28-days, and 160 to 460 psi at 182-days. The maximum flexural strength of 410 psi was achieved at 28 days with FGD-3 fly ash.
- (7) Compressive strength, splitting-tensile strength and flexural strength of both open-graded and intermediate-graded base course mixtures have increased with increasing age which clearly indicates the pozzolanic behavior of FGD fly ashes.
- (8) Results of this investigation indicate that FGD fly ashes can be used in permeable base course mixtures

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