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USE OF COAL-COMBUSTION PRODUCTS IN PERMEABLE PAVEMNET BASE

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ABSTRACT

Permeable concrete mixtures were produced using two high-carbon, flue-gas desulfurization materials (FGD-1 and FGD-2) and a variable-carbon fly ash (VCA). Incorporation of up to 45% (by mass of cement) FGD-1 (one half replacing cement and the other half added as a filler) resulted in more or less the same compressive and splitting-tensile strengths of permeable concrete compared with control concrete. The flexural strength was almost equivalent and the freezing-and-thawing (F&T) resistance was relatively high, although lower than control, for up to 30% FGD-1. When FGD-2 was used as an additional cementitious material, the strengths were equivalent for up to 30% FGD-2, and the F&T resistance was equivalent for up to 15% FGD-2. When up to 45% of cement was replaced with VCA, the strengths and F&T resistance were comparable to those of control concrete, except for the case of 15% cement replacement which resulted in a lower F&T resistance.

Keywords: compressive strength; flue gas desulfurization (FGD) materials; flexural strength; freezing and thawing; high-carbon ash; no-fines concrete; permeable base; splitting-tensile strength; variable-carbon fly ash.

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Yoon-moon Chun is a research associate at the UWM-CBU. His research interests include the use of coal fly ash, coal bottom ash, and used foundry sand in concrete, bricks, blocks, and paving stones, and the use of fibrous residuals from pulp and paper mills in concrete.

INTRODUCTION

Presence of excess water in the pavement structure is known to be a major 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 the draining capability of the pavement base is low. When high-pressure is applied to the pavement from heavy traffic loads, pumping occurs in the base course of the pavement in the presence of water. This causes erosion of the base because the fine materials get pumped out along with the water. Consequently, a loss in pavement support occurs, leading to premature failure of the pavement. This kind of failure can be avoided by using free-draining pavement base[2-7].

On the other hand, with an objective to meet current and future EPA air quality standards, electric-power utilities are utilizing supplemental flue-gas treatments to reduce emissions. These kinds of treatments either alter the quality of the coal combustion products (CCPs), or generate another type of "waste" material. The 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 materials are high-sulfite and/or sulfate products, and low-NO_X burners generate high-carbon CCPs. Approximately 26 million metric tons of FGD products were generated in 2001 in the USA with a utilization rate of 28%, mainly in manufacturing gypsum-based wallboard[8,9]. Most of FGD materials and high-carbon CCPs are landfilled at high disposal costs and potential future environmental liabilities to the utilities. To avoid these consequences, there is a need to develop beneficial uses of these products. This project was undertaken to develop high-volume applications of such CCPs in the manufacture of cement-treated permeable-base materials for pavements. Use of FGD products and high-carbon or variable-carbon CCPs in permeable base-course is expected to utilize significant quantities of these products. It will also help to reduce the material cost of permeable base for pavement, which will lead to increased use of such permeable bases for highways, roadways, and airfield pavements. Reducing the cost of permeable-base materials is expected to expand its use in many other types of construction (e.g., parking lots, industrial facility floors, material handling yards, etc.) with increased pavement life and increased utilization rate of CCPs, especially under-utilized and/or off-specification CCPs. Three sources of CCPs were obtained for the project. They were two high-carbon, sulfite/sulfate bearing flue-gas desulfurization (FGD) materials, designated as FGD-1 and FGD-2, and a variable-carbon fly ash designated as VCA.

LITERATURE REVIEW

A porous base must be capable of maintaining both permeability and stability. It is estimated that the use of a porous base would increase pavement service life by up to 70% for concrete and asphaltic pavements[1]. Due to the large size of the pores, no-fines concrete is not subject to capillary suction[10]. Therefore, no-fines concrete is highly resistant to freezing and thawing, provided that the pores are not saturated; if saturated, freezing would cause deterioration of the porous concrete. The water absorption can be as high as 25% by volume.

Porous bases are divided into two classes: treated and untreated. A treated porous base employs a binder, which typically consists of either cement or asphalt. A cement-treated porous base is typically composed of 85% aggregate, 10% cement, and 5% water by mass[5]. The coefficient of permeability for a treated base depends upon several factors such as aggregate gradation and binder content. Due to the coarse gradation and the small amount of binder used in the manufacture of a treated base, the treated base is by design quite porous. An untreated base contains a higher amount of small aggregate particles in order to provide stability through aggregate interlock. In order to have improved stability, an untreated base should preferably contain 100% crushed aggregate[4]. The coefficient of permeability for the untreated porous base is normally lower than that for the treated porous base due to greater amount of small aggregate particles.

As a paving material, porous concrete is raked or slip-formed into place with conventional spreader or paving equipment and then roller compacted, similar to asphaltic pavement. Vibratory screeds or hand rollers can be used for confined spaces or smaller project work. In order to maintain porous properties, the surfaces should not be closed or sealed; therefore, troweling and finishing are not desired. The compressive strength of different mixtures typically ranges from 3.5 to 28 MPa at 28 days[7]. Drainage rates commonly range from 80 to 700 L/min. per square meter[11].

A porous base system is composed of three major elements: permeable base, separator or filter layer, and edge drain system[7]. Information on design, construction, and material requirements are available in the literature[4-7,12-14]. Various parameters such as cross slope, longitudinal grade, and drainage-layer width and thickness can influence the permeability and performance of open-graded porous materials[15]. Although the thickness of porous bases generally varies from 10 to 30 cm, a 20 cm thickness of the porous base is the most commonly used[15-17]. Factors such as cement content, truck traffic, sublayer stability, segregation, and surface irregularities are important in affecting performance of the porous material[18].

Based on investigations in California[14,19], a minimum life increase was estimated to be 33% for asphaltic pavement and 50% for portland cement concrete pavement incorporating porous bases compared to undrained pavements. Studies conducted by several state agencies in the USA were summarized by Munn[19]. Two eight-year-old pavements on porous bases in California did not exhibit any cracking, whereas corresponding undrained pavements showed 18% and 47% cracking. Recent nondestructive testing in Iowa[20] has shown excellent performance of porous base pavements. Nondestructive testing of porous base pavements in Iowa revealed a greater support relative to undrained pavements[20]. The increased support was equivalent to a thickness of 75 to 125 mm of additional pavement. In Michigan, porous-base test sections built in 1975 did not show any faulting or cracking in the pavement and had less D-cracking compared to control sections of bituminous and dense-graded sections. In Minnesota, a jointed reinforced concrete pavement on porous base built in 1983 experienced only one mid-panel crack in its 59 panels, while undrained sections adjacent to either end showed 50% mid-panel cracks. The performance of Pennsylvania's porous base sections built in 1979-80 was rated much better than dense-graded aggregate sections. In Pennsylvania, a porous base between portland cement concrete pavement and the dense-graded aggregate subbase was standardized in 1983. It is estimated that the use of a cement-stabilized base would add 25% more service life to the concrete pavements in Wisconsin[3]. Similar rutting was observed in New Jersey for porous-base pavements constructed in 1979-1980 for either thicker or thinner sections[13]. Also, there was less deflection, no faulting or pumping, and reduced frost penetration on concrete pavements. In

1990, porous base concrete pavement became standard in nine different states[5]. The use of porous bases is rapidly increasing in the USA.

RESEARCH SIGNIFICANCE

This research was conducted to explore the possibility of using under-utilized and/or off-specification coal combustion products (CCPs) in manufacturing permeable concrete for use as pavement base for pavements. Two sources of high-carbon, flue-gas desulfurization (FGD) materials and one source of variable-carbon fly ash (VCA) were used for this project. The test results showed that the FGD materials and VCA could be used to partially replace portland cement without affecting the strengths and freezing-and-thawing (F&T) resistance of permeable concrete, thus lowering the material cost for permeable base and increasing the utilization rate of such CCPs.

MATERIALS

ASTM Type I portland cement was used in this research (**Table 1**). Three sources of CCPs were used. They were two sources of high-carbon, sulfite/sulfate bearing CCPs, designated as FGD-1 and FGD-2, and one source of variable-carbon fly ash designated as VCA. The composition of oxides were determined for the CCP materials using the X-Ray Fluorescence (XRF) technique. The chemical analysis results are shown in **Table 1**. Both FGD-1 and FGD-2 showed low quantities of SiO_2 + Al_2O_3 + Fe_2O_3 and high sulfite/sulfate contents (based on SO_3 content), and high LOI. The CCP samples were also analyzed to determine the type and amount of minerals present. The mineral species found in the CCP samples are shown in **Table 2**. The physical properties of CCPs are given in **Table 3**. Both FGD-1 and FGD-2 showed relatively high water requirement (107% and 112%). FGD-1 showed a low strength-activity index (approximately 60% of control), and FGD-2 showed a high strength-activity index (116% of control at 28 days). VCA met the chemical and physical requirements of ASTM C 618 for Class C fly ash (**Tables 1 and 2**) and also showed a very high strength-activity index (130% of control at 28 days). One source of crushed limestone aggregate with a nominal maximum size of 19 mm was used as coarse aggregate.

CASTING, CURING, AND TESTING OF SPECIMENS

All concrete mixtures were mixed in a rotating-drum concrete mixer in the laboratory. First, coarse aggregate was added to the mixer, and the mixer was allowed to rotate for about one minute. Then cement was added to the mixer, and the coarse aggregate and cement were mixed dry for two minutes. Thereafter, water was added, and all the ingredients in the mixer were mixed for three minutes, allowed to rest for three minutes, and finally mixed for two more minutes. The resulting mixture was used in making concrete test specimens.

The specimens were compacted using a vibrating hammer having a mass of 10 kg. Either a circular tamping plate for compaction of cylinders or a rectangular plate for compaction of beams was attached to the tip of the shaft of the vibrating hammer. The 100 × 200 mm cylinders were molded in cylindrical steel molds for determination of compressive strength (ASTM C 39) and splitting-tensile strength (ASTM C 496). For each cylinder, concrete in the mold was compacted in two lifts (layers) with the vibrating 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 onto the concrete while the hammer was operated for approximately 20 seconds. The 75 × 100 × 400 mm beams were prepared in wooden molds for determination of flexural strength (ASTM C 78) and resistance to freezing and thawing (modified ASTM C 1262). For each beam specimen, concrete in the mold was compacted in one lift with the vibrating 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 onto the concrete while the hammer operated for about 10 seconds.

All test specimens were cured in their molds for one day and then demolded from the molds. The specimens were then stored in a most-curing room. For evaluation of resistance to freezing and thawing, porous concrete beams in saturated surface-dry condition were subjected to a total of 50 cycles of freezing (to -17 ± 5 °C) and thawing (to +24 ± 5 °C) in air. The mass of residue (spall) from the beams due to freezing and thawing were determined once every five or ten cycles.

MIXTURE PROPORTIONS

A total of ten permeable-concrete mixtures were proportioned (**Table 4**). Control mixture C was proportioned without any CCPs. The performance of mixtures incorporating FGD-1, FGD-2, or VCA were compared to the performance of Control mixture. Mixtures F1-1, F1-2, and F1-3 respectively contained 15%, 30%, and 45% FGD-1 by mass, based on the amount of cement in Control mixture. In Mixture F1-1, one half of the FGD-1 added was considered to be an additional cementitious material without replacing any cement, and the other half was considered to be filler. In Mixtures F1-2 and F1-3, one half of the FGD-1 added was considered to be a cementitious material that replaced cement, and the other half was considered to be filler.

Respectively, Mixtures F2-1, F2-2, and F2-3 contained 15%, 30%, and 45% FGD-2 relative to the amount of cement in Control mixture. One half of the FGD-2 added was considered to be an additional cementitious material without replacing any cement, and the other half was considered to be filler. Finally, Mixtures V-1, V-2, and V-3 contained VCA as a replacement of 15%, 30%, and 45% of cement by mass. One part of cement was replaced with about 1.33 parts of VCA. Overall, average void-content of permeable-concrete mixtures was about 29% by volume.

STRENGTH

Test results for compressive, splitting-tensile, and flexural strengths of the permeable-concrete mixtures are presented in **Fig. 1** through **9**. Overall, the average 28-day compressive, splitting-tensile, and flexural strengths of permeable-concrete mixtures were about 5.9, 0.8, and 0.9 MPa, respectively. The 28-day compressive strength of the permeable-concrete mixtures exceeded the minimum desired strength of 5.5 MPa designated in this project, except for Mixtures F1-2, F2-1, and F2-3. In general, the rate of strength gain for Control mixture and that for the mixtures incorporating the CCPs were similar. Average strengths of the concrete mixtures from all test ages are presented in **Table 5**.

Overall, Mixture F1-1 showed higher compressive strength, higher splitting-tensile strength, and lower flexural strength than Control Mixture C (**Table 5, Fig. 1, 2, 3**). This means that FGD-1 can be beneficially used as an additional cementitious material. Mixtures F1-2 and F1-3 made by replacing part of cement with FGD-1 showed generally lower strengths than Control Mixture C. Compared with Mixture F1-2, Mixture F1-3 showed higher compressive and splitting-tensile strengths and lower flexural strength. Mixture F1-3 was nearly equivalent to Control Mixture C in compressive strength and splitting-tensile strength, showing the potential that up to 45% FGD-1 by mass of cement can be beneficially used, with one half of FGD-1 replacing cement and the other half functioning as filler.

In general, use of FGD-2 as an additional cementitious material resulted in lower strengths of permeable-concrete mixtures (**Table 5, Fig. 4, 5, 6**), in spite of the relatively good strength-activity index of FGD-2 (**Table 3**). Average splitting-tensile and flexural strengths of Mixture F2-1 were almost equivalent to those of Control Mixture C. The average compressive and flexural strengths of Mixture F2-2 were nearly as high as that of Control Mixture C. The average splitting-tensile strength of Mixture F2-2 was 6% higher compared with Control Mixture C. Overall, the permeable-concrete mixtures incorporating up to 30% FGD-2 by mass of cement as an additional cementitious material (Mixtures F2-1 and F2-2) were nearly equivalent to Control Mixture C in compressive, splitting-tensile, and flexural strengths.

Permeable-concrete mixtures made by replacing up to 45% of cement with VCA were, as a whole, equivalent to Control Mixture C in compressive, splitting-tensile, and flexural strengths (**Table 5, Fig. 7, 8, 9**). On average, the mixtures incorporating VCA showed slightly lower compressive strength, and slightly higher splitting-tensile strength and flexural strength than Control Mixture C.

RESISTANCE TO FREEZING AND THAWING

Test results for freezing-and-thawing mass loss of permeable-concrete mixtures incorporating FGD-1, FGD-2, and VCA are shown in **Fig. 10**, **11**, and **12**, respectively. The quantities of residue (spall) from the beams at the end of 50 cycles of freezing and thawing are included in **Table 5**.

Use of FGD-1 either as an additional cementitious material (Mixture F1-1) or as a partial replacement of cement (Mixtures F1-2 and F1-3) resulted in an increase in the amount of residue (spall) from permeable-concrete beams (lower resistance to freezing and thawing) (**Table 5**). However, the quantities of residue (spall) from Mixtures F1-1 and F1-2 were relatively low (0.26% and 0.22%). Mixture F1-3 showed very large values of residue (spall) due to freezing and thawing.

The amount of residue (spall) from Mixture F2-1 was equivalent to that of Control Mixture C (**Table 5**). Use of a high amount of FGD-2 as an additional cementitious material resulted in a lower freezing-and-thawing resistance. The quantities of residue (spall) from Mixtures F2-2 and F2-3 were about 4.5 times as much as that of Control Mixture C.

Replacement of 30% and 45% of cement with VCA resulted in either a little higher or equivalent resistance of permeable-concrete mixtures to freezing and thawing (**Table 5**) compared with Control Mixture. In spite of equivalent strength, Mixture V-1 made by replacing 15% of cement with VCA left about 5 times as much residue (spall) as Control Mixture C. The reason for this is not known.

CONCLUSIONS

Based on the results of this research on permeable base-course concrete mixtures, the following conclusions may be drawn:

1. Potentially, up to 45% (by mass of cement) high-carbon FGD-1, one half replacing cement and the other half considered a filler, could be used in a permeable-concrete mixture without affecting the compressive and splitting-tensile strengths significantly.
2. Permeable-concrete mixtures incorporating up to 30% FGD-1 showed small quantities of residue (spall) when subjected to 50 cycles of freezing and thawing (F&T). At 45% FGD-1, the resistance to F&T decreased significantly (higher residue [spall]).
3. Permeable-concrete mixtures incorporating up to 30% high-carbon FGD-2, by mass of cement, as an additional cementitious material, were nearly equivalent to Control Mixture in compressive, splitting-tensile, and flexural strengths.
4. Permeable-concrete mixture incorporating up to 15% FGD-2 was equivalent to Control Mixture in F&T resistance. At 30% and 45% FGD-2, the F&T resistance decreased.
5. When compared with Control Mixture, permeable-concrete mixture made by replacing up to 45% of cement with variable-carbon ash (VCA) showed equivalent compressive, splitting-tensile, and flexural strengths and F&T resistance, except for 15% cement replacement which resulted in a lower F&T resistance.

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Fig. 12—Residue (spall) from VCA permeable-concrete mixtures.

Table 1—Chemical properties of cement and coal-combustion products (CCPs)

Analysis parameter, %	Cement	ASTM C 150 req. for cement	CCP source			ASTM C 618 req. for fly ash	
			FGD-1	FGD-2	VCA	Class C	Class F
SiO_2	21.9	—	5.1	8.8	36.2	—	—
Al_2O_3	4.9	—	2.5	7.8	19.4	—	—
Fe_2O_3	3.0	—	1.2	2.5	6.2	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$	29.8	—	8.8	19.1	61.8	≥ 50.0	≥ 70.0
CaO	64.1	—	38.3	10.1	24.0	—	—
MgO	2.4	≤ 6.0	0.9	3.5	6.4	—	—
TiO_2	0	—	0.1	0.5	1.3	—	—
K_2O	0.5	—	0.2	0.6	0.5	—	—
Na_2O	0.1	—	0.3	7.2	2.1	—	—
C_3A	7.9	—	—	—	—	—	—
SO_3	1.4	≤ 3.0[*]	19.9	18.1	1.3	≤ 5.0	≤ 5.0
Loss on ignition (LOI)	1.7	≤ 3.0	14.4	33.2	1.7	≤ 6.0	≤ 6.0†
Moisture	0.9	—	0	0	0	≤ 3.0	≤ 3.0
Equivalent alkalies, $Na_2O + 0.658\ K_2O$	0.4	≤ 0.6‡	0.9	15.2	—	≤ 1.5‡	≤ 1.5‡

[*] When the amount of C_3A is 8% or less.

†The use of Class F pozzolan with up to 12.0% LOI may be approved by the user if either acceptable performance records or laboratory test results are made available.

‡Optional requirement for controlling alkali-silica reaction.

Table 2—Mineralogy of CCPs

Analysis Parameter, %	FGD-1	FGD-2	VCA
Quartz (SiO_2)	1.5	ND	11.4
Tricalcium Aluminate (C_3A, or $Ca_3Al_2O_6$)	ND	ND	5.6
Anhydrite ($CaSO_4$)	ND	11.3	2.3
Hematite (Fe_2O_3)	ND	ND	2.1
Lime (CaO)	17.2	ND	ND
Portlandite ($Ca(OH)_2$)	2.8	ND	ND
Periclase (MgO)	ND	2.0	3.4
Amorphous	28.8	73.1	75.3

ND: Not Detected.

Table 3—Physical properties of CCPs

	CCP source			ASTM C 618 req. for fly ash	
Test parameter	FGD-1	FGD-2	VCA	Class C	Class F
Amount retained when wet-sieved on the 45 µm sieve, %	24	30	22	≤ 34	≤ 34
Strength activity index with cement, % of control					
3-day	—	—	108	—	—
7-day	60	87	110	≥ 75	≥ 75
28-day	61	116	130	≥ 75	≥ 75
Water requirement, % of control	107	112	92	≤ 105	≤ 105
Autoclave expansion, %	0.05	0.26	0.05	≤ 0.80	≤ 0.80
Specific gravity	2.64	2.17	2.58	—	—

Table 4—Mixture proportions of permeable-concrete mixtures

CCP source	—	FGD-1			FGD-2			VCA		
Mixture designation	C	F1-1	F1-2	F1-3	F2-1	F2-2	F2-3	V-1	V-2	V-3
% cement replacement‡	0	0	15	22.5	0	0	0	15	30	45
% CCP‡	0	15	30	45	15	30	45	20	40	60
Cement, *c*, kg/m^3	116	122	104	89	117	110	126	104	85	68
CCP, 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
Coarse aggregate, saturated-surface dry, kg/m^3	1630	1700	1720	1620	1600	1510	1720	1680	1660	1700
w/cm	0.34	0.34*	0.34*	0.34*	0.32*	0.30*	0.28*	0.34†	0.34†	0.34†
Void content, %	32	28	27	31	32	35	25	29	29	27
Density, kg/m^3	1780	1880	1900	1800	1770	1680	1950	1850	1840	1890

‡Nominal percentages relative to the amount of cement in Mixture C.

*$w/(c + 0.5 \times \text{FGD-1})$, or $w/(c + 0.5 \times \text{FGD-2})$.

†$w/(c + \text{VCA})$.

Table 5—Average strengths and residue (spall) due to freezing and thawing (F&T) of permeable-concrete mixtures

CCP source	—	FGD-1			FGD-2			VCA		
Mixture designation	C	F1-1	F1-2	F1-3	F2-1	F2-2	F2-3	V-1	V-2	V-3
Avg. comp. str.*, MPa	7.11	7.76	5.06	6.41	5.58	6.07	3.58	6.69	6.94	6.58
Avg. splitting-tens. str.†, MPa	1.01	1.15	0.73	0.88	0.90	1.07	0.46	1.07	0.94	1.10
Avg. flex. str.‡, MPa	1.10	0.98	0.82	0.68	0.99	0.84	0.45	1.22	1.17	1.09
Residue (spall) due to 50 cycles of F&T, mass %	0.13	0.26	0.22	3.13	0.14	0.57	0.58	0.62	0.10	0.13

*Average of results from 3, 7, 28, 91, 182, and 365-day tests.

†Average of results from 7, 28, 91, and 182-day tests.

‡Average of results from 3, 7, 28, 91, and 182-day tests.

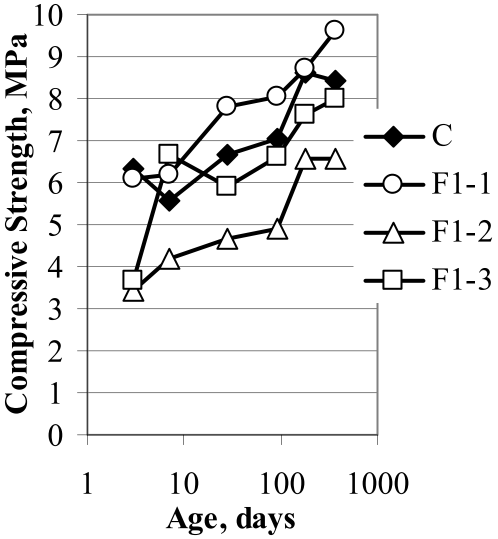

Fig. 1—Compressive strength of FGD-1 permeable-concrete mixtures.

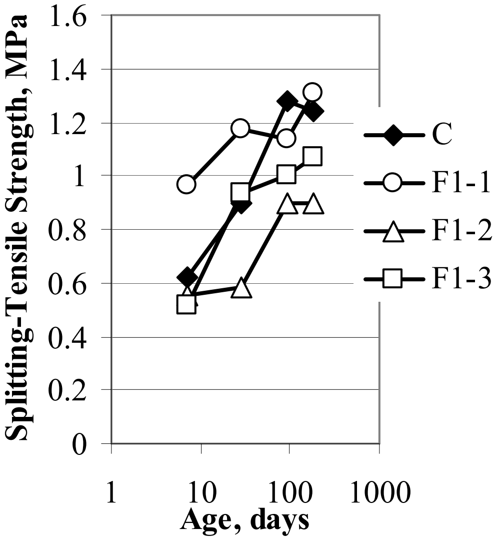

Fig. 2—Splitting-tensile strength of FGD-1 permeable-concrete mixtures.

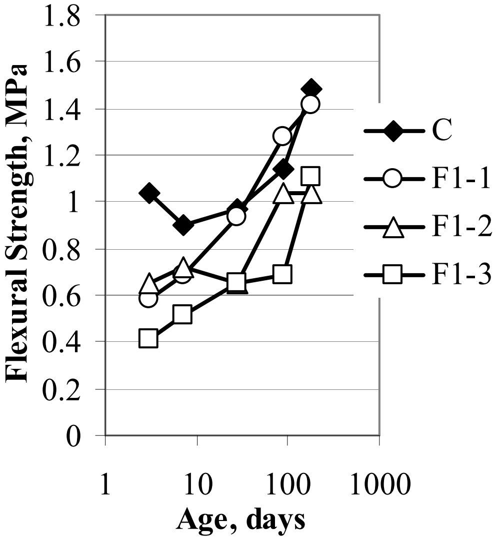

Fig. 3—Flexural strength of FGD-1 permeable-concrete mixtures.

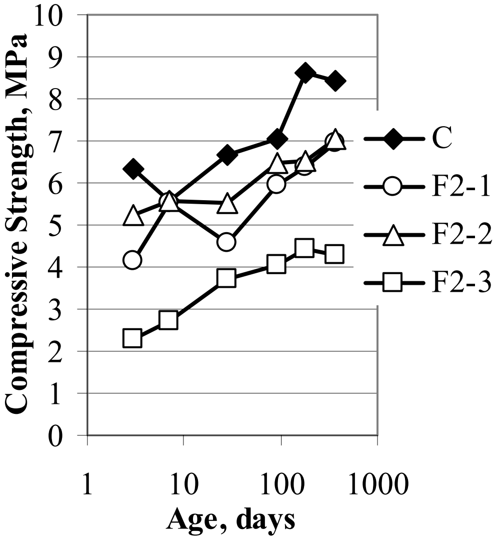

Fig. 4—Compressive strength of FGD-2 permeable-concrete mixtures.

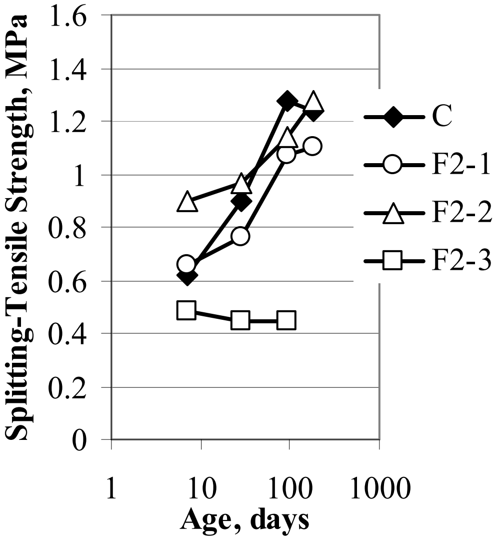

Fig. 5—Splitting-tensile strength of FGD-2 permeable-concrete mixtures.

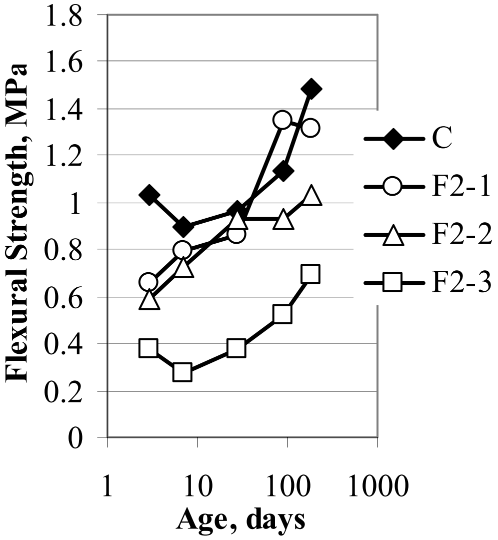

Fig. 6—Flexural strength of FGD-2 permeable-concrete mixtures.

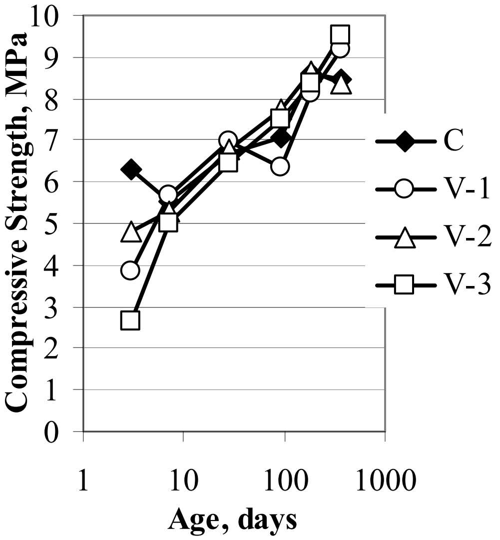

Fig. 7—Compressive strength of VCA permeable-concrete mixtures.

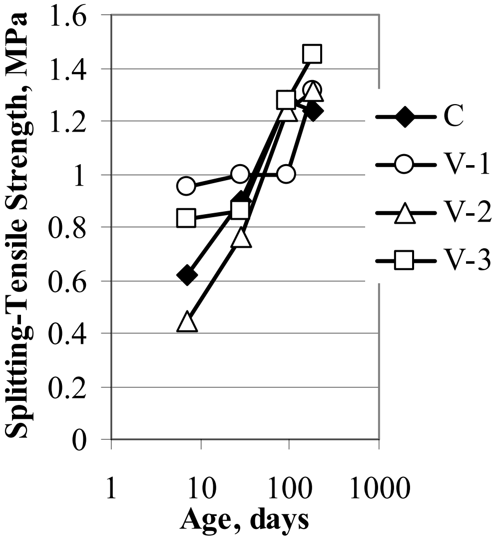

Fig. 8—Splitting-tensile strength of VCA permeable-concrete mixtures.

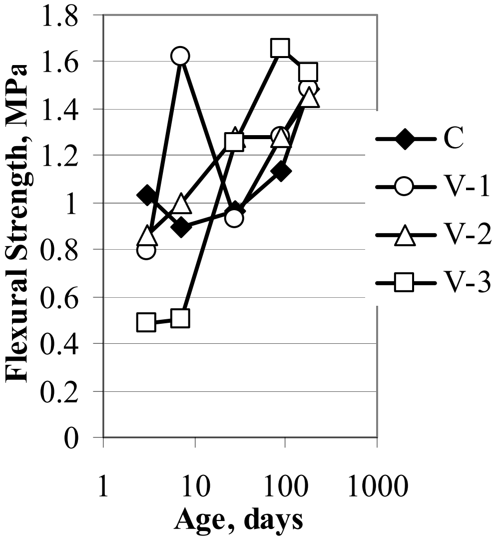

Fig. 9—Flexural strength of VCA permeable-concrete mixtures.

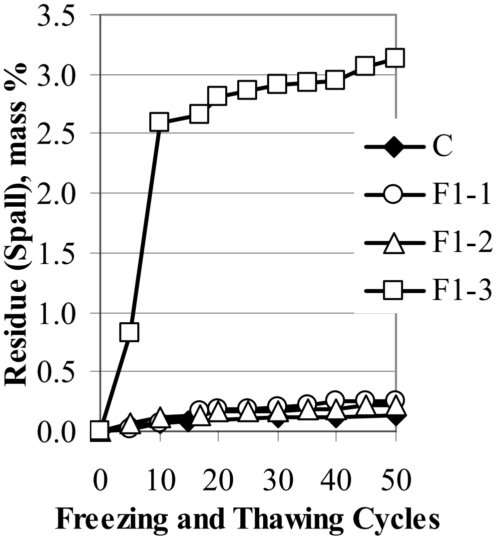

Fig. 10—Residue (spall) from FGD-1 permeable-concrete mixtures.

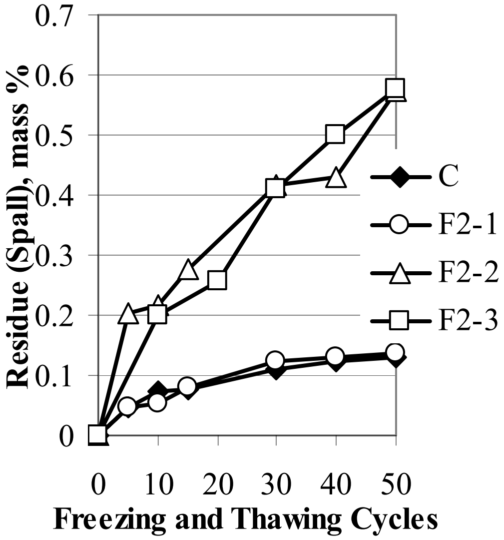

Fig. 11—Residue (spall) from FGD-2 permeable-concrete mixtures.

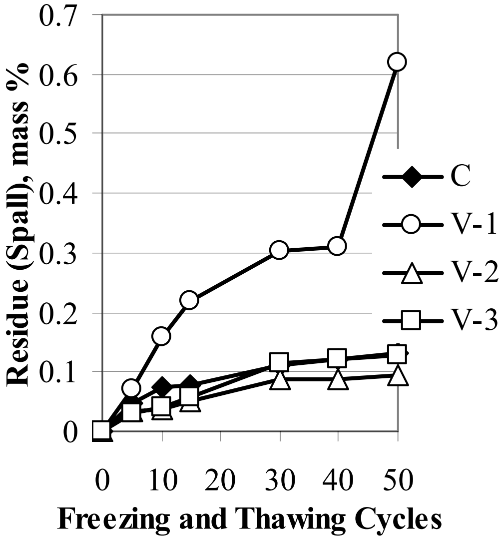

Fig. 12—Residue (spall) from VCA permeable-concrete mixtures.