FINAL REPORT

EVALUATION OF CONTINUOUSLY REINFORCED HYDRAULIC CEMENT CONCRETE PAVEMENT AT VIRGINIA'S SMART ROAD

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Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

June 2004
VTRC 04-R22

DISCLAIMER

ABSTRACT

A two-lane continuously reinforced concrete pavement (CRCP) was built in Blacksburg, Virginia, as a part of Virginia's Smart Road. One of the lanes is 12 ft wide, and the other is 14 ft wide. The additional 2 ft was part of the shoulder. Below the concrete pavement is a 3-in-thick open-graded drainage layer (OGDL); one section is asphalt stabilized, and the other section is cement stabilized. The concrete pavement was cured by a curing compound except that the 12-ft lane was also covered with plastic and straw because of concerns with cold ambient temperature.

The objective of this project was to determine the material properties of the concrete, instrument the pavement, monitor construction practices, and monitor the performance of the pavement over 4 years. The concrete had high early strength, low permeability, and high shrinkage. The average crack spacing was more than 3 ft, indicating satisfactory performance. In general, cracks were wider when they were further apart, but the differences in crack spacing and width were variable and small in some cases and could not be correlated after 4 years. The end sections had less cracking than the interior sections of the pavement.

There were fewer cracks and more space between cracks in the 12-ft lane and fewer cracks in the pavement over the asphalt-stabilized OGDL. This was attributed to a better cure in the 12-ft lane and to a lower friction over the asphalt-stabilized base. No changes to the specifications were recommended as a result of the study findings.

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INTRODUCTION

Eventually, Virginia's Smart Road will connect the town of Blacksburg to I-81. However, the road will not be open to the public until 2010. Until then, a 2-mile section serves as a testing ground for the latest in transportation technology, including road surface–to-tire interaction, lighting equipment, pavement markings, and roadbed sensors.[1] Portions of this section have been constructed with continuously reinforced concrete pavement (CRCP), jointed plain concrete pavement, and asphalt pavement.

In concrete pavements, reduced service life may result from adverse environmental conditions and heavy loading. Moisture and temperature variations cause volumetric changes, which are resisted by friction between the concrete and the base, directly affecting the transverse cracking pattern. CRCP is designed to control transverse cracks through continuous longitudinal steel reinforcement, which holds the transverse cracks tightly together to ensure the integrity of the aggregate interlock and load transfers at the crack face. The desired spacing for cracks in the pavement is 3 to 6 ft apart, since cracks spaced closer together lead to inadequate resistance to loads, leading to punch outs.

Pavement designers often incorporate an open-graded drainage layer (OGDL), which is a layer beneath the concrete pavement used to remove water beneath the concrete.[2] If the surface texture of the OGDL is too open, mortar in the concrete can easily penetrate the OGDL, which may result in high frictional resistance at the concrete and base interface when volumetric changes occur.[3] The key to reducing the potential for adverse transverse cracking patterns will be controlling these friction forces and volumetric changes within the CRCP. Construction issues, including concrete consolidation and curing, are also important for satisfactory performance. Adequate consolidation is essential to attain the desired strength and durability. Likewise, proper curing ensures that the desired strength will be achieved and also helps to minimize the volumetric changes that cause cracks to form.

PURPOSE AND SCOPE

This project focused on the sections of the Virginia's Smart Road constructed with CRCP. The objectives were:

1. to determine the material properties of the concrete mixtures used in the CRCP, including compressive strength, flexural strength, elastic modulus, coefficient of thermal expansion, permeability, and drying shrinkage

2. to monitor construction practices during placement of the CRCP

3. to instrument the CRCP to allow the measurement of temperature and strain

4. to monitor the performance of the CRCP over 4 years.

METHODOLOGY

Overview

Virginia's Smart Road is 7.7 miles long. The CRCP section is 2,247 ft long and 10 in thick. The road consists of two concrete lanes. One lane is 12 ft wide, and the other is 14 ft wide. The additional 2 ft of concrete was part of the shoulder; the remainder of the shoulder is asphalt concrete. Below the concrete pavement is a 3-in-thick OGDL with No. 57 aggregate. The OGDL was stabilized with 4 percent cement for 1,263 ft and with 2.5 percent asphalt for 984 ft. Under the OGDL is a 6-in layer of cement-stabilized aggregate containing 4 percent cement by weight, which was placed on 3 in of aggregate base. Longitudinal and transverse reinforcing steel was placed on steel chairs and tied. The percentage of steel was 0.7 percent.

Four tasks were carried out to achieve the study objectives:

1. The material properties of the concrete mixtures used in the CRCP were determined.

2. The construction practices during placement of the CRCP were monitored.

3. The CRCP was instrumented to measure temperature and strain.

4. The performance of the CRCP was monitored over 4 years.

Determining the Material Properties of the Concrete Mixtures

The mixture proportions of the concrete are given in Table 1. The mixture had Type I/II portland cement with 35 percent (by total cementitious weight) ground-granulated blast furnace slag (slag). Number 57 coarse aggregate was used; the fine aggregate was natural sand. The coarse and fine aggregates were quartzite. A synthetic air-entraining admixture and a mid-range water-reducing admixture were added. The water–cementitious materials ratio (w/cm) was low to achieve a high early strength since the contractor wanted trucks on the pavement in 7 days to allow construction of the adjacent lane.

Table 1. Mixture Proportions (lb/yd^3)

Ingredients	Amount
Portland cement	384
Slag	206
Slag %	35
Coarse aggregate	1795
Fine aggregate	1267
Water	236
w/cm	0.40

The concrete mixtures were sampled and tested at the freshly mixed state for air content, slump, concrete temperature, and density (unit weight) (Table 2) and at the hardened state for the properties listed in Table 3. Table 3 also shows the sizes of the specimens and the test ages. The specified air content was 6 ± 2 percent. The minimum 28-day design flexural strength for the pavement was 650 psi using third-point loading.

Table 2. Fresh Concrete Properties

Date/Property	B1	B2	B3	B4
Date	10/15/99	10/15/99	10/22/99	10/22/99
Slump (in)	3/4	1/4	1 ½	3/4
Air (%)	6.4	5.5	6.7	6.3
Concrete temperature (F)	68	70	61	65
Density (lb/ft^3)	144.8	145.2	142.4	144.0

Batches 1 and 2 are from the 14-ft section; Batches 3 and 4 are from the 12-ft section.

Table 3. Tests and Specimen Sizes

Tests	Specifications	Age	Size (in)
Compressive strength	AASHTO T22	1,3,7 &28 d; 1 yr	4 x 8
Flexural strength	ASTM C78	7 , 28 d; 1 yr	3 x 3 x 11¼
Elastic modulus	ASTM C469	28 d; 1 yr	4 x 8
CTE		6 m	4 x 8
Permeability	AASHTO T277	28 d	2 x 4
Drying shrinkage	ASTM C157	28, 90 d	3 x 3 x 11¼

CTE: coefficient of thermal expansion, determined by measuring length change at two temperatures.
Permeability specimens were subjected to accelerated curing and were kept moist at room temperature for 1 week and at 100ºF for 3 weeks.
Shrinkage specimens were moist cured for 7 days before drying.

Monitoring Construction Practices

The CRCP was placed on 2 days: October 15 and October 22, 1999. The CRCP was placed using a slip-form paver. The 14-ft-wide lane was placed first, moving down the slope, and then the 12-ft lane was placed 1 week later, moving up the slope. Concrete was delivered to the spreader by dump trucks. The slip-form paver had 2-in-square hydraulic vibrators operating at the maximum frequency of 10,000 vibrations per minute. Traveling behind the paver, another piece of equipment provided texture by burlap and metal tines and sprayed a curing compound on the surface. Because of concerns with cold weather during placement of the 12-ft lane, the contractor covered the curing compound with plastic and spread straw over the plastic. The straw was covered with another layer of plastic to provide better insulation and to prevent the straw from blowing away.

Instrumenting the Pavement

The CRCP was instrumented for strain and temperature as follows:

1. Strains in the 12-ft-wide lane caused by environmental factors were determined for each OGDL. Vibrating wire strain gauges were placed 1.5 in from the top and bottom of the pavement in the direction of traffic. The vibrating gages were also equipped with temperature sensors.

2. A set of five Type T thermocouples was used to determine temperatures at various depths (0.5, 2.5, 5, 7.5, and 9.5 in) of pavement at a location in both lanes. The thermocouples were tied to 1/2-in-diameter stainless steel stakes covered with rubber hoses to avoid touching the steel.

3. A falling weight deflectometer (FWD) was used to assess the stiffness of the pavement.

Monitoring Performance

Visual surveys for crack spacing and width were conducted at 1, 2, and 4 years after the pavement was placed. Sections about 200 ft long in each lane for each OGDL were surveyed. The starting point for these sections were the point where the asphalt- and cement-stabilized OGDL met. In addition, at 1 and 4 years, 100 ft of pavement at each end was surveyed for crack spacing and width.

RESULTS AND DISCUSSION

Concrete Properties

The fresh concrete properties are given in Table 2. The mixtures were stiff, and the slip-form paver was able to provide well-formed edges. The air contents were satisfactory. Densities were as expected.

The hardened concrete properties are summarized in Table 4. The flexural strengths at 28 days were 985 psi or higher, well above the minimum requirement of 650 psi. Similarly, the compressive strength and elastic modulus at 28 days were high. The measured values were slightly higher than the theoretical elastic modulus values calculated from the empirical formula.

Table 4 also shows that the permeability of specimens subjected to accelerated curing was very low and much lower than the 3500 coulombs specified for paving concrete at 28 days. Table 4 summarizes the measurements for concrete shrinkage, which were high. The low permeability is expected to improve the durability of the concrete. Shrinkage values were 50 percent higher than the 400-microstrain limit at 28 days recommended for pavements containing pozzolans or slag.[4] At 90 days, the values were about 35 percent higher than the recommended limit of 500 microstrain.

The resistance to cycles of freezing and thawing was excellent, as indicated in Table 5. The acceptance criteria at 300 cycles are a maximum weight loss of 7 percent, a minimum durability factor of 60, and a maximum surface rating of 3.

Table 4. Hardened Concrete Properties

Test	Age	B1	B2	B3	B4	Average
Compressive strength (psi)	1d	1320	1260	1220	1170	1240
	3d	3130	3420	2980	3290	3200
	7d	4780	5070	3590	4100	4380
	28d	7350	7420	6710	7540	7260
	1 yr	8480	9480	7950	9290	8800
E_{actual} (10^6 psi)	28d	5.41	5.39	5.19	5.40	5.35
	1 yr	5.56	5.80	5.93	5.77	5.77
E_{theo} (10^6 psi)	28d	4.93	4.97	4.59	4.95	4.86
	1 yr	5.29	5.62	5.00	5.50	5.35
Flexural strength (psi)	7d	840	850	655	745	775
	28d	1095	1075	985	1070	1055
	1 y	1115	1140	1060	1140	1115
Permeability (coulombs)	28d	680	630	561	573	611
CTE (10^{-6} in/in/°F)		7.84		6.51		7.16
Shrinkage (microstrain)	28d	540	540	690	620	600
	90d	650	660	750	670	680

Values are the average of 2 specimens, except for CTE (coefficient of thermal expansion), which was 1 specimen.
E_{actual} is the measured elastic modulus.
E_{theo} is determined from the empirical formula [$33*w^{1.5}sqrt(f'c)$].

Table 5. Freeze-Thaw Data at 300 Cycles

Batch	Weight Loss (%)	Durability Factor	Surface Rating
1	0.9	103	1.1
2	1.2	103	1.2
3	0.8	102	1.3
4	1.7	103	1.2

Temperature and Strain Data

Figures 1 and 2 show the air temperature within the first 72 hours and the impact of heat of hydration on the temperature of the concrete. The air temperature was colder for the 12-ft lane shown in Figure 2, dipping below 40°F and prompting the use of plastic and straw. The temperature of the concrete above the surface followed the same general pattern as did the temperature of the air. The temperature in the beginning (during placement) was close to that of the air temperature, but as hydration began, the temperature rose above the air temperature. The air temperature fluctuated greatly between day and night, whereas the variation in the concrete temperature was more gradual in response to the air temperature. During the first couple of days of placement, the effect of heat of hydration was pronounced.

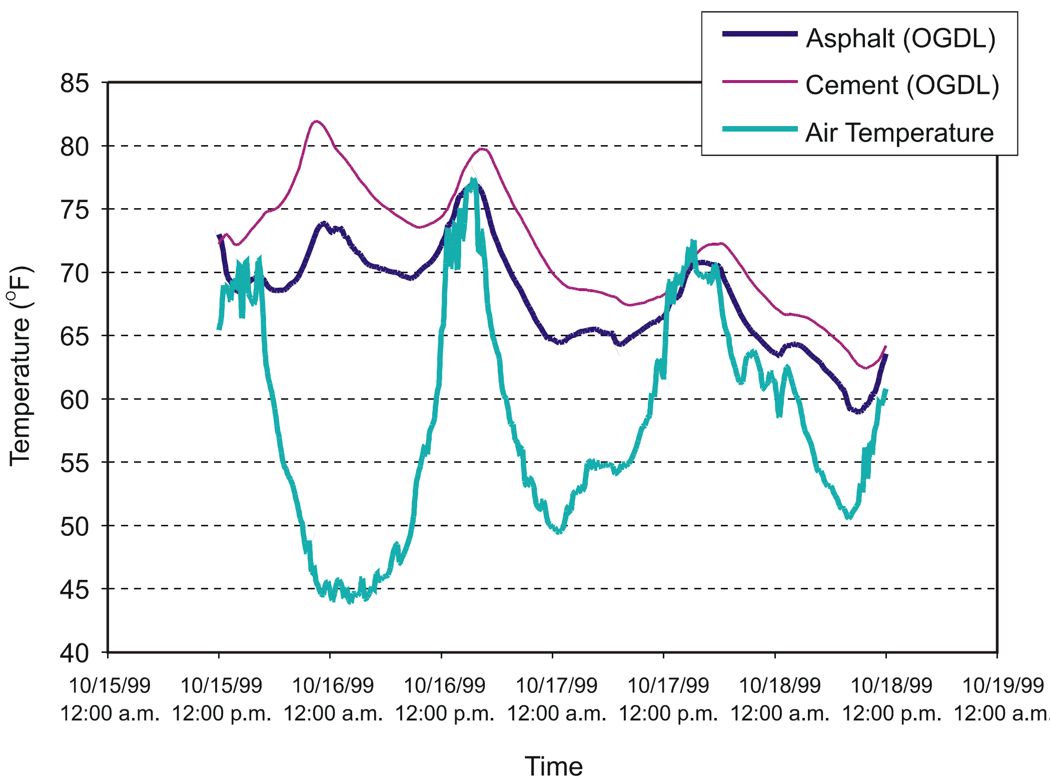

Figure 1. Temperature Data for First 72 Hours for 14-ft Lane. The temperature sensor was close to the top surface of the pavement.

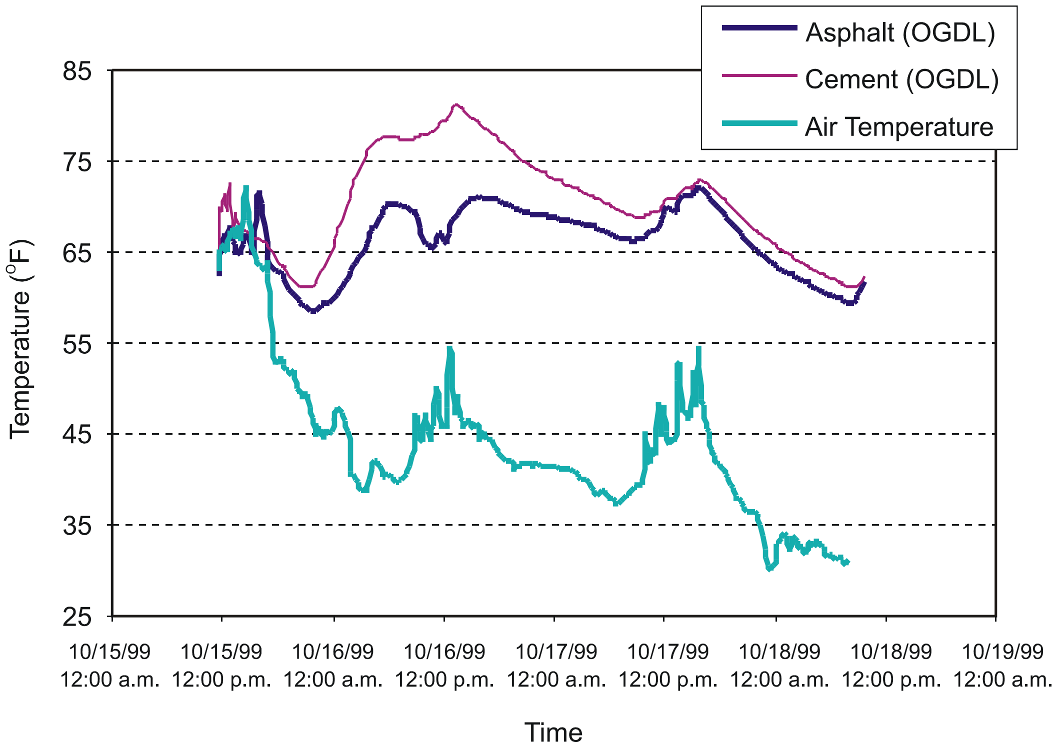

Figure 2. Temperature Data for First 72 Hours for 12-ft Lane. The temperature sensor was close to the top surface of the pavement.

In comparing the temperature gradients shown in Figure 3, there was a small difference between the OGDL sections. The temperature gradient between the top and bottom sensors was slightly higher for the pavement over the asphalt-stabilized OGDL.

The strain data were available for the 12-ft lane and are presented in Figures 4 and 5. The values were small, with the highest being in the initial 72 hours. The results indicate a similar magnitude of strain in the pavement over the asphalt-stabilized and cement-stabilized

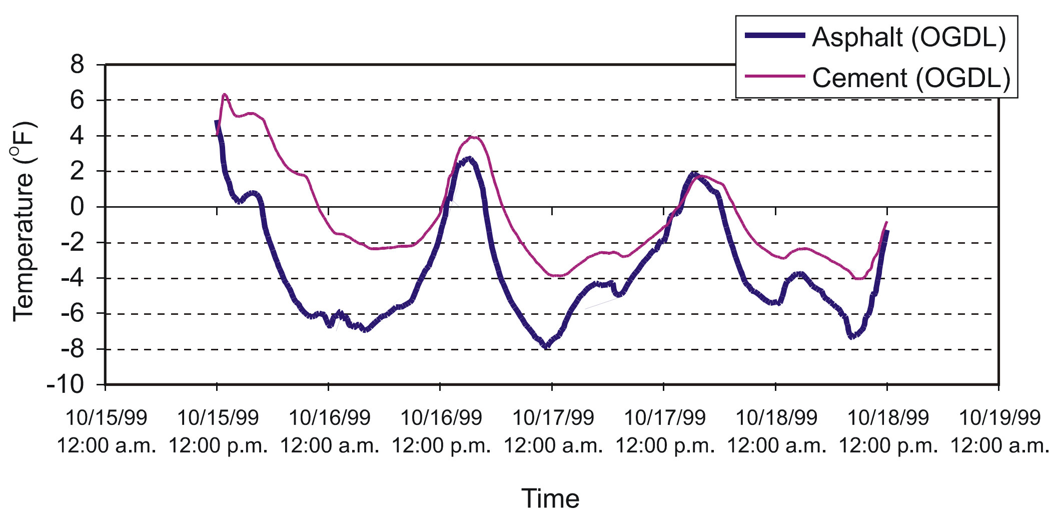

Figure 3. Temperature Gradient for First 72 Hours Between Top and Bottom of Slab in 14-ft Section.

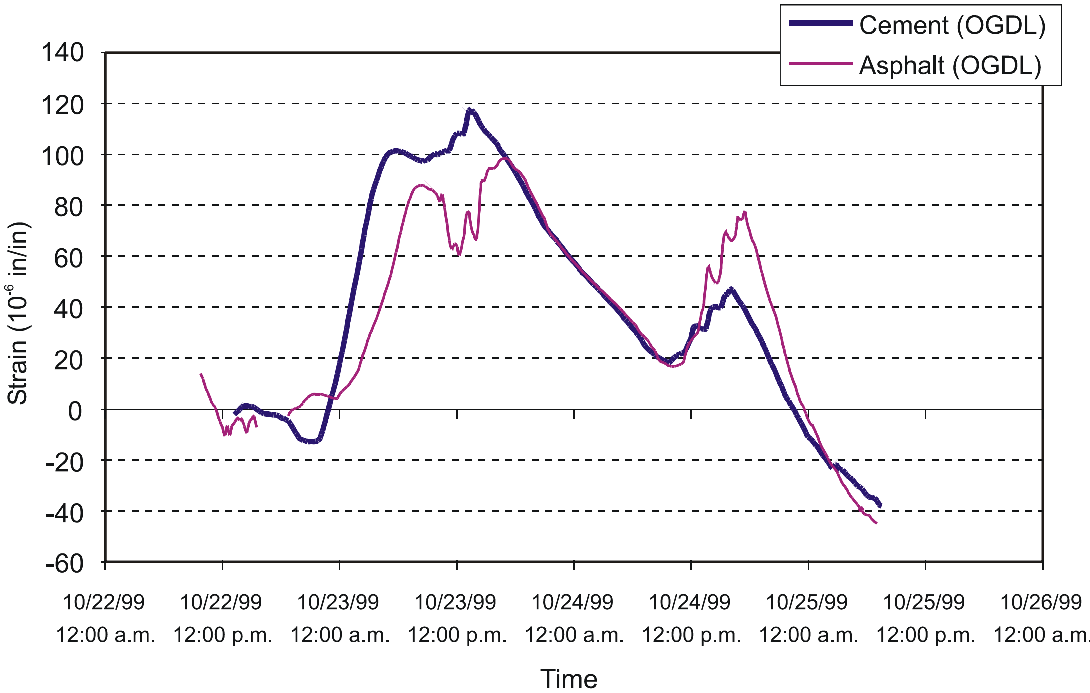

Figure 4. Strain Data for Top Section of Slab for 12-ft Lane.

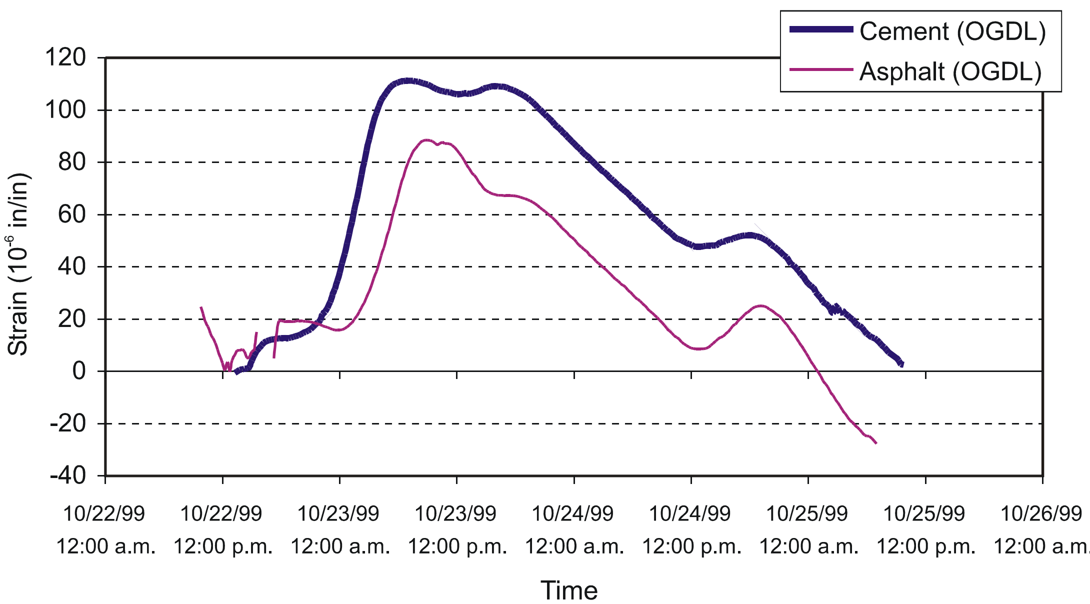

Figure 5. Strain Data for Bottom Section of Slab for 12-ft Lane.

OGDL near the top surface (Figure 4). Near the bottom surface, the strains (Figure 5) were smaller for the asphalt-stabilized OGDL. The higher strain for the cement-stabilized OGDL was attributed to the higher friction generated by better bonding of the concrete pavement to the cement-stabilized OGDL.

An FWD was used to determine the stiffness of the concrete for each OGDL. The FWD conveys a series of impact loads on a circular plate (11.8-in diameter) and measures the deflection at the center of the plate and at given offset distances. The average air temperature during the FWD testing was 68ºF, and the surface temperature of the concrete over the cement-stabilized base was 70ºF and over the asphalt-stabilized base was 69ºF. Figures 6 and 7 illustrate the total pavement stiffness moduli for the lanes. The average total stiffness moduli were high, with the value over the cement-stabilized OGDL being higher.

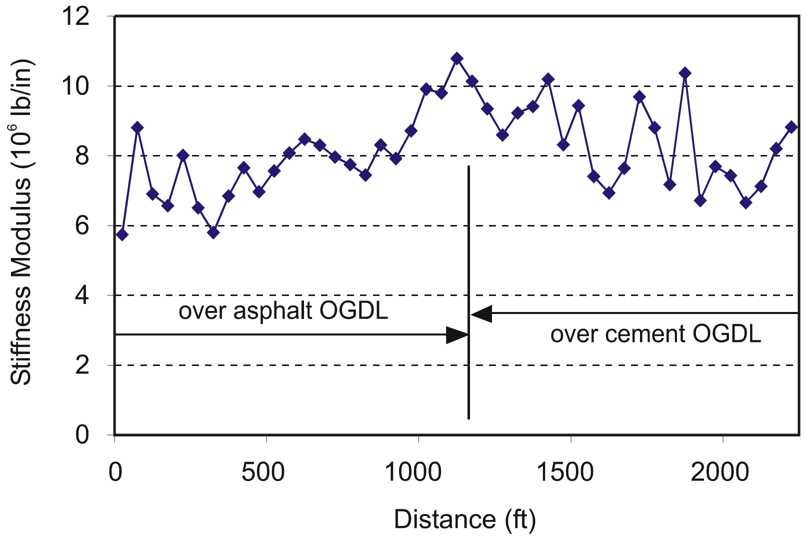

Figure 6. FWD Data for Eastbound Lanes (12-ft lane). The load was 16,000 lb; the average total pavement stiffness over the asphalt-stabilized OGDL was 7.86 x 10^6 lb/in and over the cement-stabilized OGDL was 8.42 x 10^6 lb/in.

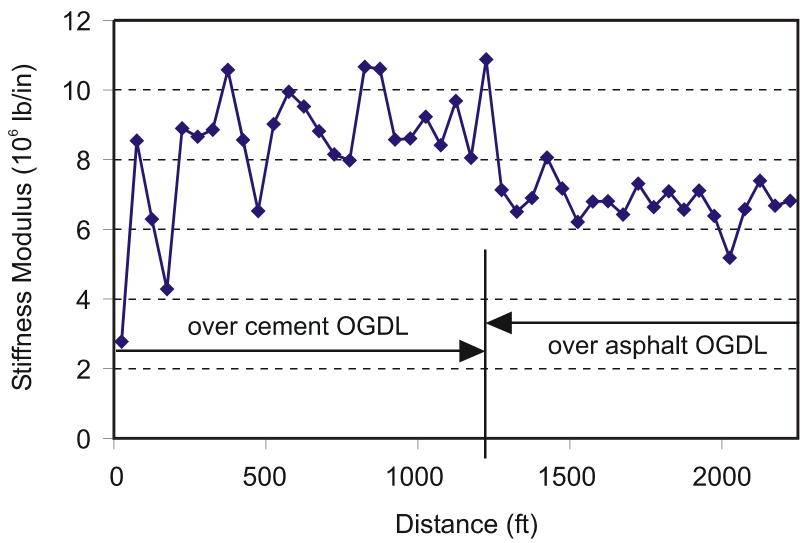

Figure 7. FWD Data for Westbound Lanes (14-ft lane). The load was 16,000 lb; the average total pavement stiffness over the asphalt-stabilized OGDL was 7.03 x 10^6 lb/in and over the cement-stabilized OGDL was 8.40 x 10^6 lb/in.

Performance

The development and severity of cracks can be attributed to four primary causes: temperature variation, moisture loss, base-slab friction levels, and the percentage of steel. Load-related distress was not considered since the road is not open to public traffic and only a limited number of test vehicles use the road.

Table 6 shows the transverse cracking data for the first year (2000). The number of cracks was less and the cracks were further apart in the 12-ft lane; this was attributed to better curing since the concrete was covered with plastic sheeting after the application of the curing compound, minimizing moisture loss. For the 12-ft lane, the spacing between the cracks was greater and the width wider over the asphalt-treated OGDL; for the 14-ft lane, the difference in crack spacing was minimal.

Table 6. One-Year Crack Data (2000)

Section	No. of Cracks	Crack Width (mm)		Crack Spacing (ft)	
		Average	Std. Error	Average	Std. Error
12 ft					
Asphalt OGDL	32	0.37	0.03	6.7	0.6
Cement OGDL	41	0.30	0.04	4.5	0.5
14 ft					
Asphalt OGDL	50	0.40	0.04	4.0	0.3
Cement OGDL	51	0.36	0.03	3.9	0.2

Standard error = Standard deviation / (√ No. of cracks).

Table 7 shows the second year data (2001). The number of cracks increased, leading to reduced crack spacing; however, the average spacing ranged from 3.5 to 5.1 ft, which is satisfactory. Again, the 12-ft lane had fewer cracks and the pavement over the asphalt-stabilized OGDL had fewer cracks in both lanes. The variability in the relationship between crack spacing and width appeared to be large.

Table 7. Two-Year Crack Data (2001)

Section	No. of Cracks	Crack Width (mm)		Crack Spacing (ft)	
		Average	Std. Error	Average	Std. Error
12 ft					
Asphalt OGDL	40	0.59	0.03	5.1	0.5
Cement OGDL	48	0.57	0.02	4.1	0.4
14 ft					
Asphalt OGDL	55	0.51	0.02	3.7	0.3
Cement OGDL	57	0.50	0.01	3.5	0.2

Table 8 shows the crack data for the fourth year (2003). The number of cracks increased slightly from the number in 2001, and the crack spacing decreased more; however, the increase in the number of cracks was less than that from 2000 to 2001. The average crack width was less in 2003 than in 2001, which was attributed to the temperature during the survey. The cracks were observed in May 2000 with a maximum temperature of 79ºF and a minimum temperature of 50ºF; in October 2001 with 62ºF and 27ºF; and in October 2003 with 72ºF and 41ºF.

Table 8. Four-Year Crack Data (2003)

Section	No. of Cracks	Crack Width (mm)		Crack Spacing (ft)	
		Average	Std. Error	Average	Std. Error
12 ft					
Asphalt OGDL	43	0.47	0.03	4.6	0.4
Cement OGDL	52	0.47	0.02	3.8	0.3
14 ft					
Asphalt OGDL	55	0.33	0.01	3.6	0.3
Cement OGDL	61	0.40	0.02	3.4	0.2

In the 2003 survey, the number of cracks in the 12-ft lane was less than in the 14-ft lane and over the asphalt-stabilized OGDL compared to the cement-stabilized OGDL. Penetration of mortar into the OGDL with cement causes the percentage of steel to decrease because the slab is thicker compared to the slab over the asphalt. In addition, the friction is expected to be less over the asphalt-stabilized OGDL, leading to less cracking. The average crack width was similar in both OGDLs in the 12-ft lane and less in the 14-ft lane. However, the data did not permit conclusions regarding the relationship between the number of cracks in the two lanes and over the two bases and the respective crack width. Crack width and crack spacing variability remained relatively high, as in the earlier surveys.

Tables 9 and 10 provide the crack data for the 100-ft end sections. Data were collected for the end sections in only 2000 and 2003. As shown in the tables, the number of cracks was very small, and the cracks were farther apart than in the interior sections of the lanes. Some of the cracks were too tight to be visible, which led to the recording of a reduced number of cracks in the section over the asphalt-stabilized OGDL in the 2003 survey compared to the 2000 survey. The reduced cracking in the end sections was attributed to a lack of end restraint. The difference in crack spacing between the two sections with different drainage layers was much larger for the 100-ft end sections than for the interior sections, indicating the importance of friction over the base layer.

Table 9. 100-Foot End Sections for 2000

Section	No. of Cracks	Crack Width (mm)		Crack Spacing (ft)	
		Average	Std. Error	Average	Std. Error
12 ft					
Asphalt OGDL	4	0.33	0.03	33.25	14.86
Cement OGDL	9	0.32	0.03	8.11	1.34
14 ft					
Asphalt OGDL	2	0.30	NA	50.00	32.0
Cement OGDL	8	0.26	0.03	8.00	2.20

Table 10. 100-Foot End Sections for 2003

Section	No. of Cracks	Crack Width (mm)		Crack Spacing (ft)	
		Average	Std. Error	Average	Std. Error
12 ft					
Asphalt OGDL	1	0.60	NA	NA	NA
Cement OGDL	19	0.35	0.03	5.21	0.819
14 ft					
Asphalt OGDL	1	0.40	NA	NA	NA
Cement OGDL	14	0.41	0.05	6.94	1.253

CONCLUSIONS

- The average crack spacing for a CRCP with high flexural strength and a high modulus of elasticity placed over a cement-stabilized or asphalt-stabilized OGDL is more than 3 ft, and the CRCP is expected to perform satisfactorily.

- The number of cracks increases over the years but at a decreasing rate.

- The end sections have less cracking than the interior sections of the pavement because of a lack of end restraint. The cracking in the end sections over an asphalt-stabilized OGDL is much less than over a cement-stabilized OGDL.

- The variability in crack width and crack spacing is relatively high in different lanes and over different bases. There were fewer cracks in the 12-ft lane that was covered with plastic and straw because of the better curing (less loss of moisture from the concrete). In addition, there were fewer cracks in the pavement over the asphalt-stabilized OGDL than in the cement-stabilized OGDL because of less penetration of mortar into the asphalt layer and less friction over the asphalt layer. In general, cracks appeared to be wider when spacing is greater (fewer cracks).

- The total pavement stiffness moduli determined by the FWD is high, with the value for the pavement over the cement-stabilized OGDL being higher.

RECOMMENDATIONS

1. VDOT should not change its specifications as the result of the study findings at this time.
2. The Virginia Transportation Research Council should continue the surveys for crack spacing and width .

ACKNOWLEDGMENTS

The author thanks the Virginia Transportation Research Council and the Federal Highway Administration for their support of this research project. The assistance of Mike Burton, Bill Ordel, and Andy Mills in making and testing specimens; of Jim Gillespie in reviewing the statistical concepts; and of Carolyn Desmond and James Woodward in evaluating the data is also acknowledged. David Clark's help in accessing Virginia's Smart Road and the generous review comments of Mohamed Elfino, Tom Freeman, Rodney Davis, James Bryant, Bob Long, and Michael Sprinkel are greatly appreciated.

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