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Development and Demonstration of High-Carbon CCPs and FGD By-Products in Permeable Roadway Base Construction

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ABSTRACT

This investigation was conducted to develop and demonstrate permeable base course materials using coal combustion products (CCPs) for highways, roadways, and airfield pavements. Three types of CCPs - two high-carbons, high-sulfate flue-gas desulfurization (FGD) by-products, and a variable-carbon fly ash - were evaluated for no-fines or low-fines concrete as a permeable base material. This report summarizes the initial work completed for this two-year project. A total of 56 mixtures were proportioned and manufactured in the laboratory. Mixture proportions for the base course materials were developed using a two-step experimental optimization process. Specimens from each mixture were made using roller-compacted concrete (RCC) technology in accordance with ASTM C 1435 Based on the mixture proportions established in the laboratory, four prototype open-graded base course mixtures containing one source of CCP were manufactured at a commercial ready-mixed concrete plant.

Keywords: Compressive strength, Flexural strength, FGD fly ash, Slump, Splitting-tensile strength.

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 in pavements (Cedergren, 1994). 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. Permeable pavement systems (PPS) and designs vary greatly. PPS is simply to collect, treat, and allow to infiltrate freely any surface runoff to support groundwater recharge. In comparison to traditional drainage systems, storm water retention and infiltration is a sustainable and cost effective process, which is suitable for urban areas (Scholz, 2007). Application of high pressure to the trapped water causes erosion of the base because the fines are pumped out along with the water. Consequently, a loss in pavement support occurs, leading to early failure of pavement. This can be avoided by using free-draining pavement base (Baumgardner, 1992; PCA, 1991; Kozeliski, 1992a, 1996b; Grogan, 1992; Hall, 1994; Kuennen, 1993). Permeable bases are divided into two classes: treated and untreated. A treated permeable base employs a binder, which would typically consist of either cement (119 to 178 kg/m^3) or asphalt (2 to 5% by mass). An untreated subbase contains more small particles than a treated subbase 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 (Baumgardner, 1992). Grogan (1992) reported that dense-graded subsurface pavement layers are virtually impermeable. Saturation of these layers will cause pumping, erosion, subgrade weakening, and freezeing/thawing damage. Use of properly designed and constructed permeable bases reduces or practically eliminates these problems, thus improving pavement performance. Hall (1994) reported that factors such as cement content, truck traffic, sublayer stability, segregation, and surface irregularities are important factors affecting the performance of the permeable base. Kozeliski (1996) reported successful applications of open-graded cement-treated base material in the construction of a parking lot for an office building, a driveway, and a ground cover of a refinery. Kuennen (1993) described construction of a high-quality, high-durability, drainable concrete pavement incorporating 18% fly ash of total cementitious materials. Naik and Ramme (1997) had presented the state-of-the-art information on permeable base road pavements. They reported the results from a demonstration project, and indicated that fly ash can be used in the manufacture of permeable base concrete pavements. Naik and Kraus (2002) reported the use of high-carbon CCPs and FGD by-products in permeable roadway base construction.

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 typically used processes 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 high-sulfate by-products, and low-NO_x burners generate high-carbon CCPs. Over 80% of the 1.2 billion tonnes of coal produced annually in USA is used for steam/power generation. This results in generation of over one million tonnes of by-products known as coal combustion products (CCPs). These include fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) products from conventional and advanced clean-coal technology combustors. Approximately 30 million tons of FGD by-products were generated in 2010 in the USA with a utilization rate of less than 40 percent (ACAA, 2012). Consequently, most FGD by-products are landfilled at high disposal costs with potential future environmental liabilities to the producer. Cost effective management of CCPs in an environmentally-friendly manner has been an important issue impacting the economics of coal production and power generation. To address this problem effectively, the U.S. Congress passed the Clean Air Act

Amendments of 1990 (CAAA'90; Public Law 101-549) with stringent restrictions (Canpolat, 2011). To avoid these, there is a need for the development of beneficial uses for these by-products.

EXPERIMENTAL PROCEDURE

Materials

Type I portland cement was used. The cement met the physical and chemical requirements of ASTM C 150 (Table 1 and 2). 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. They were two sources of high-carbon, sulfate-bearing CCPs, designated as FGD-1 and FGD-2, and one source of 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 properties 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 aggregates.

Mixture proportions

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

For the open-graded base course mixtures (Table 3), Mixture M1 was proportioned without any ash. Three mixtures, M2, M3, and M4 contained 15%, 30%, and 45%, respectively, of FGD-1 fly ash by mass of cement with half of the ash considered to be a replacement of cement and the remaining half considered to be filler. In these mixtures sand was not used. Three mixtures, M5, M6, and M7 were proportioned to have 15%, 30%, and 30%, respectively, of FGD-2 fly ash by mass of cement, as additional cementitious material. The rest of the three Mixtures, M8, M9, and M10 were proportioned to contain 15%, 30%, and 45%, respectively, of FGD-3 fly ash as a cement replacement.

For the dense-graded base course mixtures (Table 4), Mixture M11 was proportioned without any ash. Mixtures, M12, M13, and M14 were proportioned to contain 15%, 30%, and 45%, respectively, of FGD-1 fly ash with half of the ash considered to be a cement replacement and the remaining half considered to be a sand replacement. Mixtures, M15, M16, and M17, contained 15%, 30%, and 45%, respectively, of FGD-2 ash by mass of cement. The rest of the three Mixtures, M18, M19, and M20 were proportioned to have 15%, 30%, and 45%, respectively, cement replaced with FGD-3 fly ash.

Casting, curing, and testing of specimens

All concrete mixtures were mixed in a rotating drum concrete mixer in accordance with ASTM C 192. Fresh concrete was tested for air content (ASTM C 138), unit weight (ASTM C 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 (100 x 200 mm) for compressive strength (ASTM C 39) and splitting-tensile strength (ASTM C 496) measurements; and, in beam molds (75 x 100 x 400 mm) for measurements of flexural strength (ASTM C 78). For each 100 x 200 mm cylinder, concrete in the mold was compacted in two lifts (layers) with a 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 vibratory hammer was operated for about 20 seconds. For each 75 x 100 x 400 mm beam specimen, concrete in the mold was compacted in one layer by placing a rectangular tamping plate on the concrete while the vibratory hammer was operated for about 10 seconds. For each specimen, enough concrete was placed in the mold to fill its entire volume after compaction. 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.

RESULTS AND DISCUSSION

Compressive strength

Compressive strength results of open-graded and intermediate-graded permeable base course mixtures are shown in Figs. 1 to 3 and Figs 4 to 6, respectively.

The compressive strength of the Control Mixture (M1) for open-graded permeable base course was 6.7 MPa at the age of 28 days and 8.6 MPa at 182 days. It is evident from Figs. 1 to 3 that compressive strength of mixtures containing FGD-1, FGD-2, and FGD-3 fly ash increased with increase in age, but the strength generally decreased with the increase in the fly ash content. Compressive strength of mixtures with FGD-1 fly ash ranged between 4.7 and 7.8 MPa at 28 days, and between 6.6 and 8.7 MPa at 182 days. Similarly, compressive strength of mixtures with FGD-2 fly ash varied between 3.7 and 4.6 MPa at 28 days, and between 4.4 and 6.4 MPa at 182 days whereas compressive strength of mixtures with FGD-3 fly ash ranged between 6.5 and 7 MPa at 28 days, and between 8.1 and 10.8 MPa at 182 days. The maximum compressive strength (7.8 MPa) at 28 days was achieved with FGD-1 fly ash (15% ash content). This is probably because of higher CaO content in this particular type of ash.

For dense-graded permeable base course, Series 8 mixtures were proportioned based upon the candidate Mixture R1B1R of Series 6. These mixtures were developed as dense-graded base course materials. Mixture M1 was proportioned without any ash. Three Series 8 mixtures (M11, M12, and M13) were proportioned using CCP-3 fly ash. Similar to the Series 7 mixtures, these mixtures replaced 15%, 30%, and 45% of cement with CCP-3 fly ash (Table 4), at a replacement rate of 1.25 pounds of ash for each pound of cement replaced. Also, three mixtures (M14, M15, and M16) were proportioned to contain 15%, 30%, and 45% of CCP-1 fly ash (Table 4). Half of the addition of CCP-1 ash was considered to be cementitious, while the remaining half was considered to be a replacement of sand. Series 8 mixtures, M17, M18, and M19, contained 15%, 30%, and 45%, respectively, of CCP-2 ash by weight of cement (Table 4); however, only half of the ash was considered to be cementitious, while the remaining half was considered to be a replacement of sand.

Strength (compressive strength and splitting tensile strength) and durability properties (drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing) were evaluated for Series 8 mixtures (dense-graded base course). Results are shown in Figs. 4 through 6.

Compressive strength, splitting tensile strength, and flexural strength of Series 8 mixtures using CCP-3 fly ash are shown in Figs. 10, 11, and 12, respectively. Compressive strength was evaluated at the ages of 3, 7, 28, 91, 182, and 365 days; splitting tensile strength was evaluated at the ages of 7, 28, 91, and 182 days; and flexural strength were evaluated at the ages of 3, 7, 28, 91, and 182 days. Strength achieved by Mixture M11, 15% ash, was typically higher than the reference Mixture M1 without ash. Compressive strength of mixtures containing CCP-3 typically decreased when the amount of ash in the mixture was increased to 30% and 45%.

Splitting-tensile strength

Splitting-tensile strength results of open-graded and intermediate-graded permeable base course mixtures are shown in Figs. 7 to 9 and Figs 10 to 12, respectively.

For open-graded permeable base course, splitting-tensile strength of Control Mixture (M1) was 0.9 MPa at 28 days and 1.24 MPa at 182 days. It is clear from Figs. 7 to 9 that splitting-tensile strength of mixtures containing FGD-1, FGD-2, and FGD-3 fly ash increased with the increase in age. Splitting-tensile strength of mixtures with FGD-1 fly ash ranged between 0.59 and 1.17 MPa at the age of 28 days, and between 0.9 and 1.14 MPa at 182 days. Similarly, splitting-tensile strength of mixtures with FGD-2 fly ash varied between 0.45 and 1.10 MPa at 28 days, and between 1.24 and 1.27 MPa at 182 days, whereas splitting-tensile strength of mixtures with FGD-3 fly ash ranged between 0.76 and 1.0 MPa at 28 days, and between 1 and 1.27 MPa at 182 days. Splitting-tensile strength generally decreased with increase in the fly ash content. Maximum splitting-tensile strength of 1.17 MPa was achieved at 28 days with FGD-1 fly ash (15% ash content). Similar to the compressive strength, this is probably due to higher CaO content in this particular type of ash.

CONCLUSIONS

Following conclusions are drawn from this investigation:

1. Compressive strength, splitting-tensile strength, and flexural strength of both open-graded and intermediate-graded base course mixtures increased with age for all the three FGD fly ashes, which indicates the pozzolanic behavior of the fly ashes.
2. For the open-graded base course mixtures, maximum 28-day compressive strength (7.82 MPa) was achieved with FGD-1 fly ash (15% ash content), maximum 28-day splitting tensile strength (1.17 MPa) with FGD-1 fly ash (15% ash content), and maximum 28-day flexural strength (1.28) with FGD-3 fly ash (30% ash content).
3. For the dense-graded base course mixtures, 28-day maximum compressive strength (14.46 MPa) and splitting-tensile strength (1.31 MPa) were achieved with FGD-3 fly ash (30% ash content).
4. Results of this investigation indicate that FGD fly ashes can be used in permeable base course mixtures with judiciously selected mixture proportions.

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Table 1. Physical properties of CCPs

Test parameter	Ash source			ASTM C 618 Requirements for fly ash	
	FGD-1	FGD-2	FGD-3	Class C	Class F
Retained on 45 µm (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	-	-

Table 2. Chemical properties of CCPs

Analysis parameter	Ash source			ASTM C 618 Requirements for fly ash	
	FGD-1	FGD-2	FGD-3	Class C	Class F
SiO_2	5.1	8.8	36.2	-	-
Al_2O_3	2.5	7.8	19.4	-	-
Fe_2O_3	1.2	2.5	6.2	-	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	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_2O	0.2	0.6	0.5	-	-
Na_2O	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
Available alkalis* (Equivalent Na_2O) , (ASTM C-311)	0.9	15.2	-	1.5 max	1.5 max

* Optional requirement

Table 3. Mixture proportions and fresh properties of open-graded permeable base course mixtures incorporating FGD-1, FGD-2 and FGD-3 fly ashes

Source of fly ash	Control mixture	FGD-1 fly ash			FGD-2 fly ash			FGD-3 fly ash		
Mixture No.	C	M7	M8	M9	M1	M2	M3	M4	M5	M6
Ash content (%)	0	15	30	45	15	30	45	15	30	45
Cement, C (kg/m^3)	116	122	104	89	117	110	126	104	85	68
Fly ash, A (kg/m^3)	0	18	37	53	18	33	56	23	46	70
Water, W (kg/m^3)	40	44	42	40	40	37	43	43	44	47
[W/(C+A)]	0.34	0.34	0.34	0.34	0.3	0.26	0.24	0.34	0.34	0.34
SSD fine aggregate (kg/m^3)	0	0	0	0	0	0	0	0	0	0
SSD coarse aggregate (kg/m^3)	1625	1700	1716	1617	1599	1505	1721	1682	1661	1704
Air content (%)	2.0	1.6	2.2	1.4	4.8	2.5	4.2	1.2	2.6	4.6
Air temperature (^{o}C)	21	22	22	22	21	22	21	23	22	19
Concrete temperature (^{o}C)	21	21	22	19	23	23	22	21	21	19
Fresh concrete density (kg/m^3)	1833	1884	1898	1794	-	1685	1946	1852	1849	1890

Table 4. Mixture proportions and fresh properties of dense-graded permeable base course mixtures incorporating FGD-1, FGD-2 and FGD-3 fly ashes

Source of fly ash	Control mixture	FGD-1 fly ash			FGD-2 fly ash			FGD-3 fly ash		
Mixture No.	C	M14	M16	M15	M17	M18	M19	M11	M12	M13
Ash content (%)	-	15	30	46	15	30	45	15	30	45
Cement, C (kg/m^3)	119	115	101	95	119	119	119	101	83	66
Fly ash, A (kg/m^3)	0	12	36	55	18	36	53	23	44	68
Water, W (kg/m^3)	41	42	42	42	41	41	50	43	43	46
[W/(C+A)]	0.34	0.34	0.35	0.34	0.34	0.34	0.43	0.35	0.34	0.34
SSD fine aggregate (kg/m^3)	682	694	666	670	682	682	682	679	664	676
SSD coarse aggregate (kg/m^3)	1302	1320	1301	1326	1302	1302	1302	1290	1290	1320
Air content (%)	4.2	4.2	2.9	4.8	4.8	4.6	4.2	4.5	4.8	4.2
Air temperature (^{o}C)	23	24	24	26	24	27	26	24	24	24
Concrete temperature (^{o}C)	22	25	25	27	26	29	28	26	23	22
Fresh concrete density (kg/m^3)	2150	2156	2137	2150	2156	2169	2191	2103	2119	2171

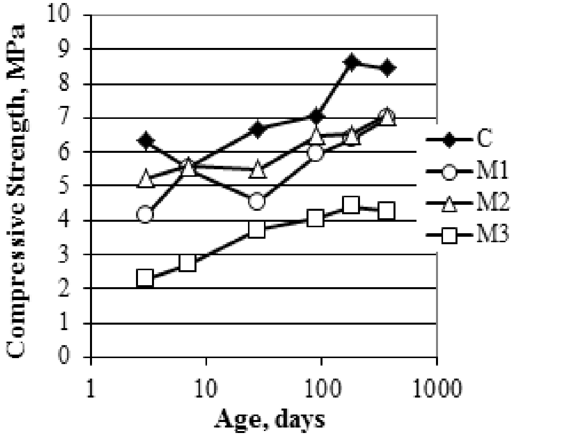

Figure 1. Compressive Strength of Open-Graded Permeable Base Course with FGD-1 Fly Ash

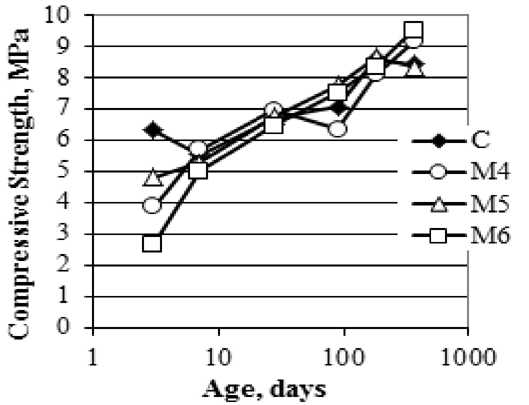

Figure 2. Compressive Strength of Open-Graded Permeable Base Course with FGD-2 Fly Ash

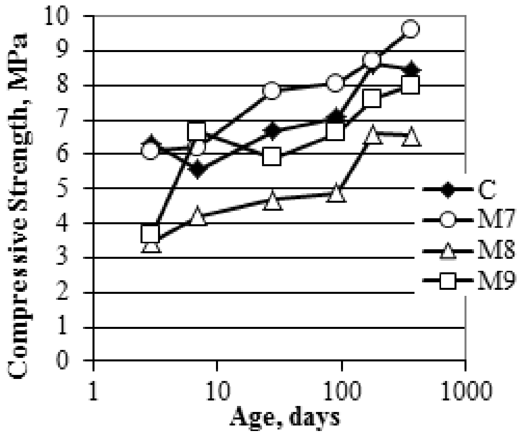

Figure 3. Compressive Strength of Open-Graded Permeable Base Course With FGD-3 Fly Ash

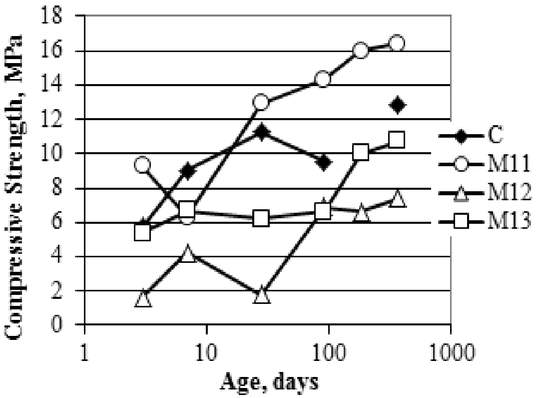

Figure 4. Compressive Strength of Dense-Graded Permeable Base Course with FGD-1 Fly Ash

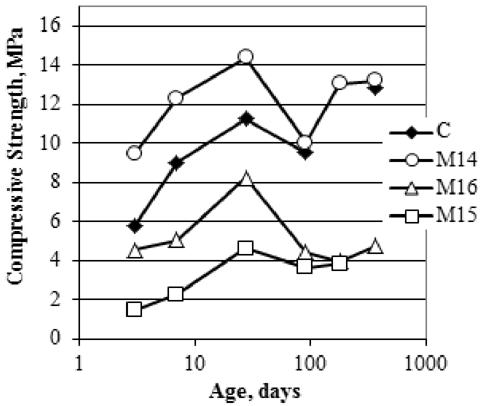

Figure 5. Compressive Strength of Dense-Graded Permeable Base Course with FGD-2 Fly Ash

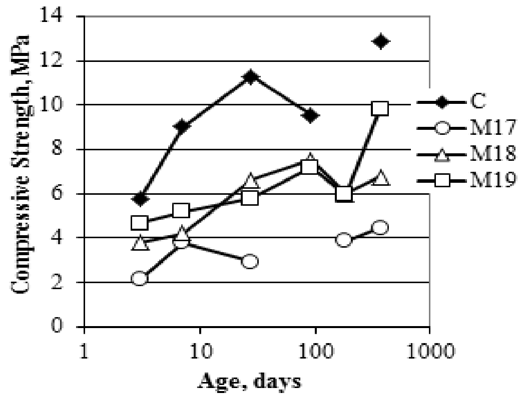

Figure 6. Compressive Strength of Dense-Graded Permeable Base Course with FGD-3 Fly Ash

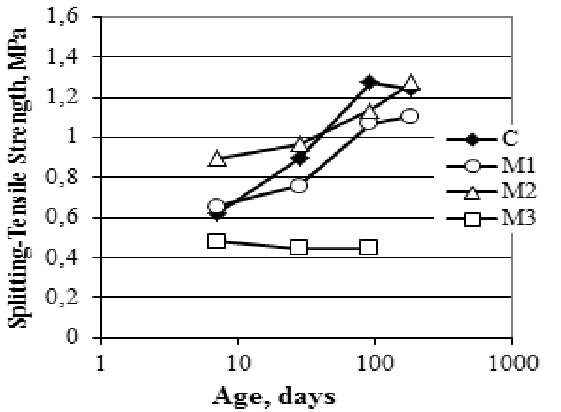

Figure 7. Splitting-Tensile Strength of Open-Graded Permeable Base Course with FGD-1 Fly Ash

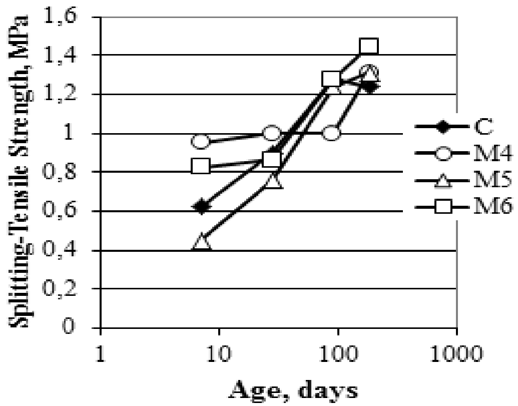

Figure 8. Splitting-Tensile Strength of Open-Graded Permeable Base Course with FGD-2 Fly Ash

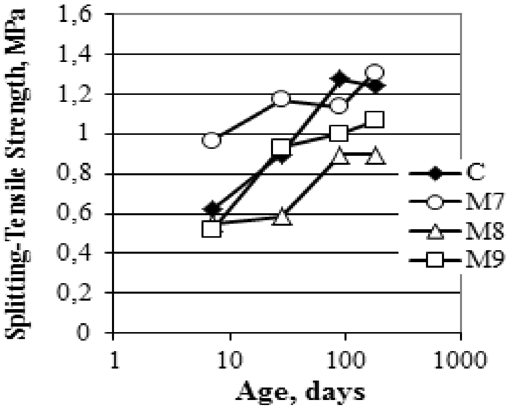

Figure 9. Splitting-Tensile Strength of Open-Graded Permeable Base Course with FGD-3 Fly Ash

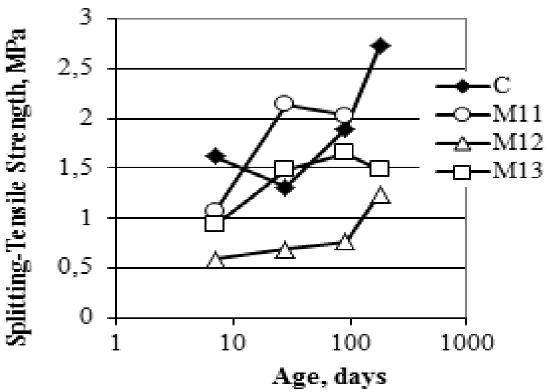

Figure 10. Splitting-Tensile Strength of Dense-Graded Permeable Base Course with FGD-1 Fly Ash

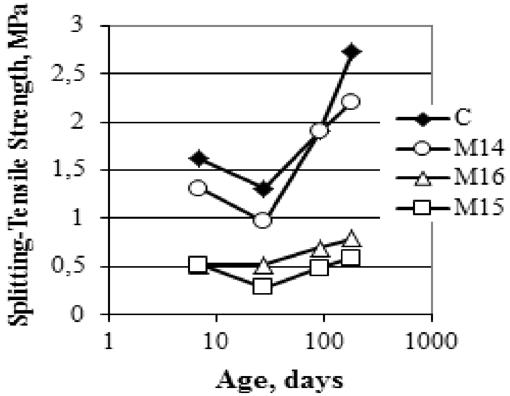

Figure 11. Splitting-Tensile Strength of Intermediate-Graded Permeable Base Course with FGD-2 Fly Ash

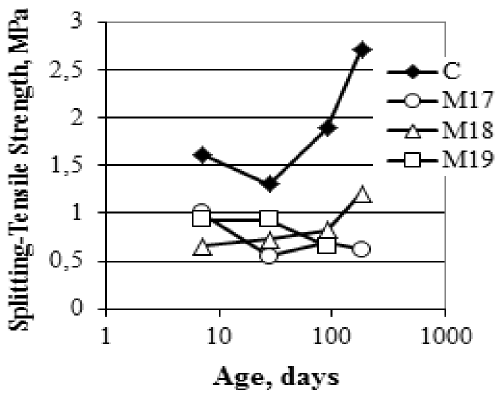

Figure 12. Splitting-Tensile Strength Of Intermediate-Graded Permeable Base Course with FGD-3 Fly Ash