

FINAL REPORT

**EVALUATION OF HIGH PERFORMANCE CONCRETE PAVEMENTS
IN NEWPORT NEWS AND HAMPTON, VIRGINIA**

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ABSTRACT

This study evaluated the properties of three high performance concrete mixtures placed in a jointed plain concrete paving project on I-64 in Newport News, Virginia, to reduce the shrinkage and improve the flexural strength of the concrete. Two mixtures contained ground-granulated blast furnace slag with 2-inch and 1-inch nominal maximum size (NMS) aggregate, and the third mixture contained Class F fly ash with 1-inch NMS aggregate.

Air-entrained paving concretes with satisfactory strength, low permeability, and dimensional stability were prepared using concretes with Class F fly ash or slag and 1-inch or 2-inch NMS aggregates. Slipform pavers satisfactorily placed these concretes. The test sections were in excellent condition after six winters based on a visual survey. Falling weight deflectometer data indicated a better load transfer with the larger aggregate size with everything else being equal.

The study also evaluated the maturity method in the continuation of the project on I-64 in Hampton, Virginia. After the evaluation, the pavement was changed to continuously reinforced concrete and the concrete properties were tested in accordance with the recently introduced *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (known as the proposed AASHTO M-E Design Guide). In the Hampton portion, a Class F fly ash mixture with the 1-inch NMS aggregate was used.

The use of large aggregate, provided the particle shape is acceptable, and uniform combined grading should be specified for concretes with reduced water and cement contents. The maturity method can be used to determine the pavement's readiness for opening to traffic and should be included in the specifications.

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INTRODUCTION

Hydraulic cement concrete pavements have generally performed well in harsh environments under high traffic volumes and heavy axle loads. However, moisture and temperature variations and repetitive traffic applications can lead to transverse cracking and premature failure in jointed pavements.¹ Such cracks can adversely affect load transfer and carrying capacity. The presence of free water beneath the slab also leads to distress. Therefore, open-graded drainage layers (OGDL) are commonly used to drain water under the concrete. When volumetric changes in concrete are restricted by friction between the slab and the base, high stresses may occur, leading to cracking. Friction increases when the mortar fraction of the concrete penetrates into the OGDL.² Reducing volumetric changes or friction forces between the slab and the base would reduce the potential for cracking.

In Virginia, paving mixtures must have at least 564 lb/yd³ of cementitious material; a maximum water–cementitious material ratio (w/cm) of 0.49; and aggregate with a No. 57 coarse aggregate grading, which has a nominal maximum size (NMS) of 1 inch. Concrete used as a riding surface must contain nonpolishing aggregates, i.e., siliceous aggregates. Class F fly ash or slag is commonly used for resistance to alkali-silica reactivity (ASR). To reduce shrinkage in concrete mixtures, a larger coarse aggregate size, leading to a lower water and paste content, is needed. Large aggregates also provide better interlock when cracks develop.

Aggregate with an NMS of 2 inches (No. 357) was common in pavements in Virginia built at least 25 years ago. The NMS was reduced to 1 inch beginning with the Virginia Department of Transportation's (VDOT's) 1978 *Road and Bridge Specifications*³ because of concerns with the availability, stockpiling, and segregation of the aggregate. In paving concrete, strength may increase with a larger aggregate because of a reduced w/cm even though larger aggregates have a reduced bond strength and an increased possibility of imperfections.⁴ Virginia's older pavements have generally performed well. At present, in airport runway construction, a maximum aggregate size larger than 1 inch is being used for better performance.⁵ Increases in maximum aggregate size are expected to reduce shrinkage.⁶ The main effect of the larger aggregate size on shrinkage is that more aggregate and less water can be used, leading to reduced shrinkage. The shape and texture of aggregates also affect shrinkage as they affect the water demand.

The need to reduce shrinkage and increase flexural strength is consistent with the high performance concrete (HPC) pavement program initiated by the Federal Highway

Administration. HPCs have enhanced specific properties, such as workability, durability, strength, and dimensional stability.⁷ They are expected to be cost-effective because of an extended service life with minimal maintenance. To construct durable pavements, attention should be paid to materials and mixture proportions, as well as to structural design, the environment, and construction practices.⁸

The strength development in concrete depends on the extent of hydration and pozzolanic reactions. These reactions occur with time and are dependent on temperature and the availability of water. The maturity method is a technique for estimating strength that is based on the assumption that samples of a given concrete mixture have equal strength if they have an equal maturity index (ASTM C 1074). The maturity index is calculated from the temperature history of the cementitious mixture using a maturity function.⁹ There are two maturity functions: one is the temperature-time factor where the temperature above a datum temperature is used since reactions cease below the datum temperature, and the other one is the equivalent age.

PURPOSE AND SCOPE

The purpose of this study was to evaluate properties and aggregate size in pavement in Newport News, the maturity method in pavement in Hampton, and the provisions of the recently introduced *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*¹⁰ (M-E Design Guide) in pavement in Hampton. All pavement sections are on I-64.

The specific objectives were as follows:

1. Evaluate the properties of high performance concrete mixtures placed in a jointed plain concrete pavement (JPCP) project on I-64 in Newport News, Virginia, to reduce shrinkage and improve the flexural strength of the concrete. Two experimental mixtures contained ground-granulated blast furnace slag with 2-inch and 1-inch NMS aggregate, and the third control mixture typically used in the entire project contained Class F fly ash with 1-inch NMS aggregate. The three mixtures were placed in the westbound lanes (WBL) and the eastbound lanes (EBL). The performance of the WBL after 6 years and the EBL after 5 years was determined.
2. Evaluate the maturity method in the continuation of the project in Hampton, Virginia. In this portion of the study, a control mixture with Class F fly ash and the 1-inch NMS aggregate was used.
3. Evaluate the provisions of the M-E Design Guide¹⁰ in the portion of the paving project that progressed into continuously reinforced concrete pavement (CRCP) in Hampton.

METHODOLOGY

Overview

In Newport News, the three sections were in the outer lanes. They were placed in 1998 in the WBL and in 1999 in the EBL. The following tasks were completed:

1. The concrete mixtures were developed, and trial batches were tested.
2. The characteristics of the pavement mixtures were determined.
3. The mixtures were placed in the test sections.
4. The pavement was instrumented, and data were collected for temperature, strain, and displacement.
5. The air-void distribution (indicative of the degree of consolidation) was determined from cores.
6. Condition surveys were conducted.

In 2001, the maturity method was evaluated in the continuation of the project from Newport News to Hampton. In this portion of the study, a control mixture with Class F fly ash and the 1-inch NMS aggregate was used in the JPCP. In 2002, the JPCP was changed to CRCP and the material properties were evaluated in accordance with the provisions of the M-E Design Guide.¹⁰

Properties and Aggregate Size in Newport News

The pavement in Newport News begins 1.471 miles west of Rte. 143 and ends at 0.911 mile east of Rte. 143 for a total length of 2.382 miles. The project involved removing and replacing the two lanes of I-64 and constructing an additional WBL and EBL. The old JPCP was more than 30 years old and had served well, considering the design life of 20 years. It had welded mesh as reinforcement and a joint spacing of 61.5 ft. Transverse in-panel cracking was evident, and numerous joints showed spalling and faulting. Inverted T and floating patches without dowels for load transfer were placed but did not perform as desired. There was no drainage, the pavement was 9 inches thick, and a 2-inch NMS aggregate was used.

Trial Batches

Trial batches were made at the plant and laboratory. The batches contained either 1-inch or 2-inch NMS coarse aggregate complying with the requirements for No. 57 or No. 357 grading, respectively. The No. 357 coarse aggregate grading was obtained by blending No. 3 and No. 57 stone. For 2-inch NMS aggregate, a uniform grading of fine and coarse aggregates was sought, as indicated in Table 1. The goal was to provide a uniform blend with 8 to 18 percent retained

Table 1. Percent Retained on Sieve for Combined Aggregate

Sieve (in)	No. 3	No. 57	Sand	Combined ^a
2 1/2	0	0	0	0
2	2	0	0	0.5
1 1/2	38	0	0	8.7
1	46	1	0	11.0
3/4	8	17	0	8.5
1/2	3	46	0	18.6
3/8	3	23	0	9.7
No. 4	0	10	0.5	4.1
No. 8	0	1.5	16.7	6.9
No. 16	0	1.5	22	8.9
No. 30	0	0	19.7	7.5
No. 50	0	0	19.7	7.5
No. 100	0	0	18.6	7.1

^aTo obtain the combined aggregate, 23% by weight No. 3, 39% No. 57, and 38% sand was used.

on each sieve, except for the largest and smallest sieves. The percent retained ranged from 4.1 to 18.6. The percent retained on the No. 4 and No. 8 sieves was 4.1 and 6.9, respectively. Because the two consecutive sizes were less than 8 percent each, gap grading would occur with high water and paste contents. Therefore, marginal water reductions were expected and were realized.

The coarse aggregate was crushed biotite gneiss and granite with a specific gravity of 2.68 and an absorption of 0.6 percent. The dry-rodded unit weight of the No. 57 coarse aggregate was 104 lb/ft³ and of the No. 3 and No. 57 aggregate blend was 102 lb/ft³. Fine aggregate was natural sand with a fineness modulus of 2.80, a specific gravity of 2.62, and absorption of 0.6 percent. Type II cement was used.

The contractor's representative tested the finishing characteristics of the plant mixtures. The trial batches indicated that concrete with a 2-inch NMS aggregate could be prepared and finished satisfactorily to yield a minimum required flexural strength of 650 psi at 28 days using third-point loading (ASTM C 78).

Pavement

The new pavement placed in the project is plain concrete with a transverse joint spacing of 15 feet and a thickness of 11 inches. It was placed on a 3-inch, asphalt-stabilized OGD. The layer complied with the requirements of No. 57 grading and had 2.5 percent asphalt by weight. A cement-treated aggregate base 6 inches thick is below the drainage layer. The width of the inside lane is 12 feet and that of the outside lane is 14 ft, including 2 feet of shoulder. The remainder of the shoulder is asphalt concrete. The joints were saw-cut after placement as soon as possible without raveling the aggregates. The depth of cut was one-third the thickness of the slab.

The contractor used fly ash concrete for the regular pavement operation. The three sections to be investigated in this study were placed in the outside lanes in November 1998 in the

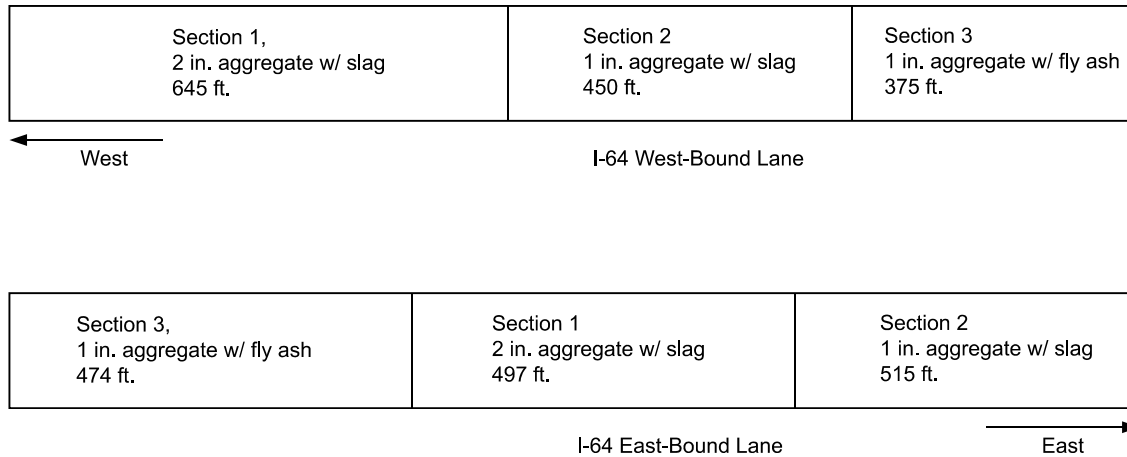


Figure 1. Test Sections.

WBL and in July 1999 in the EBL using the fly ash concrete and two additional concretes with slag, as indicated in Figure 1.

Mixtures

The three concrete mixtures used in the trial batches were also used in the experimental mixtures and are described in Table 2. Slag mixtures had 30 percent slag and either 2-inch NMS aggregate (Slag 2) or 1-inch NMS aggregate (Slag 1). There is a relationship between the slag content and the alkali content for controlling ASR.¹¹ VDOT specifies a slag content of at least

Table 2. Mixture Proportions for Pavement Concretes (lb/ft³)

Material	Slag 2	Slag 1	Fly Ash 1
PC	375	395	423
Slag	160	169	--
Fly ash	--	--	141
Pozzolan %	30	30	25
CA No.	357	57	57
CA	1935	1840	1840
FA	1171	1217	1229
Water	242	250	250
W/(C+M)	0.45	0.44	0.44
Admixture	AEA&R	AEA&R	AEA&R
Length (ft)	497	515	474

PC = portland cement, CA = coarse aggregate, FA = fine aggregate, AEA = air-entraining admixture, R = retarding admixture.

35 percent to prevent ASR for a cement alkali content between 0.60 and 0.90 percent. For cement alkali contents of 0.60 percent and below, 25 percent slag is acceptable. The cement used had an alkali content of 0.59. Because of cold weather, a slag replacement rate of 30 percent was selected. In the fly ash section, a 25 percent replacement rate was used. The same coarse and fine aggregates and the same blend of No. 3 and No. 57 coarse aggregates as in the trial batches were used.

The use of 2-inch NMS aggregate necessitated the use of less water, 8 lb/yd³, and less cementitious material, 29 lb/yd³, than with the mixtures with 1-inch NMS aggregate. Thus, the water and paste contents were less with the larger size aggregate even though the reductions were small. Better aggregate grading and a better particle shape would have enabled larger reductions.

Two batches for each section in the WBLs and EBLs were sampled. Concretes were tested in the fresh state for air content (ASTM C 231), slump (ASTM C 143), temperature (ASTM C 1064), and density (unit weight, ASTM C 138), and specimens were prepared for tests at the hardened state as indicated in Table 3.

Table 3. Tests and Specimen Sizes for Pavement Concretes

Tests	Specification	Age	Specimen Size (in)
Compressive strength	AASHTO T 22	7 and 28 d, 1 y	4 x 8 and 6 x 12
Flexural strength	ASTM C 78	28 d	3x3x11¼ and 6 x 6 x 20
Elastic modulus	ASTM C 469	28 d	4 x 8 and 6 x 12
Permeability ^a	AASHTO T 277	28 d	2 x 4
Drying shrinkage ^b	ASTM C 157		3x3x11¼ and 6 x 6 x 20
Freezing and thawing	ASTM C 666 ^c		3 x 4 x 16

^aMoist cured 1 week at 73° F and 3 weeks at 100° F.

^bMoist cured for 7 days.

^cProcedure A, except that specimens were air dried for at least 1 week before testing and the test solution contained 2% NaCl.

Placement

The outer lanes were 14 feet wide . Concrete mixtures were placed in three sections, starting at the west end. Dowels were epoxy coated except at the ends and spaced 1 foot apart. They were 18 inches in length and 1.25 inches in diameter, and they were coated with grease to enable movement. Dowel baskets were placed before the concrete was placed at the joint locations and secured to the OGD. L.

The pavement was slip-formed. The paving train had three units: a spreader in the front, then a slipform paver that consolidated and screeded the concrete, and then a texturing and curing unit. The vibrators in the paver had a cross section of 2 inches by 2 inches and were spaced 18 inches apart. The vibrators were operating at a high frequency, about 10,000 vibrations per minute. Paving was completed satisfactorily with no discernible difference among the mixtures.

Behind the paver, the surface was bull floated manually. Then, the third unit dragged wet burlap and pulled metal tines in the transverse direction to texture the surface. In general, a wax emulsion-curing compound was used except that the contractor had difficulty obtaining a specification material during placement of the experimental sections in the WBL and used white plastic sheeting for 10 days to cure the concrete. In all three sections of the WBL, most of the plastic sheeting was placed later in the day after the transfer joints were saw-cut. The first cut was 3/16 inch wide and one-third the depth of the pavement. A second cut was made 2 weeks later to widen the joints. The joints were sealed with silicon after a backer rod was placed.

Field Instrumentation and Testing of Slabs

In the WBL, a comprehensive testing program composed of three groups of tests was conducted:

1. *Temperature, strains, and displacements were measured in three slabs, one in each section.* A thermocouple was placed at ¼ inch, 3.0 inches, 5½ inches (mid-depth), 8.0 inches, and 10¾ inches above the base. In addition, vibrating wire gages had thermistors, which provided temperatures at the level of the gages.

Strains at the middle of the slabs were determined using two vibrating wire gages. One gage was placed 1.5 inches from the bottom and the other 1.5 inches from the top in the direction of the traffic. The two gages were tied to two stainless steel stakes ½ inch in diameter driven into the base. The gages were placed 6.5 feet from the outside edge and avoided the vibrator of the paver.

To measure vertical displacements for curling, two linear variable differential transformers (LVDTs) were placed 1 week later in two of the experimental sections containing slag. Both were placed on the outside edge, one at midlength and the other 11 inches from the joint. The LVDTs were attached to the pavement and were touching a stake ¾ inch in diameter about 1.5 feet long driven into the ground. The LVDTs were located in an iron pipe 4.0 inches in diameter to protect them from the environment. There were only four LVDTs, and they were placed in the slabs with slag concrete containing 2-inch NMS aggregate.

A falling weight deflectometer (FWD) was used to determine the transfer of load across the joint. The FWD imparts a series of impact loads and measures the deflection at each impact point.

2. *Cores were taken to determine the air-void system.* Two cores 4 inches in diameter were obtained from each section. The cores were cut in two sections, top and bottom, and subjected to linear traverse analysis (ASTM 457) to determine the air content and spacing factor.

3. *Transverse joint movement was determined.* The transverse joint movement was determined by measuring the distance between two studs located on each side of the joint by a Whittemore gage. For each section, 10 consecutive joints were instrumented to obtain an average value. Gages were placed 1 week after placement, and the first reading was taken 1 day

after placement of the gages. Gage points were spaced about 10 inches apart. Studs were placed 1 foot from the outside edge to enable further readings without blocking the lane.

Condition Survey

The concrete pavement was surveyed visually on March 1, 2004, for distress, including scaling and cracking.

The Maturity Method and the M-E Design Guide

Maturity Method

The JPCP constructed in Hampton in 2001 begins at milepost 261 on I-64 and ends at milepost 262 on the EBL. The concrete was sampled and tested mainly to evaluate the maturity method in June.

Materials

The concrete for the 2001 placement had the mixture proportions listed in Table 4, which were similar to those of the fly ash mixture used earlier in Newport News. Two data loggers were placed in the concrete, one on milepost 261 and the second 200 feet before milepost 262. Fly ash was added at a replacement rate of 25 percent of total cementitious material. Type II cement was used. Aggregates similar to those described earlier were used.

Table 4. Mixture Proportions for Hampton Section (lb/yd³)

Material	2001	2002
Cement	443	472
Fly ash	147	118
Fine aggregate	1178	1220
Coarse aggregate	1837	1763
Water	244	250

Testing

For the 2001 JPCP, three batches of concrete were tested in the fresh state for air content, slump, temperature, and density (unit weight). Specimens from the same three batches were cast for tests in the hardened state.

To determine the maturity of the concrete, thermocouples were placed in the pavement to measure the temperature. The cumulative product of a temperature above 32 °F and time provided the maturity (temperature-time factor). A relationship was established between compressive and flexural strengths of specimens and the temperature-time factor. This relationship was used to determine the strength of the pavement in place. The temperature-time factor in the field was determined from the temperature at mid-depth and the time elapsed.

Condition Survey

This section of JPCP was not opened to traffic.

The M-E Design Guide

The CRCP constructed in 2002 was between milepost 262 and 263 on the EBL. The concrete was sampled in August. The mixture proportions are given in Table 4.

For the 2002 CRCP, three batches of concrete were tested. At the hardened state, the concrete was tested at the ages recommended in the M-E Design Guide.¹⁰ The variables determined were compressive and flexural strength, splitting tensile strength, thermal coefficient of expansion, modulus of elasticity, and Poisson's ratio. In addition, permeability and shrinkage were determined.

Condition Survey

This section of CRCP was not opened to traffic. Transverse cracks in a 400-foot section were measured to determine the crack spacing.

RESULTS

Properties and Aggregate Size

Properties of Concrete

WBL

The characteristics of the freshly mixed concrete are given in Table 5. The specified slump was 0 to 2 inches, and the specified air content was 6 ± 2 percent. The slumps complied with the requirements of the specifications, and the concrete was consolidated and finished with ease. The presence of large aggregates did not raise any problems for the slipform paving operation. The air contents also complied with the specifications.

The properties of the hardened concretes are given in Table 6. Compressive strengths increased with age, resulting in high values at 1 year. Flexural strengths at 28 days were slightly lower than specified in some batches, especially the fly ash concretes. However, compressive strengths increased more than enough to indicate satisfactory flexural strength values with age. Permeability values were much lower than the maximum required value of 3500 for

Table 5. Characteristic of Freshly Mixed Concrete for Westbound Lane

Test	Slag 2		Slag 1		Fly Ash 1	
	B1	B2	B3	B4	B5	B6
Slump (in)	1.75	1.25	1.25	1.25	1.5	1.0
Air (%)	5.5	5.0	6.5	5.1	5.6	5.3
Concrete temperature (°F)	68	67	68	68	68	67
Unit weight (lb/ft ³)	144.4	144.1	143.6	147.6	143.2	144.4

Table 6. Properties of Hardened Concretes for Westbound Lane

Test	Age	No. Specimens	Size (in)	Slag 2		Slag 1		Fly Ash 1	
				B1	B2	B3	B4	B5	B6
Compressive strength (psi)	1 d	1	6 x 12	1040	1160				
	7 d	2	6 x 12	2870	2860				
	28 d	2	6 x 12	4430	4630	4450	4800	4120	3720
	1 yr	2	6 x 12	5740	5460				
	1 d	1	4 x 8			890	820	890	780
	7 d	2	4 x 8			3060	3160	2720	3000
	28 d	2	4 x 8			4830	5040	3960	3720
	1 yr	2	4 x 8			6310	6680	6500	6760
Elastic modulus (10 ⁶ psi)	28 d	2	6 x 12	3.64	3.54	3.34	3.48	3.12	3.10
	28 d	2	4 x 8			4.14	4.00	3.50	3.51
	1 yr	2	6 x 12	4.36	4.40				
	1 yr	2	4 x 8			4.87	4.85	4.56	4.68
Flexural strength (psi)	7 d	1	6 x 6 x 20	555	485	565	580		
	28 d	2	6 x 6 x 20	700	640	640	730		
	7 d	1	3 x 3 x 11¼			600	665	555	515
	28 d	1	3 x 3 x 11¼			740	715		
	28 d	3	3 x 3 x 11¼					625	610
Permeability (coulombs)	28 d	2	4x4	1848	1700	1719	1624	1322	1208
Shrinkage (%)	28d	2	6 x 6 x 14	0.0310	0.0300	0.0348	0.0358		
	28d	2	3 x 3 x 11¼					0.0385	0.0345
	90d	2	6 x 6 x 14	0.0430	0.0430	0.0470	0.0495		
	90d	2	3 x 3 x 11¼					0.0531	0.0477
Shrinkage (%)	1 yr	2	6 x 6 x 14	0.051	0.052	0.057	0.061		
	6 mo	2	3 x 3 x 11¼					0.054	0.050

low-permeability paving concrete. Fly ash concretes had lower permeability. Shrinkage values were lower than the 400-microstrain limit at 28 days recommended for pavements containing pozzolans or slag.¹² Shrinkage values were similar, with Slag 2 having slightly less shrinkage than Slag 1. Large reductions in shrinkage did not occur mainly because of marginal reductions in water and paste contents with the use of larger size aggregates.

The freezing and thawing data are given in Table 7. The acceptance criteria at 300 cycles were a weight loss of 7 percent and less, a durability factor of 60 and more, and a surface rating (ASTM C 672) of 3 or more. Concretes complied with these requirements except that the fly ash concretes had a higher weight loss and surface rating than required. However, this laboratory test is severe, and fly ash concretes are expected to perform satisfactorily in the field provided they have adequate strength and an adequate air-void system.¹³

Table 7. Freezing and Thawing Data at 300 Cycles

Lane	Section	Weight Loss (%)	Durability Factor	Surface Rating
WBL	Slag 2	4.0	91	1.8
	Slag 1	6.0	89	2.3
	Fly ash 1	14.1	83	3.9
EBL	Slag 2	5.3	69	1.7
	Slag 1	2.3	88	1.2
	Fly ash 1	11.6	82	2.4

EBL

The characteristics of the freshly mixed concrete are given in Table 8. Slumps complied with the specifications as did the air contents except for Slag 1 for slump and Slag 2 for air.

The properties of hardened concretes are given in Table 9. The strengths were generally higher and the permeability lower than the WBL values, but they showed trends similar to those of the WBL concretes. Shrinkage values were low, with Slag 2 having slightly less shrinkage than Slag 1.

The freezing and thawing data given in Table 7 show that concretes complied with the specifications except that the fly ash concretes had a higher weight loss than required. The Slag 2 from the EBL had a low durability factor compared with that of the other mixtures because one of the batches had a failing durability factor of 46. The failing batch had an air content of 3.4 percent, which is below the lower specification limit of 4 percent.

Table 8. Characteristics of Freshly Mixed Concrete for Eastbound Lane

Tests	Slag 2		Slag 1		Fly Ash 1	
	B1	B2	B3	B4	B5	B6
Slump (in)	0.5	1.25	1.25	2.5	1.5	1.5
Air (%)	3.4	5.2	4.9	5.0	4.2	--
Concrete temperature (°F)	87	86	84	87	82	--
Unit weight (lb/ft ³)	148.4	142.8	146.8	147.2	--	147.6

Table 9. Properties of Hardened Concretes for Eastbound Lane

Test	Age	No. Specimens	Size (mm)	Slag 2		Slag 1		Fly Ash 1	
				B1	B2	B3	B4	B5	B6
Compressive strength (psi)	1 d	1	6 x 12	2890	2000				
	7 d	2	6 x 12	4490	3940				
	28 d	2	6 x 12	5750	5150	5780	5300	4920	4310
	1 yr	2	6 x 12	6070	6330				
	1 d	1	4 x 8			1900	1830	1910	2880
	7 d	2	4 x 8			4040	4300	3680	3360
	28 d	2	4 x 8			5970	5880	5260	4400
	1 yr	2	4 x 8			7100	6850	7410	6640
Elastic modulus (10 ⁶ psi)	1 yr	2	6 x 12	4.95	4.45				
	1 yr	2	4 x 8			5.00	5.33	5.53	4.57
Flexural strength (psi)	7 d	1	6 x 6 x 20	500	545	645	620		
	28 d	2	6 x 6 x 20	730	675	785	785		
	7 d	2	3 x 3 x 11¼					560	495
	7 d	1	3 x 3 x 11¼			665	585		
	28 d	1	3 x 3 x 11¼			715	840		
	28 d	2	3 x 3 x 11¼					640	635
Permeability (coulombs)	28 d	2	4x4	1224	1504	1511	1584	700	660
Shrinkage (%)	28 d	2	6 x 6 x 14	0.0193	0.0275	0.0230	0.0295		
	28 d	2	3 x 3 x 11¼					0.0365	0.0365
	90 d	2	6 x 6 x 14	0.0295	0.0375	0.0320	0.0390		
	90 d	2	3 x 3 x 11¼	0.038	0.044	0.040	0.047	0.0443	0.0400
	1 yr	2	6 x 6 x 14						
	1 yr	2	3 x 3 x 11¼					0.046	0.046

Field Testing

WBL

The temperature data from the top gage for the first 72 hours are given in Figure 2. In Figure 3, the differences between the top and bottom gage are given to display the thermal gradient. Results indicate that the heat generation attributable to hydration in the beginning shows different temperature profiles, especially since the concretes were prepared at different times. The difference in temperature between different sections became smaller with age. The thermal gradients were largest for Slag 1, then Slag 2, followed by fly ash concrete. However, the differences were small, within a few degrees, which could be largely influenced by the accuracy of the instrument and the exact location of the thermocouples.

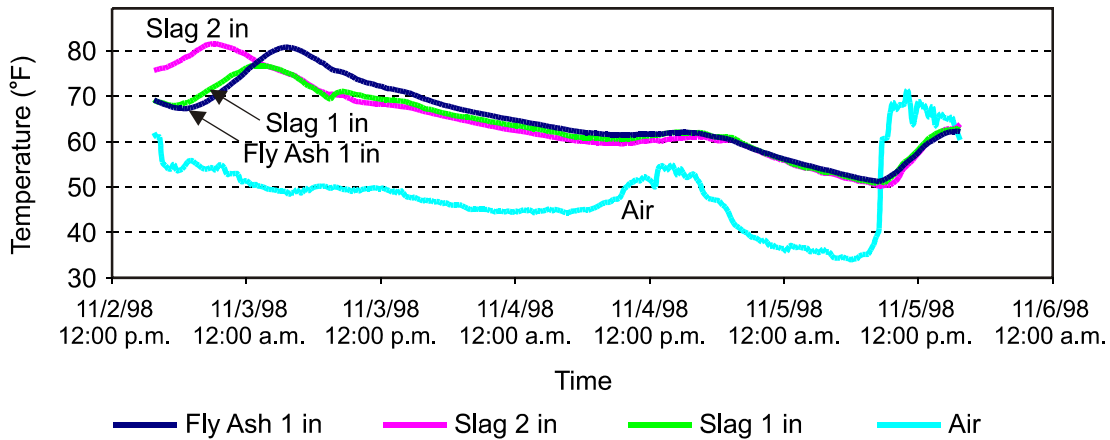


Figure 2. Temperature Data From Top Gage for First 72 Hours.

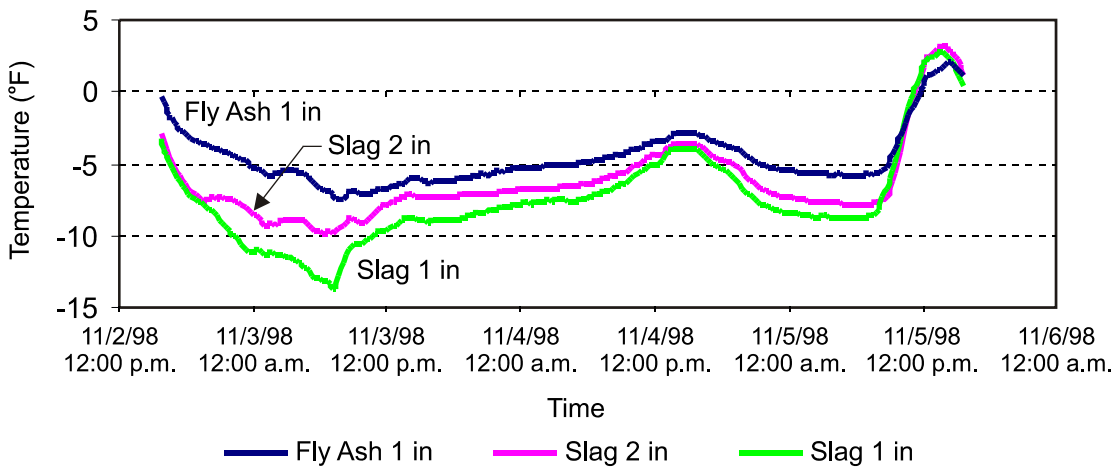


Figure 3. Temperature Difference Between Top and Bottom Gages for First 72 Hours.

The difference in strains between the top and bottom at 3 weeks is shown in Figure 4. The results indicate that fly ash had the smallest difference followed by the Slag 1 and Slag 2 concretes. However, the values and differences were very small.

The difference between the edge and center displacement at 1 week indicated that Slag 1 had higher values than Slag 2. However, the values and differences were small, as indicated in Figure 5.

The FWD data are summarized in Table 10. When the data were obtained, the maximum and minimum temperatures for December 8, 1998, were 79 °F and 58 °F, respectively. On January 8, 2004, the temperatures ranged from 38 °F to 22 °F. The average percent load transfer at the joints was compared at the 5 percent significance level. The analysis is summarized in Table 11.¹⁴ The analysis assumed that the variability of each section is unknown. There was more variability in the 2004 values attributed to cold weather, which causes opening of the joints. Slag 2 had higher values than Slag 1, indicating better load transfer across the joint, attributed to the use of larger aggregate. Fly ash 1 had higher load transfer than Slag 1, indicating that other factors were also effective in the load transfer. Figure 6 illustrates the comparison in percent load transfer between 1998 and 2004.

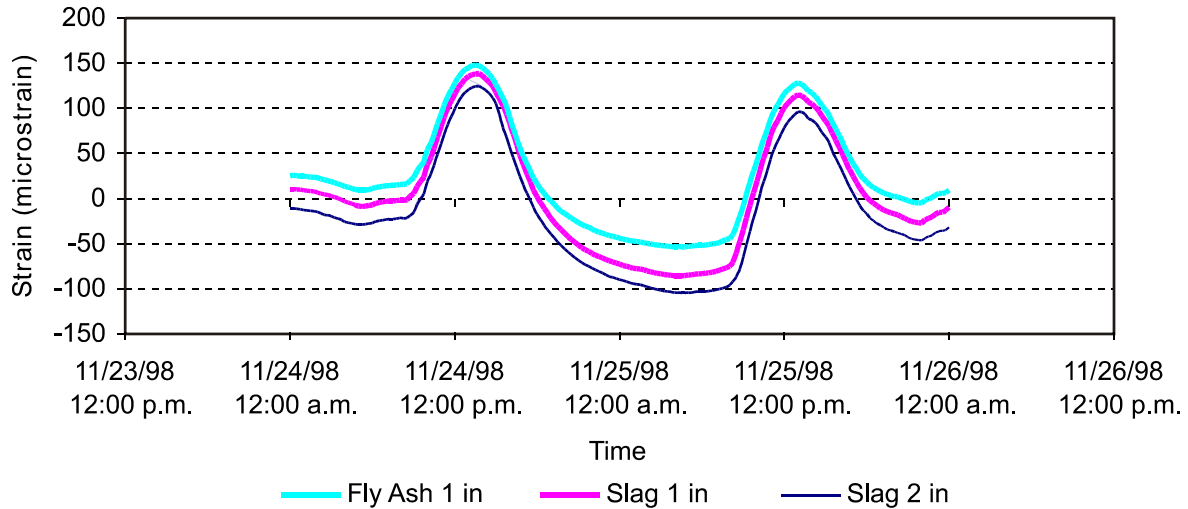


Figure 4. Strain Difference Between Top and Bottom Gages After 3 Weeks.

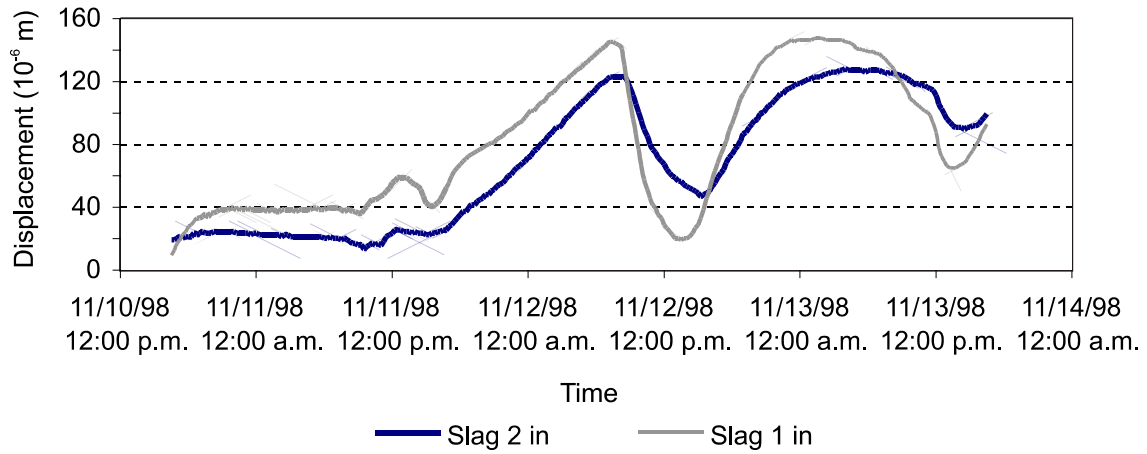


Figure 5. Displacement Gradient for First 72 Hours.

Table 10. FWD Testing for Westbound Lane

Mixture	Statistic	1998	2004
		Joints Load Transfer (%)	Joints Load Transfer (%)
Fly ash 1	Average	85	81
	St. Dev.	12	9
	COV	15	11
Slag 1	Average	85	65
	St. Dev.	11	23
	COV	13	35
Slag 2	Average	88	78
	St. Dev.	10	15
	COV	11	19

Table 11. Statistical Analysis of Percent Load Transfer

Mixture	Average	St. Dev.	n	$t_{0.975}$	u	Different
Slag 2	78	15	42			
Slag 1	65	23	30			
Slag 2 -Slag 1	13			2.02	9.69	Yes
Fly Ash 1	81	9	25			
Slag 1	65	23	30			
Fly Ash 1 -Slag 1	16			2.02	9.23	Yes

$u = t_{0.975} \sqrt{[(s_a^2/n_a) + (s_b^2/n_b)]}$. If the absolute value of average difference is larger than “u,” average performance is different.

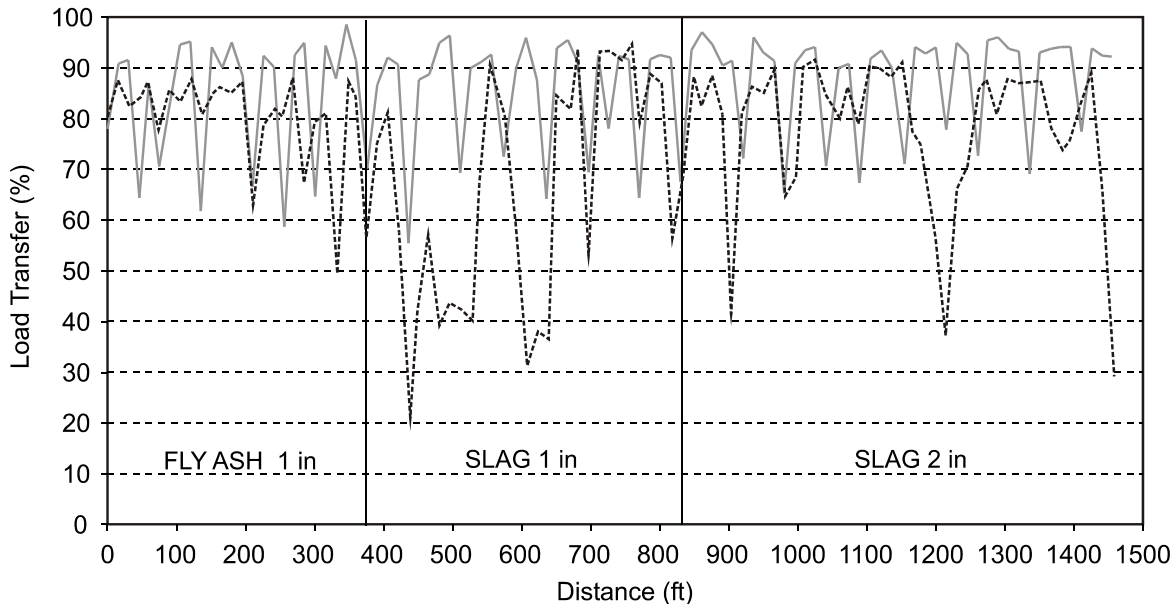


Figure 6. Percent Load Transfer for 1998 and 2004.

The results of the air-void analysis for the tops and bottoms of cores are given in Table 12. The total air contents were close to the upper specification limit. The voids are separated into two groups: those smaller than 1 mm and those larger than 1 mm. The larger voids in amounts larger than 2 percent indicate a lack of proper consolidation provided excess water is not present. The results indicated that three of the six cores had inadequate consolidation in some part of the core. Variability was higher on the top sections. The spacing factors were less than 0.20 mm, indicating satisfactory resistance to cycles of freezing and thawing. The strengths were satisfactory, indicating that excess water was not present.

In the cores, the interface between the asphalt base layer and the concrete could not be sheared since the asphalt layer was not rigid enough for a firm hold.

The average change in joint movement is given in Table 13 and indicated that the slabs were shrinking and the joint spacing was getting wider. However, the movement and the difference in movement between sections were small.

Table 12. Air Voids in Concrete Cores for Westbound Lane

Mixture		Voids > 1 mm (%)		Total Air (%)		Spacing Factor	
		Core 1	Core 2	Core 1	Core 2	Core 1	Core 2
Slag 2	Top	0.2	3.0	3.7	8.0	0.13	0.13
	Bottom	1.7	1.4	7.9	7.3	0.12	0.12
Slag 1	Top	0.9	1.5	6.0	6.3	0.12	0.12
	Bottom	1.6	0.9	8.3	8.0	0.11	0.10
Fly ash 1	Top	1.3	2.9	8.1	9.3	0.09	0.10
	Bottom	2.3	2.2	10.2	9.5	0.09	0.10

Table 13. Average Joint Spacing

No.	WBL		EBL	
	Temp (°F)	Spacing (in)	Temp (°F)	Spacing (in)
<i>Slag 2</i>				
1	67	-0.003	107	0.006
2	63	-0.008	102	-0.004
3	68	-0.007	73	-0.020
4	57	-0.011	88	-0.008
5			97	-0.005
<i>Slag 1</i>				
1	62	-0.003	107	0.005
2	62	-0.012	104	-0.002
3	68	-0.016	73	-0.016
4	53	-0.019	88	0.000
5			97	-0.006
<i>Fly ash</i>				
1	65	-0.005	107	0.004
2	60	-0.010	95	-0.002
3	66	-0.009	73	-0.023
4	56	-0.015	88	-0.011
5			93	-0.010

Condition Surveys

The experimental sections are in excellent condition, with no cracking or scaling, after six winters of exposure to weather and traffic in the WBL and after five winters in the EBL.

The Maturity Method

For the 2001 project, the air content, slump, concrete temperature, and density (unit weight) are given in Table 14 for all three batches. The specified values for air content and slump were within the specified range. The unit weight of Batch 3 was slightly higher than that of the other two, which is attributed to the lower air content.

Table 14. Characteristics of Freshly Mixed Concrete for 2001

Tests	B1	B2	B3
Air (%)	5.4	5.6	5.0
Slump (in)	1.75	0.9	1.0
Concrete temperature ((°F)	77	81	88
Unit weight (lb/ft ³)	146.0	146.0	148.4

The results for the hardened concrete are given in Table 15. Satisfactory strength and permeability were obtained. The compressive and flexural strength and temperature-time factor relationship are given in Figures 7 and 8. The relationship is used to determine the pavement strength with age, as shown in Figure 9. The design strength of 650 psi was obtained in 11 days, much earlier than 28 days, and corresponded to a compressive strength of 3,690 psi. Shrinkage values were low and satisfactory.

There is a good relationship between the compressive strength and flexural strength as shown in Figure 10. Pavement design is based on flexural strength; however, testing for flexural strength is not as convenient as the compressive strength testing and the variability is higher. Therefore, current VDOT paving projects develop relationships between compressive strength and flexural strength and base acceptance of field concrete using the compressive strength.

Table 15. Hardened Concrete Properties for 2001

Test	Age	B1	B2	B3
Compressive strength (psi)	1d	--	2060	1950
	3 d	2620	2750	2780
	7 d	2740	3250	3340
	14 d	3240	3620	3700
	28 d	3880	4190	4330
	1 yr	5550	6120	6240
Flexural strength (psi)	3 d	450	490	525
	7 d	520	525	560
	14 d	650	650	665
	28 d	675	725	725
	1 yr	780	855	895
Permeability (coulombs)	28d	558	384	471
Shrinkage	28 d	0.036	0.036	0.037
	90 d	0.046	0.045	0.040
	6 mo	0.050	0.055	0.048
	1 yr	0.050	0.056	0.050

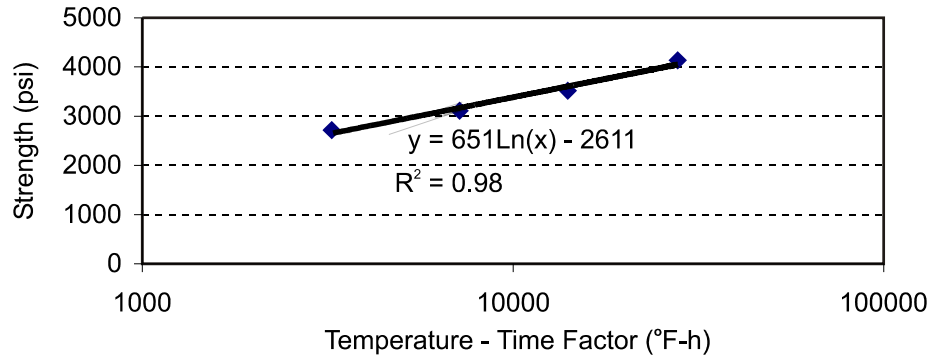


Figure 7. Relationship Between Compressive Strength and Temperature-Time Factor (2001).

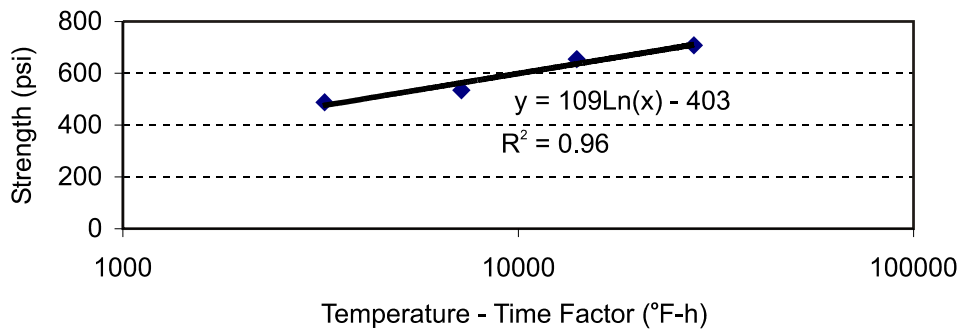


Figure 8. Relationship Between Flexural Strength and Temperature-Time Factor (2001).

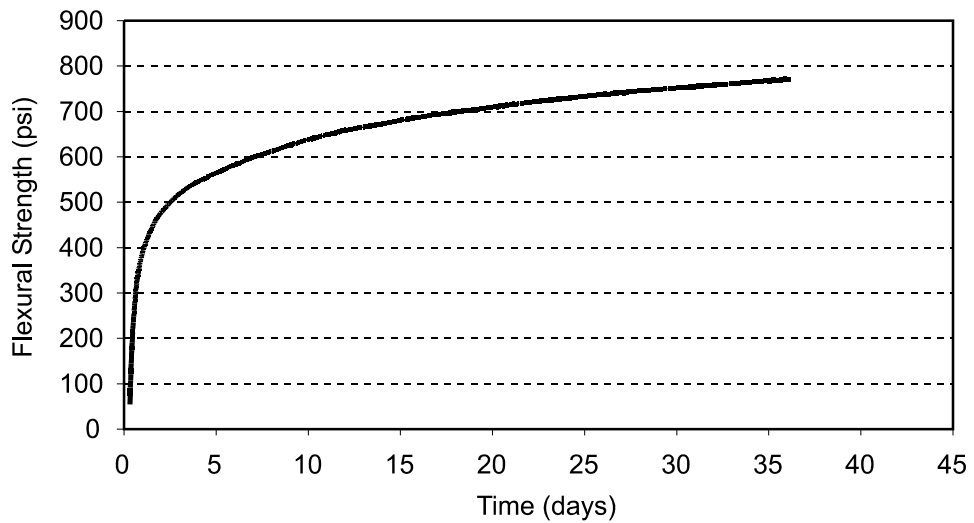


Figure 9. Relationship Between Compressive Strength and Age (2001).

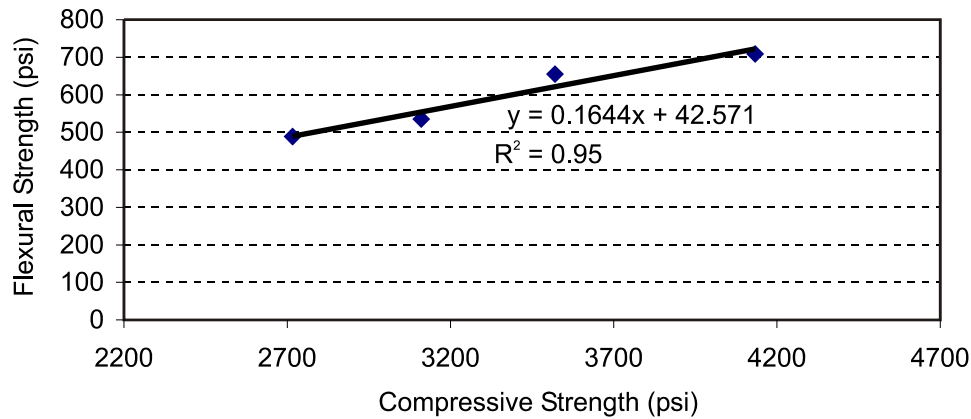


Figure 10. Relationship Between Compressive Strength and Flexural Strength (2001).

Condition Surveys

This section was not open to traffic, and there was no visible distress.

The M-E Design Guide

For the 2002 project, the fresh concrete properties are given in Table 16. Satisfactory strength and air content were obtained. The hardened concrete properties are given in Table 17. Strengths and permeability were satisfactory. The M-E Design Guide specifies ages of 7, 14, 28, and 90 days. There were not large differences in compressive and splitting tensile strength tested at 14 and 28 days and in flexural strength and elastic modulus tested at 14, 28, and 90 days. As with the 2001 data, the shrinkage values were low and satisfactory.

Table 16. Fresh Concrete Properties for 2002

Test	B1	B2	B3
Air Content (%)	5.2	5.4	6.0
Slump (in)	0.75	1.0	1.25
Concrete Temperature (°F)	81	80	80

Condition Surveys

This section was not opened to traffic. There was no visible distress, and the transverse crack spacing in the CRCP was 6.3 feet in a 400-foot section measured.

Table 17. Hardened Concrete Properties for 2002

Test	Age	B1	B2	B3
Compressive strength (psi)	7d	4370	4830	4060
	14 d	5390	5150	4730
	28d	5860	6160	5800
	90 d	7380	7610	7140
	1 yr	7910	8080	7870
Flexural strength (psi)	7 d	633	639	619
	14 d	684	723	650
	28 d	774	792	692
	90 d	781	797	726
	1 yr	873	832	850
Perm (coulombs)	28 d	782	781	764
Splitting tensile strength (psi)	7 d	505	495	440
	14 d	535	560	535
	28 d	540	550	515
	90 d	675	640	590
	1 yr	740	790	760
Elastic modulus (10 ⁶ psi)	7 d	4.06	4.33	3.78
	14 d	4.41	4.36	4.30
	28 d	4.38	4.61	4.32
	90 d	4.80	4.91	4.89
	1 yr	5.30	5.49	5.22
Coefficient of thermal expansion (/°F)	3 mo	5.7	--	5.9
Poisson's ratio	3 mo	--	0.17	0.16
Shrinkage	28 d	0.039	0.035	0.037
	90d	0.048	0.044	0.048
	6 mo	0.054	0.049	0.052
	1 yr	0.052	0.048	0.052

DISCUSSION

Properties and Aggregate Size

Air-entrained paving concretes with satisfactory strength, low permeability, and dimensional stability can be prepared using concretes with Class F fly ash or slag and 1-inch or 2-inch NMS aggregates. Slipform pavers can satisfactorily place these concretes.

The performance of the WBL after six winters and the EBL after five winters was excellent. The use of large maximum size aggregate is expected to yield better performance in the field because of aggregate interlock. The test procedures used in this study included standard testing using small test specimens, which could not address the interlock issue. Long-term performance in the field would indicate the effect of aggregate size on performance. The FWD data already show that Slag 2 has a better load transfer at the joints than does Slag 1. The fly ash

mixture with the small aggregate had better load transfer than did the slag concrete with the small aggregate and had load transfer equal to that of the slag concrete with the large aggregate, indicating that factors other than aggregate size are also effective.

In this project, the reductions in water and cement contents were minimal since the combined aggregate grading provided marginal improvements compared to regular aggregate grading. The benefit of the large size aggregate in reducing water and paste contents can be augmented by improved, more uniform combined grading and improved particle shape.

The Maturity Method

The maturity method provides a convenient means to evaluate the in-place strength of pavements. There is a good relationship between the compressive and flexural strength of concrete, and the compressive strength has less variability. Acceptance of concrete by compressive strength after developing a relationship between compressive and flexural strength would be more convenient.

The M-E Design Guide

There was a continuous increase in strength and elastic modulus with time as shown in Table 17. The rate of increase was higher at early ages, as expected. These validate the provisions of the M-E Design Guide in this regard.

CONCLUSIONS

- Slag or fly ash concretes can be successfully used in pavements.
- Concrete with 2-inch NMS aggregate can be successfully slipformed.
- Large aggregate provides better aggregate interlock than smaller aggregate, with everything else being equal.
- For reduced water and cement contents, large size aggregates with good shape and uniform grading are needed.
- The maturity method can be used to predict the strength of concrete and can be used to determine when pavement should be opened to traffic.

RECOMMENDATIONS

The following changes to VDOT's *Road and Bridge Specifications*¹⁵ are recommended:

1. Permit a large NMS aggregate up to 2 inches in paving concrete.
2. Permit combined, uniform aggregate grading rather than the selection of separate fine or coarse aggregates.
3. Permit the maturity method to be used to determine the strength of in-place pavement for opening to traffic.

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