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An Evaluation of the Performance of Concretes Containing Fly Ash and Ground Slag in Bridge Decks

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Supplementary Notes

Abstract:

Cores from 36 bridge decks were evaluated to assess the condition and quality of the concrete by petrographic methods and direct and indirect measures of the transport properties. Transport properties were measured by a rate of absorption test (ASTM C 1585) and by electrical conductance using the rapid chloride permeability apparatus (ASTM C 1202). The decks were distributed across Virginia to reflect the varied geographic and climatic regions. Two bridge age groups, each constructed under different specifications, were represented: (1) from 1968 through1971, where portland cement concrete with a maximum specified water–cementitious material ratio (W/C) of 0.47 was used with uncoated reinforcing steel; and (2) from 1984 through1991, where the specification required a maximum W/CM of 0.45, required epoxy-coated reinforcement, and allowed the use of fly ash or ground slag as supplementary cementitious materials. The older group included 10 decks, and the younger included 26. In the younger group, 8 were identified as containing fly ash and 7 were identified as containing slag.

Five of the concretes exhibited excessively high spacing factors, suggesting susceptibility to freezing and thawing damage, although only two showed signs of such damage. Four of the decks exhibited excessively small spacing factors that could significantly affect strength. Signs of poor paste quality attributable to excessive water were noted in approximately one-third of the concretes. Cracking was of significance in 12 decks but was limited to paste cracking in 6; of these, 5 contained either fly ash or slag. Four showed signs of damage related to alkali-aggregate reactions, including 3 with carbonate rocks, 1 of which contained slag. A general assessment based on petrographic observations showed a fairly even distribution of good, fair, and poor ratings.

Fly ash and slag concretes tended to have initial rates of absorption in the lower third, often despite their petrographic rating, suggesting they are providing beneficial reductions in transport properties in field concretes. The secondary (longer term) rate of absorption related better with the petrographic ratings, and the fly ash and slag concretes again tended to have lower rates. Of the fly ash and slag concretes exhibiting paste cracking, only one consistently had high absorption rates. In contrast to the rate of absorption results, the electrical conductivity results suggested little differences between the concretes, raising questions about its usefulness in evaluating mature field concretes.

This study demonstrates the beneficial contributions that fly ash and ground slag as supplementary cementitious materials provide to concrete durability, and they should continue to be used as an integral part of efforts to increase the service life of concrete structures. ASTM C 1585 provides a direct measure of the transport properties of concrete and should be incorporated into both the concrete materials acceptance and asset evaluation and management programs.

FINAL REPORT

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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DISCLAIMER

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ABSTRACT

Cores from 36 bridge decks were evaluated to assess the condition and quality of the concrete by petrographic methods and direct and indirect measures of the transport properties. Transport properties were measured by a rate of absorption test (ASTM C 1585) and by electrical conductance using the rapid chloride permeability apparatus (ASTM C 1202). The decks were distributed across Virginia to reflect the varied geographic and climatic regions. Two bridge age groups, each constructed under different specifications, were represented: (1) from 1968 through1971, where portland cement concrete with a maximum specified water–cementitious material ratio (W/C) of 0.47 was used with uncoated reinforcing steel; and (2) from 1984 through1991, where the specification required a maximum W/CM of 0.45, required epoxy-coated reinforcement, and allowed the use of fly ash or ground slag as supplementary cementitious materials. The older group included 10 decks, and the younger included 26. In the younger group, 8 were identified as containing fly ash and 7 were identified as containing slag.

Five of the concretes exhibited excessively high spacing factors, suggesting susceptibility to freezing and thawing damage, although only two showed signs of such damage. Four of the decks exhibited excessively small spacing factors that could significantly affect strength. Signs of poor paste quality attributable to excessive water were noted in approximately one-third of the concretes. Cracking was of significance in 12 decks but was limited to paste cracking in 6; of these, 5 contained either fly ash or slag. Four showed signs of damage related to alkali-aggregate reactions, including 3 with carbonate rocks, 1 of which contained slag. A general assessment based on petrographic observations showed a fairly even distribution of good, fair, and poor ratings.

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FINAL REPORT

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INTRODUCTION

In a study of the performance of concrete bridge decks, Ozyildirim and Halstead (1991) reported that chloride-induced corrosion was the major factor in the deterioration of bridge decks but that none of the performance attributes they measured (absorption, rapid chloride permeability) was useful in judging the likelihood that the concrete was susceptible to chloride ingress. They recommended that chloride contents at the level of the steel be measured periodically as an indicator that a deck is in or near a state of accelerated deterioration. Another major cause of premature concrete deterioration in Virginia has been alkali-aggregate reactions (AAR) (Lane, 1994).

Fly ash and ground slag, as supplementary cementitious materials, play an integral role in increasing the durability of concrete. They serve as a primary means of reducing the transport properties and thus reduce the ability of chloride to penetrate concrete, as well as preventing damaging alkali-silica reactions (ASR). The effectiveness of these materials in providing resistance to damaging ASR and impeding the ingress of chlorides into concrete is largely based on laboratory investigations. Concretes containing fly ash or slag have now been in service in Virginia for approximately 20 years and thus have sufficient exposure to allow an exploration of their performance under field conditions. This study examines concretes removed from field structures for their petrographic characteristics and transport properties as measured under laboratory conditions. Associated ongoing studies are examining the actual ingress of chlorides into the concretes and will be reported by others at a later time.

PROBLEM STATEMENT

The Virginia Department of Transportation (VDOT) has allowed use of fly ash and ground slag as cementitious materials in hydraulic cement concrete since the mid 1980s; since 1991, VDOT has essentially required the use of pozzolans or slag to enhance concrete durability. Most studies that have demonstrated the beneficial aspects of fly ash and ground slag on concrete durability have been laboratory based because of the scarcity of structures with a service life sufficient to allow field performance to be assessed. In addition, some have questioned whether laboratory studies conducted under ideal conditions accurately reflect actual performance under field conditions.

PURPOSE AND SCOPE

The purpose of this study was twofold:

1. to examine the field performance of concretes containing fly ash or ground slag as cementitious materials with respect to key durability parameters

2. to compare concretes placed under earlier specifications with those placed under more recent specifications.

The concretes evaluated were removed from 38 bridge decks across Virginia representing different geographic/climatic settings and differing traffic volumes that are expected to impact the severity of the exposure.

METHODS

Cores were obtained from 36 bridge decks distributed over Virginia. The bridge decks represented two age groups: (1) bridge decks constructed from 1968 through 1971, and (2) decks constructed from 1984 through 1991. The older group consisted of 10 decks constructed under a specification that permitted the use of only portland cement as a cementitious material, a maximum water-cement ratio (W/C) of 0.47, and uncoated reinforcement. The younger group consisted of 26 decks constructed under specifications that allowed the use of fly ash or ground slag with portland cement, required a maximum water–cementitious materials ratio (W/CM) of 0.45, and required epoxy-coated reinforcement. The geographic distribution of both groups was fairly uniform across the state. Thirty-two bridge decks were represented by three cores each, and four decks were represented by two cores each. General information on the decks is given in Table 1.

The cores were logged in and examined for general characteristics and features. Two cores from each deck were selected for evaluation of the concrete's transport properties. A 50-mm disk was cut from the top of both cores for use as the test specimen. The transport properties were evaluated by using ASTM C 1585 (ASTM International, 2004), a rate of absorption test, and by measuring the electrical conductivity of the concrete using the apparatus described in ASTM C 1202 (ASTM International, 2003a). These methods were described in detail by Lane (2006a, 2005). Since the rate of absorption test requires the concrete pore system to be unsaturated and the conductivity test presumes a saturated system, and because the specimens as received were in an unknown moisture condition, the specimens were first conditioned for the rate of absorption test. The conditioning consists of storage for 3 days at a temperature of 50^{o}C and a relative humidity of 80% followed by 2 weeks in individual sealed containers at laboratory room temperature (23 ^{o}C). Ideally, the top surface of the specimen would be exposed to water in the absorption test since that is the surface through which solutions enter. However, the exposed surface area is included in calculating the test result and thus must be accurately measured. Because the top surface area of the specimens was quite variable because of variations in grooving, scaling, and abrasion, the researcher decided to expose the sawed surface to the water to achieve a more accurate surface area measurement. Following completion of the rate of absorption test, the specimens were vacuum saturated and the electrical conductivity was

Table 1. Bridge Decks

District	City/County	Structure	Route	Over	Average Daily Traffic	Year Constructed	No. Cores
Bristol	Washington	1-6101		NF Holston R	1852	1969	3
	Richlands	1-1804		Clinch R	11680	1969	3
	Wytheville	1-2819	Litha Rd	I-81	1373	1986	3
	Wytheville	1-2820	I-81	Reed Cr	17000	1986	3
	Wytheville	1-2815	I-81	N-S RR	17000	1986	3
	Russell	1-1132	US 19	Rt 658	11840	1988	3
	Russell	1-1133	US 19	Rt 654	11840	1988	3
	Smyth	1-6051	Rt 645	MF Holsten R	1003	1990	3
Salem	Montgomery	2-2007	I-81	Roanoke R	19500	1970	3
	Giles	2-1020	US460	New R	4718	1986	3
	Montgomery	2-1009	US11	Plum Cr	6747	1988	2
	Franklin	2-1021	US220	Magodee Cr	2334	1988	2
Lynchburg	Nelson	3-1021	Rt 56	Tye R	886	1971	3
	Cumberland	3-1003	US60	Willis R	2754	1988	3
	Campbell	3-1017	US501	Opossum Cr	4786	1990	2
	Campbell	3-1000	US501	Beaver Cr	4361	1991	2
Richmond	Dinwiddie	4-2049	I85	Hatcher Rn	9000	1968	3
	Brunswick	4-1062	Rt 46	I-85	1785	1969	3
	Chesterfield	4-1007	Rt 288	Rt 654	10426	1990	3
	Pr George	4-2901	Rt 295	Appomattox R	16118	1991	3
Hampton Roads	Emporia	5-1800	US 301	Meherrin R	12370	1970	3
	Chesapeake	5-2547	I464	US 460	21580	1984	3
	Suffolk	5-2812	I164	US 17	14448	1991	3
Fredericksburg	Stafford	6-1032	Rt 3	CSX RR	23652	1971	3
Culpeper	Orange	7-1920	US 15	Rapidan R	6999	1991	3
Staunton	Rockbridge	8-1019	US 60	Maury R	14777	1984	3
	Alleghany	8-1133	US 220	CSX RR	2900	1987	3
	Augusta	8-1002	US 11	Middle R	9863	1988	3
NOVA	Fairfax	9-6042	Rt 638	Southern RR	2022	1969	3
	Alexandria	9-2801	Rt 420	I 395	8000	1970	3
	Loudoun	9-1014	US 15	Goose Cr	9155	1987	3
	Loudoun	9-1139	Rt 7 BP	SF Catoctin Cr	14554	1987	3
	Arlington	9-1002	US 50	Four Mile Rn	61172	1987	3
	Arlington	9-1098	US 1	15th St	44183	1988	2
	Loudoun	9-1031	Rt 7	Rt 7 Bus	15974	1990	3
	Fairfax	9-6058	Rt 7100	Rt 267	5000	1991	3

measured. Following completion of the conductivity measurements, the specimens were weighed and dried to a constant mass and the absorption was determined.

A slab was cut axially from the third core from each bridge deck. For the decks for which only two cores were available, the transport specimen was cut in two parallel with the surface following the conductivity test. A cut surface was then finely lapped for microscopic examination. The volumetric proportions of the major constituents were determined by point count. The characteristics of the air void systems were determined by linear traverse in accordance with ASTM C 457 (ASTM International, 2003b). The slab and associated concrete pieces were then carefully examined with a stereoscopic microscope at magnifications generally ranging from 10X to 100X and supplemented as needed with examinations of immersions mounts with a petrographic microscope for characteristics and features related to the overall quality and condition of the concrete.

RESULTS AND DISCUSSION

The results of the rate of absorption, total absorption, and electrical conductivity tests are given in Table 2. Two rate of absorption values were obtained, an initial rate (Ci) that reflects the absorption rate over the first few hours controlled by capillary suction and a usually slower secondary rate (Cs) reflecting the longer term absorption and are direct measures of fluid transport that impact the durability of concrete (Martys and Ferraris, 1997; Bentz et al., 2001; Lane, 2006a). The rate of absorption results include individual core values, the average, the range between individual core values as a percentage of the average, and the ratio of the secondary to the initial rate (Cs/Ci). Also included are total absorption for the individual cores and the individual core electrical conductivity values, their average, and the range between the individual values.

The average initial rate of absorption ranged from a low of 8.2 to a high of 57.8 x 10^{-4} mm/$s^{1/2}$. These values compare to a suite of 28-day laboratory concretes that exhibited values ranging from 4.8 x 10^{-4} mm/$s^{1/2}$ for a 0.38 W/CM concrete with 6% silica fume by mass to 35.2 x 10^{-4} mm/$s^{1/2}$ for a portland cement concrete with a 0.58 W/CM (Lane, 2006a), suggesting a broad range in concrete quality. The secondary rate of absorption values had a smaller range, from 5.8 to 24.8 x 10^{-4} mm/$s^{1/2}$. Secondary absorption rates for the laboratory concretes ranged from 2.3 to 15.3 x 10^{-4} mm/$s^{1/2}$. An example of the graphical plot of data is shown in Figure 1.

The range between individual rates of absorption values can be used to estimate the homogeneity of the concrete. From the laboratory study, the expected maximum range of two tests representing the same concrete is 25.5% for Ci and 18.6% for Cs (Lane, 2006a). Approximately one-half of the decks exceeded the expected range for Ci, with approximately one-third exceeding the range for Cs.

In their study of capillary transport, Martys and Ferraris (1997) noted the tendency for Cs to be lower than Ci and suggested that the transition between the initial and secondary rates reflects a shift in dominance from the larger capillary pores in the initial rate to the smaller gel pores in the secondary rate. In the laboratory study, the ratio of Cs/Ci consistently fell between 0.40 and 0.50; for the concretes in this study, the Cs/Ci ranged from 0.22 to 0.92.

Individual total absorption values were based on the difference between vacuum-saturated and oven-dried mass and ranged from 3.4% to 6.7% with one exception. These values are comparable to the range of absorption values reported by Ozyildirim and Halstead (1991) in an earlier evaluation of concrete bridge deck performance. The exception that fell outside the stated range was a concrete containing expanded shale lightweight coarse aggregate with absorptions of 7.6% to 8.0%. Although the rate of absorption and absorption measurements are generally conceived of as measures of the quality of the cementitious matrix, the relatively absorptive nature of the expanded shale confounds both. This deck (8 1019) had Ci and Cs values in the top one-third of those obtained, but because the relative impact of the aggregate is unknown, they cannot be used in comparison with those of the other decks. For the most part, the difference between absorption values from the same deck was less than 1%, with only a few approaching 1.5%.

Table 2. Results of Rate of Absorption, Absorption, and Conductivity Tests

Structure	Initial Absorption (Si)				Secondary Absorption (Ss)					Total Absorption, %		Electrical Conductivity			
	C_i (mm/s ^{½} x 10^{-4})				Cs (mm/s $^{1/2}$ x 10^{-4})							Siemens/m x 10^{-3}			
Structure	Core 1	Core 2	Average	Range, %	Core 1	Core 2	Average	Range, %	Cs/Ci	Core 1	Core 2	Core 1	Core 2	Average	Range, %
1-1132	18.1	30.1	24.1	49.5	13.9	23.3	18.6	50.2	0.77	5.15	5.76	7.7	9.7	8.7	22.6
1-1133	18.1	24.4	21.2	29.7	10.1	17.1	13.6	51.5	0.64	5.02	5.72	7.0	9.9	8.4	33.5
1-1804	34.4	39.4	36.9	13.5	12.2	12.6	12.4	3.3	0.34	5.16	4.87	9.3	8.6	8.9	7.4
1-2815	22.0	16.4	19.2	29.2	9.1	11.8	10.5	25.7	0.54	4.54	4.27	3.3	3.7	3.5	14.1
1-2819	23.3	24.9	24.1	6.4	9.7	9.7	9.7	0.2	0.40	4.64	4.22	4.4	4.0	4.2	9.4
1-2820	16.1	19.1	17.6	17.3	8.7	12.9	10.8	38.7	0.62	3.66	4.29	4.7	7.6	6.1	47.2
1-6051	14.0	12.2	13.1	13.6	11.4	11.0	11.2	2.7	0.85	4.08	4.13	6.4	5.5	6.0	14.2
1-6101	51.5	64.2	57.8	22.0	13.9	14.1	14.0	1.8	0.24	4.95	5.52	4.2	3.8	4.0	11.9
2-1009	9.8	13.8	11.8	33.4	7.2	4.4	5.8	49.3	0.49	---	---	2.9	4.0	3.5	31.0
2-1020	19.8	20.8	20.3	4.9	9.7	9.3	9.5	4.0	0.47	3.82	3.78	5.5	7.0	6.2	24.8
2-1021	16.2	19.3	17.7	17.5	8.6	8.6	8.6	0.2	0.48	4.85	---	1.9	2.3	2.1	19.1
2-2007	36.9	70.6	53.8	62.9	16.9	6.9	11.9	83.7	0.22	5.16	5.33	8.9	6.0	7.4	38.8
3-1000	11.3	9.9	10.6	13.6	6.4	5.4	5.9	16.2	0.56	---	---	2.9	2.7	2.8	6.4
3-1003	18.2	21.5	19.9	16.4	12.2	13.3	12.7	8.8	0.64	4.15	4.35	7.7	12.1	9.9	44.6
3-1017	14.7	22.1	18.4	40.6	7.1	7.4	7.3	4.4	0.39	---	---	2.1	2.4	2.2	14.8
3-1021	25.2	33.0	29.1	26.6	19.8	17.6	18.7	11.6	0.64	4.73	4.69	7.1	6.5	6.8	9.4
4-1007	34.7	26.7	30.7	25.9	23.1	19.2	21.2	18.3	0.69	6.70	5.06	12.4	9.8	11.1	23.3
4-1062	63.6	22.2	42.9	96.6	10.7	13.0	11.9	19.8	0.28	4.52	3.83	5.6	4.2	4.9	28.7
4-2049	62.2	43.8	53.0	34.7	11.1	19.2	15.1	53.7	0.29	4.58	4.37	7.3	5.1	6.2	35.1
4-2901	9.0	7.4	8.2	18.9	7.3	7.0	7.1	5.0	0.87	3.86	3.83	8.4	5.1	6.7	47.9
5-1800	46.4	45.6	46.0	1.7	19.7	25.6	22.7	26.2	0.49	5.29	5.61	3.2	5.9	4.5	60.5
5-2547	22.6	23.2	22.9	2.4	19.6	22.5	21.0	13.8	0.92	4.33	4.35	5.2	4.4	4.8	16.9
5-2812	14.0	22.2	18.1	45.4	9.1	7.9	8.5	13.6	0.47	4.35	4.46	3.6	3.3	3.4	6.4
6-1032	47.1	40.3	43.7	15.4	24.2	20.1	22.2	18.7	0.51	5.23	4.72	5.1	4.6	4.9	9.8
7-1920	33.3	36.3	34.8	8.6	25.9	23.4	24.6	10.3	0.71	5.20	4.89	13.8	12.0	12.9	13.8
8-1002	15.4	23.0	19.2	39.7	11.8	13.8	12.8	15.4	0.67	4.34	4.65	3.2	4.1	3.6	25.2
8-1019	32.9	34.9	33.9	5.9	22.2	22.0	22.1	1.1	0.65	7.97	7.62	9.9	9.6	9.7	2.4
8-1133	10.2	23.3	16.8	77.7	7.1	13.9	10.5	65.3	0.63	4.06	5.25	4.2	7.0	5.6	50.0
9-1002	25.0	18.1	21.5	31.9	16.2	14.3	15.2	12.6	0.71	5.26	4.43	3.9	3.4	3.6	14.8
9-1014	23.7	31.6	27.6	28.4	19.4	21.4	20.4	9.8	0.74	5.36	5.24	8.5	8.6	8.6	1.2
9-1031	34.0	31.9	33.0	6.3	23.7	25.9	24.8	8.7	0.75	5.22	5.43	11.3	13.0	12.2	13.7
9-1098	30.9	22.7	26.8	30.5	23.3	16.7	20.0	33.4	0.75	4.97	4.61	6.5	5.3	5.9	21.3
9-1139	35.2	47.5	41.3	29.9	20.1	21.3	20.7	5.7	0.50	4.86	6.17	11.5	19.5	15.5	51.7
9-2801	27.9	24.8	26.4	11.7	10.0	7.3	8.6	31.2	0.33	3.64	3.42	2.4	2.5	2.4	5.1
9-6042	24.0	19.0	21.5	23.2	10.5	11.9	11.2	12.1	0.52	4.21	3.91	8.6	4.9	6.7	54.7
9-6058	26.3	15.5	20.9	51.4	17.7	12.6	15.1	33.6	0.72	4.46	4.07	5.4	5.7	5.5	6.1

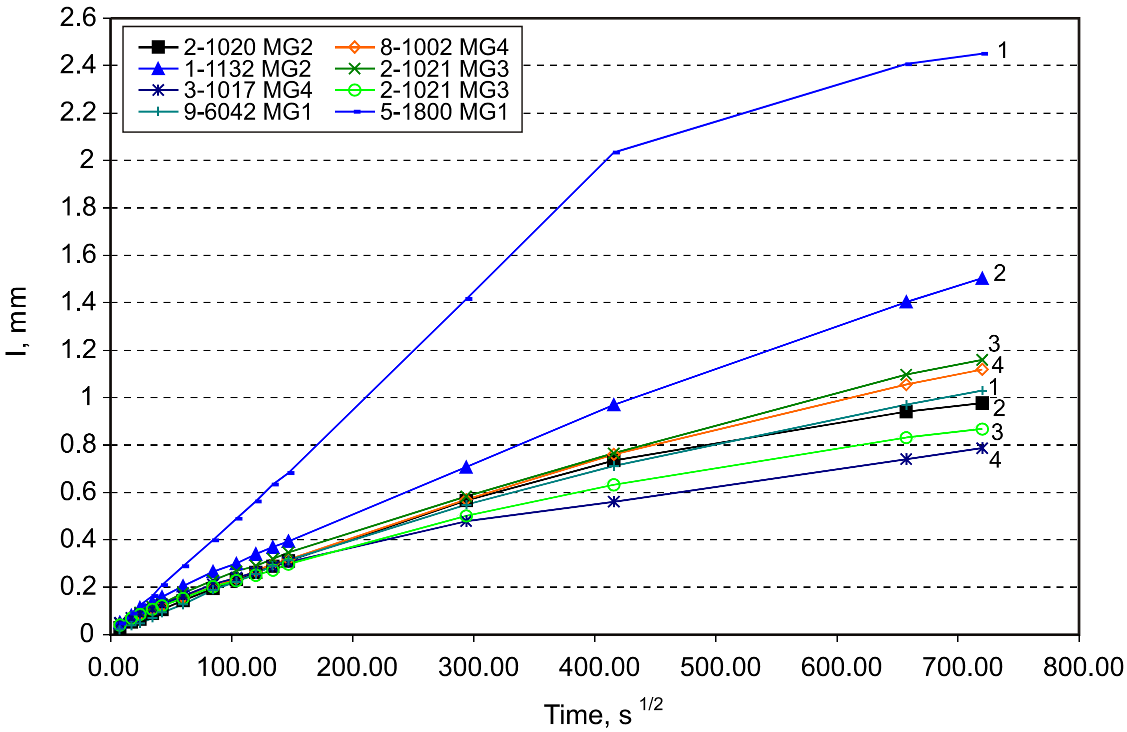

Figure 1. Graphical Example of Rate of Absorption (ASTM C 1585) Data. Materials group: 1 – PCC 0.47; 2 – PCC 0.45; 3 – fly ash; 4 – ground slag.

Electrical conductivity values ranged from 2.1 x 10^{-3} to of 19.5 x 10^{-3} Siemens/m (S/m); however, the average for only four decks exceeded 10 x 10^{-3} S/m. Conductivity measurements for 28-day concretes in the laboratory study of the method (Lane, 2005) ranged from 3 x 10^{-3} S/m for the 6% silica fume concrete with a 0.38 W/CM to 16 x 10^{-3} S/m for the portland cement concrete at 0.58 W/CM. From an analysis of a large block of data in the earlier study (Lane, 2005), conductivity values of 5, 10, and 12.5 x 10^{-3} S/m translate into 1500, 2500, and 3500 Coulombs passed in the standard 6-hour test (ASTM C 1202). The results obtained in this study are similar to those reported by Ozyildirim and Halstead (1991), where only 2 of 34 decks tested yielded values in excess of 3500 Coulombs in the 6-hour test. The range between individual values is also reported and can be compared to the expected maximum of approximately 14.3% estimated from the laboratory study results. The values for approximately one-half of the decks exceeded this value but were not necessarily the same as for the decks with highly variable Ci values.

The results of the petrographic analyses are given in Tables 3 and 4. Table 3 contains the results of the point count and linear traverse analyses. Table 4 reports the results of the petrographic examinations. The point count results establish the volumetric proportions of the concretes. Although a distinction is made between fine and coarse aggregate, ambiguities often exist and should be considered general in nature. Total aggregate contents ranged from 56.0% to 68.0%, paste contents from 25.5% to 34.9%, and air contents from 4.1% to 11.8%.

In the linear traverse analyses, the characteristics of the air void system are determined. Although resistance to damage by freezing and thawing cycles is typically handled in concrete specifications by air content, the spacing factor is generally considered the most important

Table 3. Point Count and Linear Traverse Results

	1-1132	1-1133	1-1804	1-2815	1-2819	1-2820	1-6051	1-6101	2-1009	2-1020	2-1021	2-2007
Point Count Results	**P2710**	**P2712**	**P2674**	**P2695**	**P2691**	**P2701**	**P2655**	**P2642**	**P2686**	**P2703**	**P2714**	**P2616**
Fine agg. (<5 mm), %	26.3	25.2	30.2	26.7	28.3	27.5	27.0	28.1	23.2	29.0	26.7	30.0
Coarse agg. (>5 mm), %	34.7	36.1	30.9	33.1	30.2	36.8	32.4	37.5	41.9	35.5	35.2	32.9
Total agg., %	61.0	61.3	61.1	59.8	58.5	64.3	59.4	65.6	65.1	64.5	61.9	62.9
Paste, %	30.2	30.4	34.2	33.1	33.1	26.9	32.1	29.5	28.9	29.8	29.0	29.8
Air, %	8.8	8.3	4.6	11.8	8.4	8.7	8.5	4.9	6.2	5.7	9.1	7.3
Linear Traverse Results												
Air, %	7.7	7.7	4.1	11.6	7.4	7.1	7.1	4.8	5.9	5.8	7.9	7.8
Specific surface (mm^{-1})	14.3	19.0	18.5	26.5	19.4	17.8	19.3	24.6	22.8	17.7	25.3	26.9
Spacing factor (mm)	0.27	0.20	0.32	0.09	0.23	0.21	0.23	0.21	0.20	0.27	0.15	0.14
Paste-air ratio	3.90	3.88	8.3	2.41	4.44	3.81	4.52	6.00	4.90	5.20	3.69	3.83

	3-1000	3-1003	3-1017	3-1021	4-1007	4-2049	4-1062	4-2901	5-1800	5-2547	5-2812	6-1032
Point Count Results	**P2688**	**P2698**	**P2717**	**P2660**	**P2645**	**P2682**	**P2666**	**P2623**	**P2649**	**P2636**	**P2684**	**P2638**
Fine agg. (<5 mm), %	29.8	26.7	27.7	26.3	27.2	27.2	23.0	25.6	26.4	23.9	26.4	28.7
Coarse agg. (>5 mm), %	26.2	33.7	34.5	34.5	29.1	34.7	41.6	38.4	37.4	40.6	37.5	35.4
Total agg., %	56.0	60.4	62.2	60.8	56.3	61.9	64.6	64.0	63.8	64.5	63.9	64.1
Paste, %	34.9	32.8	28.4	31.1	31.9	31.2	26.8	27.3	31.6	28.1	29.6	28.4
Air, %	9.2	6.9	9.3	8.1	11.8	6.9	8.6	8.7	4.6	7.5	6.5	7.5
Linear Traverse Results												
Air, %	7.9	7.0	8.6	8.9	11.1	4.6	7.7	8.2	3.9	5.1	6.9	7.5
Specific surface (mm^{-1})	22.9	24.2	17.1	25.2	25.3	31.1	18.7	21.0	19.3	19.7	23.2	25.7
Spacing factor (mm)	0.19	0.19	0.19	0.14	0.11	0.17	0.19	0.16	0.30	0.24	0.19	0.16
Paste-air ratio	4.45	4.70	3.26	3.50	2.89	6.7	3.51	3.31	8.29	5.46	4.33	3.73

	7-1920	8-1002	8-1019	8-1133	8-1133	9-1002	9-1014	9-1031	9-1098	9-1139	9-2801	9-6042	9-6058
Point Count Results	**P2669**	**P2706**	**P2679**	**P2663**	**P2663**	**P2630**	**P2619**	**P2657**	**P2632**	**P2673**	**P2622**	**P2626**	**P2651**
Fine agg. (<5 mm), %	25.9	25.5	25.9	23.9	23.9	25.7	28.6	22.9	23.8	23.6	25.1	24.5	24.1
Coarse agg. (>5 mm), %	37.4	36.5	34.2	39.4	39.4	30.9	39.4	39.0	39.4	34.8	42.3	40.6	36.8
Total agg., %	63.3	62.0	60.1	63.3	63.3	56.6	68.0	61.9	63.2	58.4	67.4	65.1	60.9
Paste, %	30.4	29.9	31.3	28.5	28.5	34.5	25.8	29.2	27.5	32.2	25.1	28.1	27.9
Air, %	6.3	8.1	8.6*	8.1	8.1	8.8	6.1	8.8	9.3	9.4	7.6	6.7	11.2
Linear Traverse Results													
Air, %	5.5	9.7	5.4*	7.3	7.3	6.7	6.0	7.3	9.3	9.5	6.9	7.2	9.8
Specific surface (mm^{-1})	16.2	15.2	12.8	16.0	16.0	31.5	33.8	27.3	25.1	27.6	17.7	17.2	26.2
Spacing factor (mm)	0.30	0.20	0.38	0.25	0.25	0.15	0.13	0.15	0.12	0.12	0.20	0.23	0.11
Paste-air ratio	5.44	3.09	5.71	3.99	3.99	5.21	4.37	3.97	3.00	3.35	3.61	3.91	2.86

*Voids filled/lined with secondary deposits; PC – void filling included in void; LT – only unfilled portion counted.

Table 4. Petrographic observations (only significant features noted)

Structure	Coarse Aggregate	Paste Color/ Distribution	Paste Texture	Bleeding	Retempering	Fly Ash/Slag	Paste-Aggregate Bond	Paste Carbonation	Paste Cracks	Aggregate Cracks	ASR Product	Voids Filled	General Condition	General Observations
1-1132	Q	LT/M			Y			12	O	O	S	L	F	CA reaction rims, sweating, cracks short into paste and tight
1-1133	Q	LG			Y	F	P	12		O			F	Surface: crack to 25 mm depth. CA reaction rims, minor cracks do not extend into paste
1-1804	L	G	G					---	F	F	Y		P	Surface: scaled, CA polished. Rebar 56 mm cover, horizontal fracture in vicinity, around CA, appears to be plastic, possibly settlement
1-2815	Q	G		Y	Y	F	P	12			S		P	Surface: scaled. Some ASR with CA and chert, no apparent damage, coalescing voids
1-2819	L	LG/M	G			F	P	13	O				F	Surface: cracks to 50 mm depth; rough, chipped, or scaling; coarse void structure; some ASR sweating of chert
1-2820	Q	LG		Y			P	12	O				F	Surface: cracks, scaled; some sub-horizontal discontinuities, large voids
1-6051	Q	LG/M	G			F	P	12*	F				P	Surface: *top 3 mm pH 9; spotty ASR sweating around chert
1-6101	Q	LG/M					G	13					G	Surface: cracks, light scaling; zone of large voids, 50-70 mm depth
2-1009	Q	LG			Y	F	F	12					F	CA reaction rims, no associated damage
2-1020	DL	LG/M						13					G	Surface: Cracks to 25 mm depth, patchy areas of quartz sand brown epoxy mortar; at base of cores, adherent mortar of a different color from concrete
2-1021	L	G				F		---	O				G	Surface: some wear, patchy areas of quartz mortar with brown epoxy; crack from surface to rebar at 125 mm depth, then horizontal in rebar plane; crack often associated with large voids
2-2007	Q	G	G	Y			G	13					G	
3-1000	GD	T				S	G	13*					G	Surface: some scaling; *top 3 mm pH 9; small blotches of BG paste
3-1003	Gn	T	G		Y			12		O	Y	F L	F	Surface: scaling; ASR sweating, darkened CA rims; sub-horizontal crack at 110-115 mm depth thru CA and FA particles
3-1017	Gn	T	P c			S		---	O				G	Surface: scaled; paste cracks, short and tight
3-1021	Gn	LG/M	G	Y	Y		P	12*					P	Surface: some cracks, scaled; *top 3 mm pH 9; poor consolidation
4-1007	Gr	LG/M			Y	F	P	12*	O			C	P	Surface: some scaling, *top 7 mm pH 9; spotty ASR sweating around CA and chert; coalescing entrained voids
4-1062	Gn	LG		Y			P	12			Y		F	Surface: some scaling; ASR product sweating from CA; void structure uneven
4-2049	G	LG	G	Y				12					F	Surface: crack to 50 mm depth, scaled
4-2901	G	LG					P	12					G	Uneven void distribution, coalescing, surface crack to 30 mm depth
5-1800	Gr	G/M						13			Y		G	Surface: cracks, scaled; some discontinuities in paste; ASR product around CA

5-2547	G	W/M	G					---					G	Sub-horizontal discontinuities at 60 and 95 mm below surface; plastic/settlement cracks
5-2812	Gr	T				S		12*					G	Surface: some scaling; *top 2 mm pH 9; uneven air void system
6-1032	G	G/E	G	Y			P	13*					P	Surface: faint cracks, scaled; *top 7 mm pH 9; some large voids
7-1920	Gd	W/M	R				P	12			Y		P	Surface: some scaling; ASR sweating from CA and chert; large entrained voids.
8-1002	DL	T/M			Y	S	F-P	13	F	F	Y		P	Surface: scaled; cracking associated with CA; areas of corroded whitish paste; frequent short microcracks throughout
8-1019	ES	W/M						12				F	F	Surface: pocked exposing CA; many voids filled/lined with ettringite
8-1133	DL	LG						12	F	F	Y		P	Surface: cracks to 50 mm, scaled; ASR product associated w/ CA and chert; sub-horizontal discontinuities at 70 and 90 mm depth
9-1002	Di	T		Y	Y	S		12					P	Surface cracks, sub-horizontal crack 12 mm below surface; large voids and related plastic cracks related to poor consolidation
9-1014	Di	W/M			Y	S	P	13					F	
9-1031	Di	W/M			Y		P	12					F	Surface: transverse and random cracks, some scaling; coalescing entrained voids
9-1098	G	LG		Y	Y	F		13					F	Some spotty ASR sweating around chert particles
9-1139	Di	W/M			Y		P	12	O	O			F	Surface: longitudinal crack, scaled; some ASR sweating around chert
9-2801	Di/G	G/E		Y			P	13					F	
9-6042	Di/G	LG/M		Y				13					F	Bleed channels, large voids common lower half, surface crack to 8mm depth, surface scaling
9-6058	Di	T			Y	S	P	12*	F		S		P	Surface: fine map cracking, scaled; top 2 mm pH 9; spotty ASR sweating around chert

Coarse aggregate (CA): Di – diabase; DL – dolomitic limestone; ES – expanded shale; G – quartzose gravel; Gd – granodiorite; Gn – gneiss; Gr – granite; L – limestone; Q – quartzite.
Paste color/distribution: G – gray; LG – light gray; T – tan; W – white/E – even; M – mottled.
Paste texture: G – coarse granular; Pc – porcelaneous (fine-grained).
Bleeding, Retempering: Y – yes.
Fly ash/Slag: F – fly ash; S – ground slag.
Paste-Aggregate Bond: G – good; F – fair; P – poor.
Paste/Aggregate Cracks: F – frequent, O – occasional.
ASR products: Y – yes, relatively abundant; S – scarce.
Voids: F – filled; L – lined (with secondary deposits).
General condition: G – good; F – fair; P – poor.

characteristic in this regard. The specified fresh air content range for the concretes covered in this study was 5% to 8%. Values determined by linear traverse ranged from 3.9% to 11.6% and included both purposefully entrained voids and the larger voids resulting from incomplete consolidation. Spacing factor values ranged from 0.09 to 0.38 mm, although there was considerable infilling of the voids in the concrete with the 0.38 mm spacing factor and the analyses considered only that portion of the original void that remained empty. For comparison, the point count air content for this bridge, 8-1019, was 8.6% and the linear traverse air content was 5.4%. Excluding this deck, the next highest spacing factor value was 0.32 mm.

In a recent study, Lane (2006b) suggested a spacing factor range of 0.15 to 0.25 mm as providing adequate protection from damage by freezing and thawing cycles while avoiding excessively close spacing that negatively impacts strength. The spacing factors in five of the decks exceeded 0.25 mm, suggesting susceptibility to freezing and thawing damage. Eight were less than 0.15 mm, but only four of these were more than marginally less (<0.13 mm) and thus likely to have impacted strength greatly. The specific surface is an inverse measure of the void size; thus, larger values indicate smaller bubbles. Specific surface values ranged from 12.8 to 33.8 mm^{-1}. Paste-air ratios range from 2.4 to 6.0.

Observations and assessments made during the petrographic examinations are reported in Table 4. Coarse aggregate type is noted and reflects the variety of rocks used as construction aggregates in Virginia. Two of the decks, 9-2801 and 9-6042, constructed during the earlier period used a blend of coarser diabase with finer quartzose gravel as the coarse aggregate.

The fine aggregate in all concretes was primarily composed of natural quartz sand. Paste features related to quality, color, color distribution, and granularity are noted along with evidence of bleeding and retempering (late addition of water). Relative color lightness and mottling are associated with higher paste porosity. The specimens were examined for evidence of the presence of fly ash or slag. Short acid-etching of polished surfaces coupled with examination of immersion mounts of pulverized paste (Figure 2) was used to identify the presence of fly ash particles. The presence of ground slag was determined through examination of the polished surfaces for the presence of areas of greenish bluish paste characteristic of unoxidized slag cement (Figure 3) coupled with an examination of immersion mounts (Figure 4). Only small, isolated areas of unoxidized paste remained in the specimens examined. Generally, the clear identification of fly ash or slag particles in the immersion mounts involved considerable searching, suggesting that these supplementary materials had hydrated to a considerable extent. This task would have been easier to perform with thin sections, but the tradeoff would have been the considerable effort and expertise necessary to produce good-quality thin sections.

Most of the decks exhibited little carbonation, and below the top surface all were sufficiently high to maintain steel passivity. Six decks exhibited some surface carbonation, but in only two, 4-1007 and 6-1032, was the depth greater than 2 to 3 mm. In both cases, the surface layer had a paste pH of 9 to a depth of 7 mm. Both were in the top one-third for both initial and secondary rates of absorption.

The frequency of cracking in the paste and aggregates was noted. Cracking was of significance in specimens representing one-third of the structures. In approximately one-half of

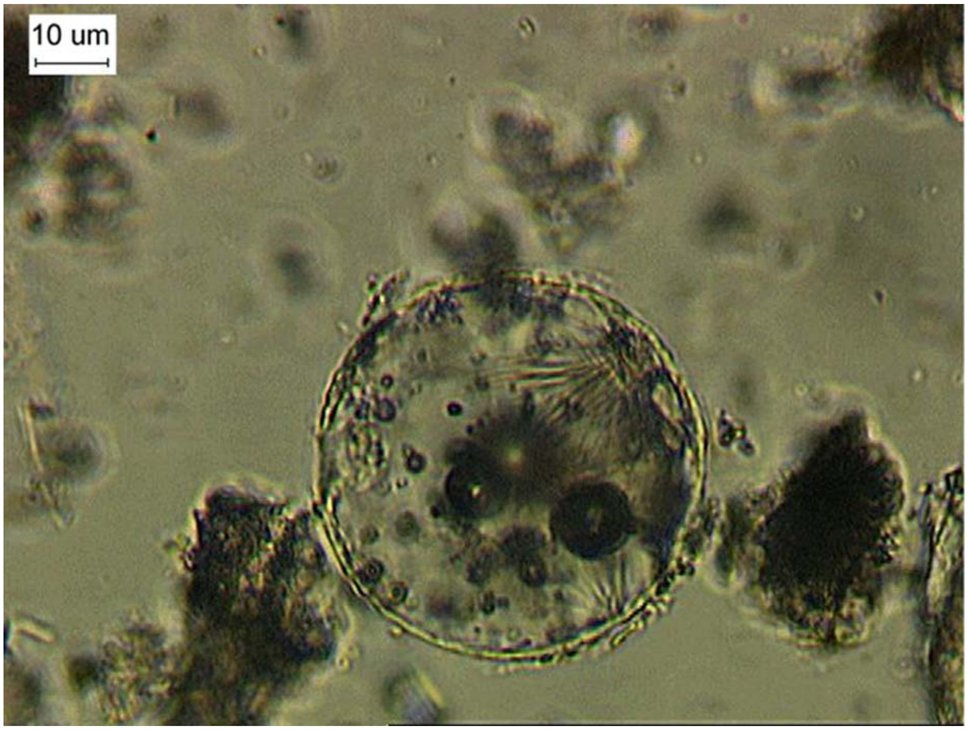

Figure 2. Fly Ash Particle in Immersion Mount of Pulverized Paste (2-1021)

Figure 3. Small Area of Greenish Bluish Paste Adjacent to Aggregate Particle on Right Margin Is Indicative of Presence of Slag Cement (3-1000)

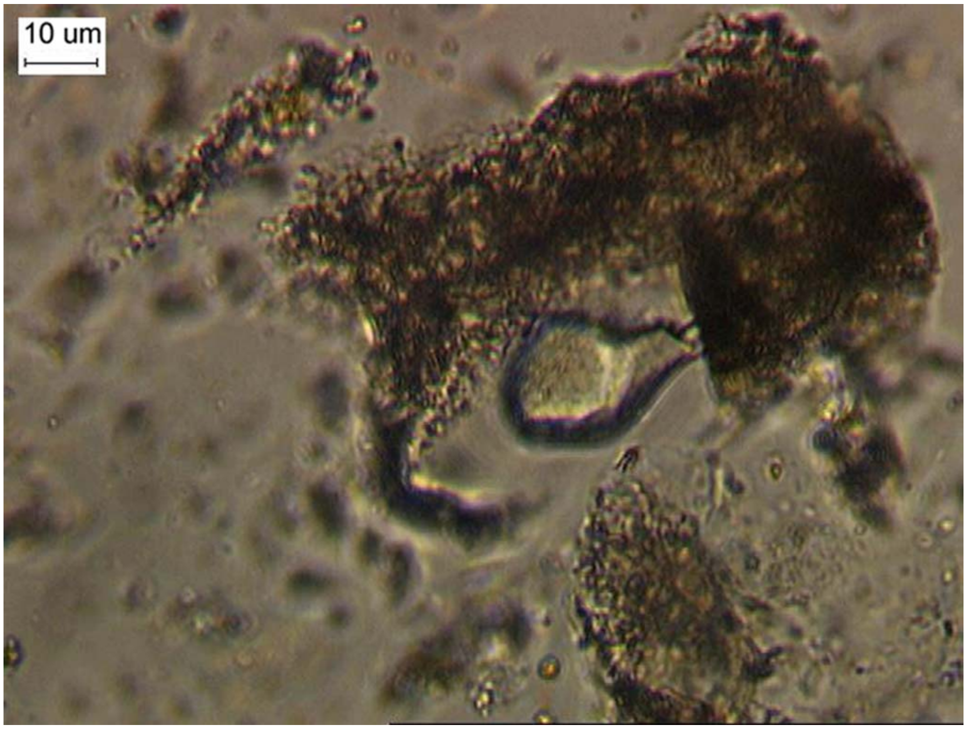

Figure 4. Unhydrated Core of Slag Particle in Immersion Mount of Pulverized Paste (9-1014)

these, the cracking was predominately a paste phenomenon, not involving the aggregates. Of the seven cases where paste cracking was prominent, four were fly ash concretes (1-2819, 1-6051, 2-1021, 4-1007), two were slag (3-1017, 9-6058), and one was portland (1-2820). All were in the later age group. Despite the apparent cracking, only one of these (4-1007) ranked in the top one-third for Ci and Cs and only two (1-2819 and 9-6058) in the middle one-third for Ci.

In four cases, cracking of paste and coarse aggregate was noted along with the presence of reaction products indicating ASR involvement in the distress. Three of these cases involved carbonate rocks. One of these rocks (8-1002) is known to be expansive in the accelerated mortar-bar test for ASR but also exhibits characteristics of alkali-carbonate rock (Lane, 1994). The occurrence of damaging AAR in 8-1002 has added significance since the concrete was produced with ground slag. Several issues need to be resolved: (1) the possibility of alkali-carbonate reaction with this aggregate since there are reports that ground slag is not effective in preventing this type of reaction (Rogers and Hooton, 1992); (2) questions of whether the paste quality was poor as a result of improper manufacturing such as late addition of excess water or as a result of chemical deterioration related to the aggregate reactions; and (3) the extent to which the deterioration noted in the core is manifested in the deck and affecting its actual performance. In this regard, it is interesting to note that this concrete ranked in the lower one-third for Ci and the lower one-half for Cs. The cases involving all three carbonate rocks should be examined in more detail to identify and characterize clearly the rocks involved and the reactions taking place.

The fourth case involves a quartzite coarse aggregate showing mild signs of ASR. This concrete (1-1132) was a straight portland cement mixture, but a companion structure (1-1133) contained fly ash. It also exhibits some features of ASR, occasional aggregate cracking, and reaction rims, but these seems manifested less than in 1-1132. These cases should be examined to determine the extent of manifestations on the decks and tracked to determine if damage associated with ASR progresses.

In five other cases, the presence of ASR product was noted with little or no evidence of associated damage. In one, 3-1003, a gneiss coarse aggregate was involved exhibiting some occasional cracks, reaction rims, and the "sweating" of reaction product into the adjacent paste. The sweating suggests the reaction product is of a fairly fluid nature and thus can move relatively freely through the paste microstructure without causing damage. The other cases involved only the appearance of reaction product sweating, primarily associated with chert particles.

In 16 of the decks, scaling of the top surface was noted based on the exposure of coarse aggregate. In 10 of the cases the exposure was near complete, with 6 of these cases being a more partial exposure. In these cases it was not clear whether the loss of surface material was the result of physical processes associated with freezing and thawing and deicing salts, or abrasive wear, or both. Scaling or excessive wearing can be associated with several factors, such as a high spacing factor or low strength, which can be tied to either the surface layer or the concrete as a whole. If the problem exists only in the surface layer, the evidence will disappear with the scaling. Another factor often cited is a tendency for fly ash and slag concretes to scale. However, of the 10 cases with significant scaling, only 1 contained fly ash and 2 contained slag. These 3 all had adequate spacing factors. Of the remaining 6, 2 had excessively high spacing factors, which might explain the problem, and 2 had excessively low spacing factors, suggesting low strength may be resulting in low abrasion resistance.

Structural flaws in the form of horizontal to sub-horizontal fractures or discontinuities were noted in seven cores. These flaws appear to be related to plastic cracking associated with settlement and poor consolidation. This type of flaw significantly reduces the protection of the steel when it occurs at or near the reinforcement plane and thus may negatively impact the performance of the deck. The structures involved were 1-1804, 1-6101, 2-1021, 3-1003, 5-2547, 8-1133, and 9-1002. Poor consolidation was noted in 3-1021 and 9-1002.

The observations made during the petrographic examinations were used to rate qualitatively the general condition of the concrete. The primary focus of the rating was on paste quality with an accumulation of several flaws resulting in a "poor" rating, two flaws a "fair" rating, and fewer a "good" rating. On this basis, 10 decks were rated "good," 15 "fair," and 11 "poor." Tables 5 through 7 present the distribution of decks across Ci, Cs, and electrical conductivity values, along with the petrographic quality rating and the materials group for the deck noted.

The highest Ci values were associated with the older group of concretes, with little relationship to the petrographic rating. This suggests that finer details of the microstructure in these concretes were at play than were resolvable at the magnifications used and a more detailed examination would be necessary to reveal them. With only a few exceptions, the fly ash and slag concretes clustered at the lower end of the Ci range, often even for concretes with a low petrographic rating. This indicates that these materials are effective in producing concretes that restrict fluid penetration, even under challenging conditions, although it is clear that good quality control during manufacturing should be exercised. For Cs, the values tended to range higher

Table 5. Distribution of Initial Absorption Values (Ci)

Equivalent W/CM from Laboratory Study							
	0.38		**0.48**			**0.58**	
Ci, mm/s $^{1/2}$ x 10^{-4}							
<10	**.<15**	**<20**	**<25**	**<30**	**<35**	**<40**	**>40**
4 2901 G2	3 1000 G4	8 1133 P2	2 1020 G2	9 2801 F1	4 1007 P3	1 1804 P1	9 1139 F2
	2 1009 F3	1 2820 F2	9 6058 P4	9 1098 F3	9 1031 F2		4 1062 F1
	1 6051 P3	2 1021 G3	1 1133 F3	9 1014 F4	8 1019 F2		6 1032 P1
		5 2812 G4	9 6042 F1	3 1021 P1	7 1920 P2		5 1800 G1
		3 1017 G4	9 1002 P4				4 2049 F1
		8 1002 P4	5 2547 G2				2 2007 G1
		1 2815 P3	1 2819 F3				1 6101 G1
		3 1003 F2	1 1132 F2				

Petrographic rating from Table 4: G – good, F – fair, P – poor.
Materials group: 1 – PCC 0.47; 2 – PCC 0.45; 3 – fly ash; 4 – ground slag.

Table 6. Distribution of Secondary Absorption Values (Cs)

Equivalent W/CM from Laboratory Study							
38	**48**		**58**				
Cs, mm/s $^{1/2}$ x 10^{-4}							
<7.5	**<10**	**<12.5**	**<15**	**<17.5**	**<20**	**<22.5**	**>22.5**
2 1009 F3	5 2812 G4	1 2815 P3	3 1003 F2	4 2049 F1	1 1132 F2	9 1014 F4	5 1800 G1
3 1000 G4	2 1021 G3	8 1133 P2	8 1002 P4	9 6058 P4	3 1021 P1	9 1139 F2	7 1920 P2
4 2901 G2	9 2801 F1	1 2820 F2	1 1133 F3	9 1002 P4	9 1098 F3	5 2547 G2	9 1031 F2
3 1017 G4	2 1020 G2	9 6042 F1	1 6101 G1			4 1007 P3	
	1 2819 F3	1 6051 P3				8 1019 F2	
		4 1062 F1				6 1032 P1	
		2 2007 G1					
		1 1804 P1					

Petrographic rating from Table 4: G – good, F – fair, P – poor.
Materials group: 1 – PCC 0.47; 2 – PCC 0.45; 3 – fly ash; 4 – ground slag.

Table 7. Distribution of Conductivity Values

Equivalent W/CM from Laboratory Study					
		38	**48**		**58**
Conductivity, Siemens/m x 10^{-3}					
<5	**<7.5**	**<10**	**<12.5**	**<15**	**.>15**
2 1021 G3	9 6058 P4	1 1133 F3	4 1007 P3	7 1920 P2	9 1139 F2
3 1017 G4	8 1133 P2	9 1014 F4	9 1031 F2		
9 2801 F1	9 1098 F3	1 1132 F2			
3 1000 G4	1 6051 P3	1 1804 P1			
5 2812 G4	1 2820 F2	8 1019 F2			
2 1009 F3	4 2049 F1	3 1003 F2			
1 2815 P3	2 1020 G2				
8 1002 P4	9 6042 F1				
9 1002 P4	4 2901 G2				
1 6101 G1	3 1021 P1				
1 2819 F3	2 2007 G1				
5 1800 G1					
5 2547 G2					
4 1062 F1					
6 1032 P1					

Petrographic rating from Table 4: G – good, F – fair, P – poor.
Materials group: 1 – PCC 0.47; 2 – PCC 0.45; 3 – fly ash; S4– ground slag.

than in the laboratory study. This suggests that for field concretes, there is less tendency to transition absorptive control from the capillary pores to the gel pores. This may reflect differences in curing or factors related to the long-term effects of field exposure. Interestingly, and counter-intuitively, the petrographic rating seemed to relate better to the Cs value than the Ci values. The electrical conductivity values were bunched at the low end of expected results. This could result from flawed conditioning procedures that failed to saturate the pore system or may reflect real changes in the pore solution chemistry or other concrete properties that affect the concrete's conductance. In either case, these results indicate that the good correspondence between electrical conductance and transport properties observed in concretes at early ages may not carry through for mature field concretes. As noted previously, Ozyildirim and Halstead (1991) noted a similar lack of correspondence between the electrical properties and the performance of bridge deck concretes.

The rate of absorption test provides a direct measure of fluid transport in concrete and is thus directly involved in the process of chloride ingress into concrete, which Ozyildirim and Halstead identified as the predominant cause of bridge deck deterioration. Two other projects are evaluating the actual chloride penetration into the decks evaluated in this study, and the synthesis of those results with the finding of this study will shed more light on the performance of these concretes.

CONCLUSIONS

- Nearly one-half of the deck concretes had absorption rates higher than those obtained with a portland cement concrete having a W/CM of 0.48 and moist cured for only 28 days.
- Based on the rate of absorption results, concretes containing fly ash and slag are effective in lowering the transport properties of concretes, even when petrographic characteristics suggest lower-than-normal quality.
- The electrical conductivity test does not seem to be an effective measure of the transport properties of mature field concretes.
- Fly ash and slag concretes are not inherently prone to scaling problems.
- The concrete alkalinity below the top few millimeters was sufficiently high in all concretes to maintain steel passivity.
- AAR appears pronounced in four bridge decks, three of which contain carbonate aggregate. In one of these, the presence of slag did not prevent the damage; however, its use in this case was by happenstance rather than by design to control reactivity.
- Most evidence of ASR did not appear to be associated with damage; however, monitoring of these structures should continue in the future.

- Horizontal to sub-horizontal flaws were noted in the cores removed from seven bridge decks. Such flaws may seriously impact the long-term performance of the deck.

- From the absorption data obtained in this study, desirable upper limits for Ci and Cs are 20×10^{-4} mm/s$^{1/2}$ and 10×10^{-4} mm/s$^{1/2}$, respectively, and represent the upper values for the lower third of results obtained.

RECOMMENDATIONS

1. *VDOT's Materials Division and Structure & Bridge Division should incorporate ASTM C 1585 rate of absorption tests in bridge evaluation programs as a primary measure of concrete quality.* Work should continue to define appropriate limits to be used in quality assessments including the development of the relationship between rate of absorption and chloride ingress.

2. *VDOT Materials Division and Structure & Bridge Division should consider the application of penetrating sealers or other means to impede solution penetration as a maintenance item for concretes with Ci values in excess of 25 to 30 x 10^{-4} mm/s$^{1/2}$.*

3. *VDOT should continue to use fly ash and slag in its concrete.*

4. *VDOT's Materials Division should increase it efforts to prevent the addition of too much water to plastic concrete.*

5. *VTRC should identify or develop non-destructive techniques that are effective in locating structural flaws in decks shortly after construction.*

6. *VTRC should carefully evaluate and monitor the structures identified with structural flaws in this study to determine how these flaws impact performance.*

7. *VTRC should more closely examine structures identified as being affected by AAR to determine the extent of the damage and to assess whether the reactions are still active.* The cases involving carbonate rocks should be evaluated to determine whether alkali-silica, alkali-carbonate, or both were involved.

8. *VTRC should undertake a study to assess the effectiveness of supplementary cementitious materials with carbonate rocks.*

COSTS AND BENEFITS ASSESSMENT

The benefits of the described research are believed to lie in improved knowledge of the behavior of the materials used to construct the transportation system, including the result that the use of fly ash and slag in concrete enhances its durability, and improvements in the assessment of the quality of the materials and prediction of performance that will enhance asset management. The implementation of the absorption test for deck evaluations should enable VDOT to perform more effective rehabilitations, thereby extending the life of the deck and saving money.

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