FABRICATING AND TESTING LOW-PERMEABILITY CONCRETE FOR TRANSPORTATION STRUCTURES

Celik Ozyildirim, Ph.D.
Principal Research Scientist

Virginia Transportation Research Council
(A Cooperative Organization Sponsored 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

August 1998
VTRC 99-R6

ABSTRACT

Many concrete structures are not providing the expected service life. Repairs are costly, cause inconvenience to motorists, and raise safety concerns. The durability of concrete depends on, among other things, the ability to resist the penetration of harmful solutions, e.g., chlorides. Recently, pozzolanic materials have been widely used to decrease the permeability of concretes. In this study, the permeability of concretes containing portland cement alone or portland cement with a pozzolan (fly ash, silica fume) or a slag was determined by either the rapid permeability test (AASHTO T 277) or the ponding test (AASHTO T 259). Concretes were tested with either test to determine the reduction in permeability with time.

Results show that both tests indicate the permeability of concretes. The rapid permeability test is more convenient and relatively faster than the ponding test. Permeability decreases with time, and the addition of pozzolans or slag is very effective in decreasing permeability.

FABRICATING AND TESTING LOW-PERMEABILITY CONCRETE FOR TRANSPORTATION STRUCTURES

Celik Ozyildirim, Ph.D.
Principal Research Scientist

INTRODUCTION

Concrete is widely and effectively used in transportation facilities. However, some concretes exposed to the environment have deteriorated rapidly, requiring expensive corrective measures. Concretes exposed to the environment are subject to intrusion by water and aggressive solutions that may result in four major types of deterioration: corrosion of the reinforcement, alkali-aggregate reactivity, freeze-thaw deterioration, and attack by sulfates.[1] In each case, physical or chemical changes occur within the concrete that cause expansion, leading to high stresses beyond the capacity of most concretes to withstand. One very effective method of minimizing these stresses is to reduce or minimize the intrusion of water and aggressive solutions. Since reducing the water–cementitious material ratio (W/CM) makes concretes more resistant to penetration of solutions, the American Concrete Institute recommends a maximum W/CM of 0.45 for concretes exposed to severe environments.[2]

Pozzolanic materials are now being widely used to decrease the permeability of concretes. Pozzolans react with lime produced in the hydration reaction and form a binder. The additional binder resulting from this pozzolanic reaction provides a low permeability and high-strength matrix.[3] Lime also accumulates at the interface between the matrix and the aggregate. Reactions with pozzolanic material in these regions create dense transition zones with enhanced properties.

Early work in measuring the permeability of concrete measured the flow of water under pressure.[4] This is a time-consuming process. Since chloride intrusion is the main source of distress in transportation structures, AASHTO adopted the ponding test, AASHTO T 259, which is also time-consuming. In this test, slabs are ponded with a salt solution for 90 days after a 42-day conditioning period. Then, samples are obtained from different depths and analyzed for chloride content to indicate the degree of penetration. Since the ingress of chloride into concrete follows Fick's diffusion equation, the ponding test also makes determining the diffusion coefficients possible.[5] Recently, a rapid and convenient electrical test called the rapid permeability test, AASHTO T 277 or ASTM 1202, began to be used to indicate the permeability of concretes. In this test, specimens are vacuum saturated and the next day subjected to a 60-volt DC for 6 hours. The resulting charge, in coulombs, is related to the chloride permeability. A charge of more than 4,000 coulombs indicates high chloride permeability; 2,000 to 3,000, moderate; 1,000 to 2,000, low; 100 to 1,000, very low; and less than 100 negligible. Some have questioned the validity of this test.[6] A Virginia Department of Transportation (VDOT) special provision being evaluated in the field requires the use of the rapid permeability test for acceptance and suggests the use of pozzolans or slag for extended service life.

PURPOSE AND SCOPE

The objectives of this study were (1) to evaluate the permeability of hydraulic cement concretes with and without a pozzolan (fly ash, silica fume) or a slag, (2) to determine the reduction in permeability with time, and (3) to compare the rapid permeability test and the ponding test by comparing the chloride contents and diffusion coefficients obtained from the ponding test with the coulomb values obtained from the rapid permeability test. Twenty-four batches of concrete containing different cementitious materials at different percentages were prepared at three W/CM: 0.35, 0.40, and 0.45. Concrete batches were prepared and tested in the laboratory using both the rapid permeability test and the ponding test.

METHODOLOGY

Mixes

Twenty-four batches of concrete were prepared with the proportions given in Table 1. The cementitious material content was 377 kg/m^3 except for the fly ash mixtures, which were higher (391 kg/m^3 for batches 5 and 8 and 415 kg/m^3 for batch 6) to obtain comparable strengths at 28 days. A Type II cement was used in all the mixtures. The chemical and the physical analyses of the cement, slag, fly ash, and silica fume are given in Table A-1 of the Appendix. The coarse aggregate was crushed granite gneiss, and the fine aggregate was natural sand. The nominal maximum size was 25 mm.

The concretes were prepared at three W/CM: 0.35, 0.40, and 0.45. All batches contained an air-entraining admixture and a water-reducing admixture at a rate of 2.0 ml/kg of cementitious material. A naphthalene-based high-range water-reducing admixture (HRWRA) was added as needed to achieve satisfactory workability. HRWRA was used in all concretes with a W/CM of 0.35 and 0.40 and in concretes containing silica fume and slag with a W/CM of 0.45. The lower W/CM concretes required more of the admixture. The combination of portland cement and silica fume at the W/CM of 0.35 required the most HRWRA. HRWRA enables a high dispersion of the cement particles, resulting in improved properties, and is expected to contribute to the higher strengths. The concretes were mixed in accordance with ASTM C 192. Specimens for testing in the hardened state were consolidated by rodding except for the ponding slabs, which were vibrated to ensure proper consolidation. Specimens for the compressive strength and the rapid permeability tests were moist cured until tested.

Testing

Slump, Air Content, and Unit Weight

In the freshly mixed state, the slump (ASTM C 143), air content (ASTM C 231), and unit weight (ASTM C 138) were measured.

Table 1. Mixture Proportions

Batch	Mixture (% PC/S/FA/SF)	W/CM	Cement (kg/m^3)	Slag (kg/m^3)	Fly Ash (kg/m^3)	Silica Fume (kg/m^3)	Fine Aggregate (kg/m^3)
1A	100/0/0/0	0.35	377				675
1B		0.40	377				627
1C		0.45	377				578
2A	95/0/0/5	0.35	358			19	669
2B		0.40	358			19	620
2C		0.45	358			19	572
3A	65/35/0/0	0.35	245	132			667
3B		0.40	245	132			618
3C		0.45	245	132			570
4A	50/50/0/0	0.35	189	188			664
4B		0.40	189	188			615
4C		0.45	189	188			567
5A	80/0/24/0	0.35	301		90		636
5B		0.40	301		90		588
5C		0.45	301		90		539
6A	79/0/31/0	0.35	298		117		610
6B		0.40	298		117		561
6C		0.45	298		117		513
7A	62/35/0/3	0.35	234	132		11	664
7B		0.40	234	132		11	615
7C		0.45	234	132		11	566
8A	77/0/24/3	0.35	290		90	11	632
8B		0.40	290		90	11	583
8C		0.45	290		90	11	535

Note: Coarse aggregate = 1,126 kg/m^3.

Compressive Strength

In the hardened state, 100-mm cylindrical specimens were tested for compressive strength (AASHTO T 22 with neoprene pads in steel end caps). Compressive strengths were determined at 3 and 28 days and 12 months.

Rapid Permeability Test

Cylindrical specimens (100 mm) were tested for chloride permeability using the rapid permeability test (AASHTO T 277 or ASTM C 1202) at 28 and 90 days and 12 and 32 months.

Ponding Test

Slabs measuring 300 by 300 by 75 mm were tested for chloride content by the ponding test (AASHTO T 259). In the ponding test, the chloride content of powdered samples obtained from 6 to 19 mm, 19 to 32 mm, 32 to 44 mm, and 44 to 57 mm were determined. The values are reported as chloride content at depths of 13 mm, 25 mm, 38 mm, and 50 mm. For this test, the standard cure is 2 weeks moist followed by air drying until an age of 42 days at which time a 3 percent sodium chloride solution is ponded on the surface. The standard ponding duration is 90 days. However, for low-permeability concretes, a 90-day ponding is not sufficient to observe differences with depth. Therefore, specimens were ponded as long as 30 months in this study.

Specimens were tested after ponding for 9, 15, and 30 months. Specimens with a W/CM of 0.40 were also tested at an earlier age of 4 months but only at the top two depths because of the short ponding time. To simulate field conditions, curing procedures that differ from the standard (42 days with the first 2 weeks moist cured) were also included for concretes with a W/CM of 0.40. These were (1) 7-day moist curing to simulate concretes exposed to solutions at a very early age after the initial curing as in the marine environment, and (2) 3 months moist curing to simulate concretes that are exposed to deicing chemicals after several months of natural curing. The samples for chloride analysis were obtained by drilling two holes 29 mm in diameter into a separate quadrant of the slab. The drill provides powdered samples that are analyzed by the acid titration method for the total chloride content. Results at 9 months appeared to be variable. A new drilling procedure was adopted for the 15- and 30-month tests whereby the top 0 to 6 mm, which was always discarded, was drilled with a larger 50-mm bit to prevent shavings from this salt-laden layer from contaminating successive layers.

Ponding Test (Diffusion Coefficients) versus the Rapid Permeability Test (Coulomb Values)

An attempt was made to develop a relationship between diffusion coefficients determined from the chloride contents obtained from the ponding test and coulomb values obtained from the rapid permeability test.

Drying Shrinkage

Beams measuring 75 by 75 by 285 mm were tested for drying shrinkage (ASTM C 157).

RESULTS AND DISCUSSION

Air Content, Slump, and Unit Weight

Table 2 gives the air content, slump, and unit weight. The air content ranged from 5.0% to 7.8% and met the bridge deck concrete requirement of 6.5% →1.5%. All mixes were workable,

Table 2. Characteristics of Freshly Mixed Concrete

Batch	Mixture (% PC/S/FA/SF)	W/CM	Air Content (%)	Slump (mm)	Unit Wt. (kg/m^3)	HRWRA (ml/100 kg cem)
1A	100/0/0/0	0.35	7.8	150	2288	977
1B		0.40	6.4	85	2320	331
1C		0.45	7.2	95	2275	0
2A	95/0/0/5	0.35	6.4	115	2333	1173
2B		0.40	6.8	100	2339	772
2C		0.45	6.0	115	2307	469
3A	65/35/0/0	0.35	7.8	205	2275	1095
3B		0.40	5.5	85	2339	331
3C		0.45	5.2	140	2339	469
4A	50/50/0/0	0.35	7.5	175	2281	938
4B		0.40	6.0	100	2300	276
4C		0.45	5.0	120	2313	117
5A	80/0/24/0	0.35	5.7	135	2326	750
5B		0.40	5.8	90	2307	212
5C		0.45	6.0	115	2281	0
6A	79/0/31/0	0.35	5.5	125	2345	782
6B		0.40	5.3	85	2326	226
6C		0.45	5.6	120	2294	0
7A	62/35/0/3	0.35	6.3	95	2313	860
7B		0.40	6.0	95	2365	386
7C		0.45	5.3	75	2307	0
8A	77/0/24/3	0.35	6.5	140	2320	865
8B		0.40	5.6	85	2320	292
8C		0.45	5.0	65	2313	0

with slump values ranging from 65 to 205 mm. Unit weights ranged from 2275 to 2365 kg/m^3, with lower values corresponding to high air contents as expected.

Compressive Strength

The compressive strengths are given in Table 3 and displayed in Figures 1 through 3 for different W/CM. The results show an increase in strength with age, and higher strengths with lower W/CM as expected. Concrete with portland cement and fly ash had the lowest 7-day and 28-day

Table 3. Compressive Strength

Batch	Mixture (% PC/S/FA/SF)*	W/CM	Strength (MPa)		
			7 Days	28 Days	1 Year
1A	100/0/0/0	0.35	48.8	58.9	76.7
1B		0.40	33.9	41.3	51.6
1C		0.45	24.1	33.1	40.2
2A	95/0/0/5	0.35	54.2	63.4	79.6
2B		0.40	39.9	51.4	61.3
2C		0.45	30.5	43.4	51.8
3A	65/35/0/0	0.35	49.9	68.5	83.6
3B		0.40	33.9	48.5	57.4
3C		0.45	32.9	51.2	63.8
4A	50/50/0/0	0.35	47.2	66.3	80.6
4B		0.40	31.2	52.4	67.2
4C		0.45	23.3	44.3	57.9
5A	80/0/24/0	0.35	40.0	52.8	80.8
5B		0.40	26.2	36.4	56.9
5C		0.45	20.0	29.7	46.0
6A	79/0/31/0	0.35	38.5	52.4	80.8
6B		0.40	25.6	37.4	63.8
6C		0.45	19.6	30.2	48.1
7A	62/35/0/3	0.35	44.5	67.2	78.5
7B		0.40	34.2	53.0	65.2
7C		0.45	21.9	40.5	53.6
8A	77/0/24/3	0.35	41.4	56.1	76.5
8B		0.40	29.8	41.3	59.6
8C		0.45	22.1	33.0	47.4

*Percentages are based on total control quantity of 377 kg/m^3.

strengths. However, even the lowest strength in concretes with fly ash was close to 20 MPa at 7 days and 30 MPa at 28 days at the highest W/CM of 0.45. The minimum 28-day design strength for bridge deck concrete is 28 MPa. Strength improved greatly with a decrease in W/CM. At 1 year, concretes with pozzolans or slag had higher strengths than the controls with portland cement only except in the mixture with fly ash and silica fume at a W/CM of 0.35, where they were about equal. Generally, the concretes with slag had the highest strengths. At 1 year, at a W/CM of 0.35, concretes had strengths ranging from 76.5 to 83.6 MPa and at a W/CM of 0.45 from 40.2 to 63.8 MPa.

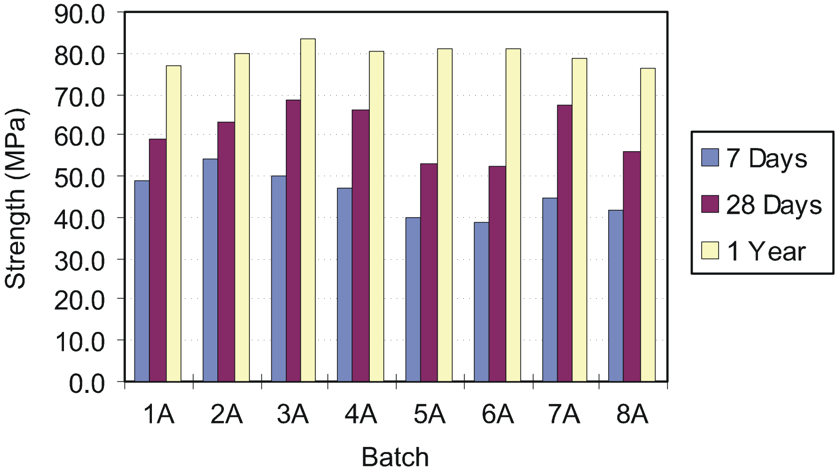

Figure 1. Strength of Concretes with a W/CM of 0.35

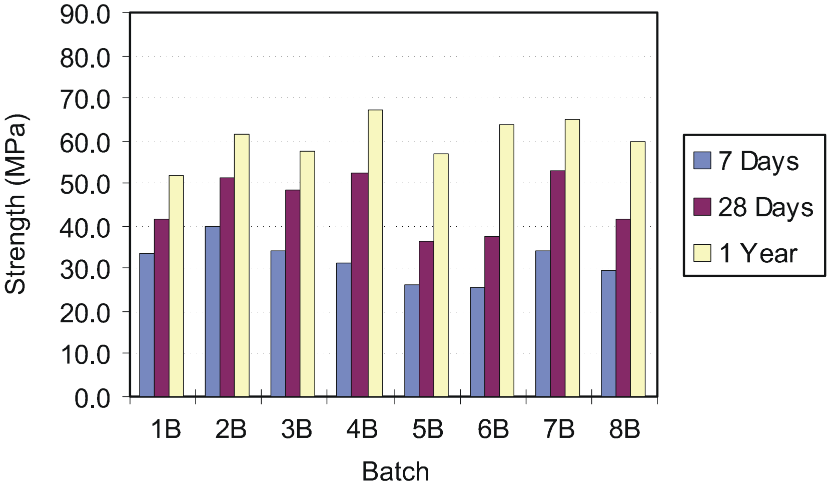

Figure 2. Strength of Concretes with a W/CM of 0.40

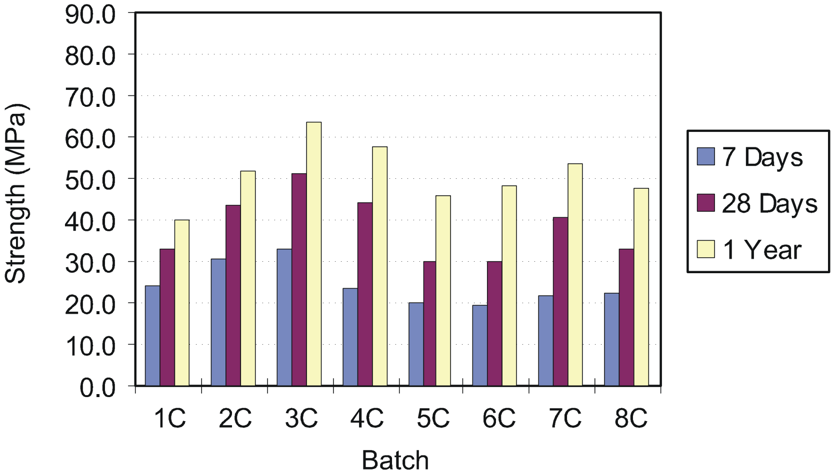

Figure 3. Strength of Concretes with a W/CM of 0.45

Rapid Permeability Test

Coulomb values are given in Table 4 and are displayed in Figures 4 through 6 for different W/CM. The results show that permeability decreases with time. Figure 7 shows that the reduction in permeability is different for each concrete. The effectiveness of pozzolans or slag in reducing permeability is clearly demonstrated. Reducing the W/CM also reduces the permeability, but the effect of W/CM is less than the presence of the pozzolans or slag.

Table 4. Permeability

Batch	**Mixture (% PC/S/FA/SF)**	**W/CM**	**Permeability (C)**			
			28 Days	**90 Days**	**1 Year**	**32 Months**
1A	100/0/0/0	0.35	2820	2229	1688	1514
1B		0.40	3905	3043	2508	2402
1C		0.45	4384	3457	3187	2492
2A	95/0/0/5	0.35	864	515	501	599
2B		0.40	1122	710	813	936
2C		0.45	1556	933	1021	1086
3A	65/35/0/0	0.35	1441	1244	885	780
3B		0.40	2239	1635	1374	1238
3C		0.45	2510	1672	1257	1070
4A	50/50/0/0	0.35	1216	903	657	628
4B		0.40	1727	1066	848	878
4C		0.45	2166	1192	929	912
5A	80/0/24/0	0.35	3371	1013	276	181
5B		0.40	6263	1706	499	326
5C		0.45	6999	1984	505	322
6A	79/0/31/0	0.35	2924	837	214	167
6B		0.40	5733	1215	313	210
6C		0.45	5427	1232	342	222
7A	62/35/0/3	0.35	1270	563	392	388
7B		0.40	1666	692	501	496
7C		0.45	2259	814	651	704
8A	77/0/24/3	0.35	1454	490	225	150
8B		0.40	2689	842	297	216
8C		0.45	2219	711	274	201

*Percentages are based on total control quantity of 377 kg/m^3.

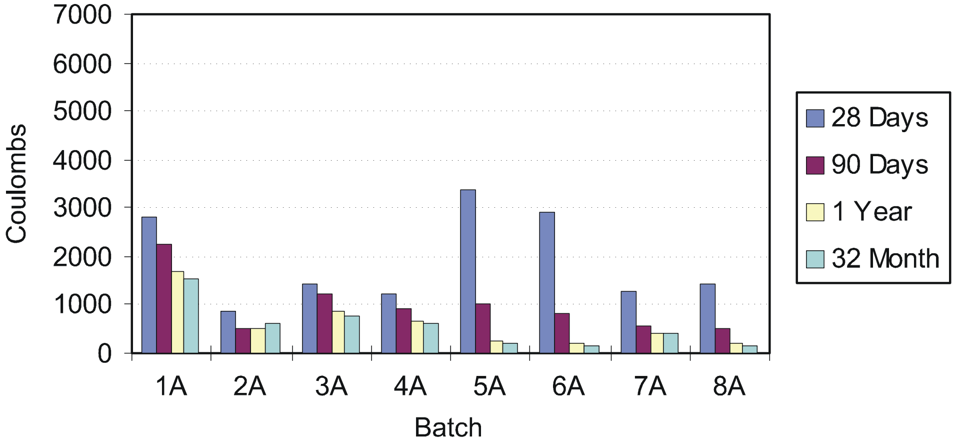

Figure 4. Permeability of Concretes with a W/CM of 0.35

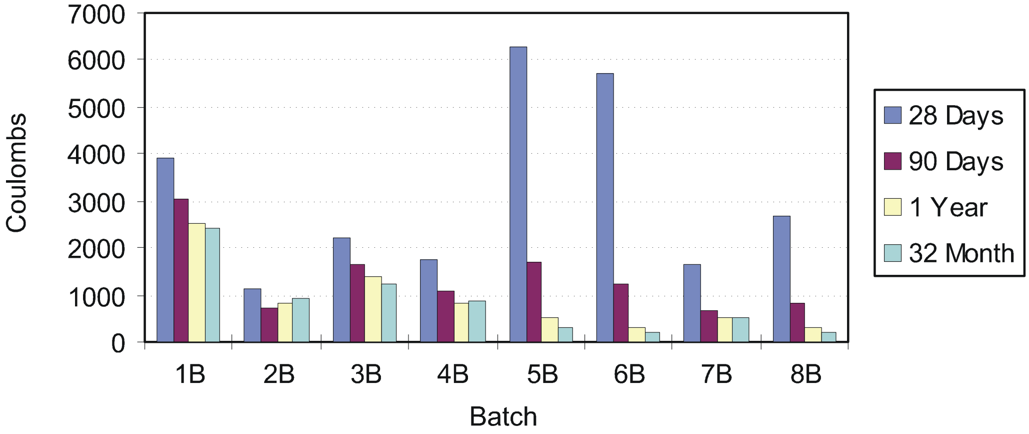

Figure 5. Permeability of Concretes with a W/CM of 0.40

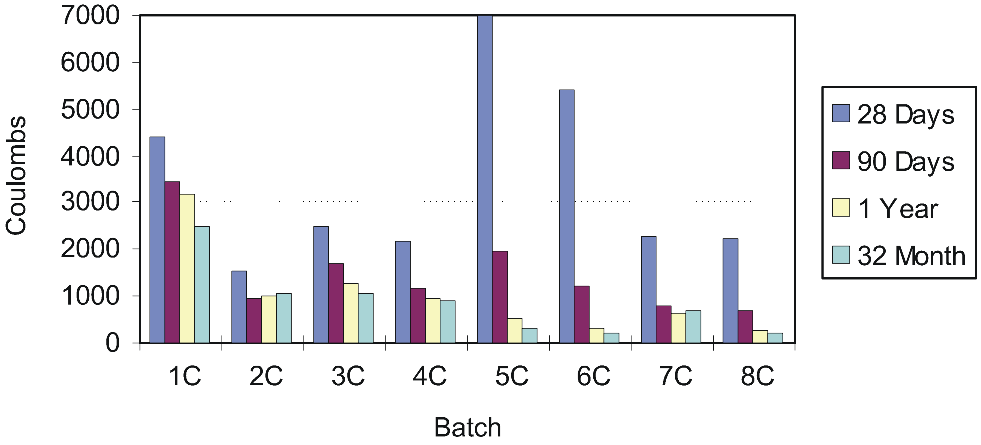

Figure 6. Permeability of Concretes with a W/CM of 0.45

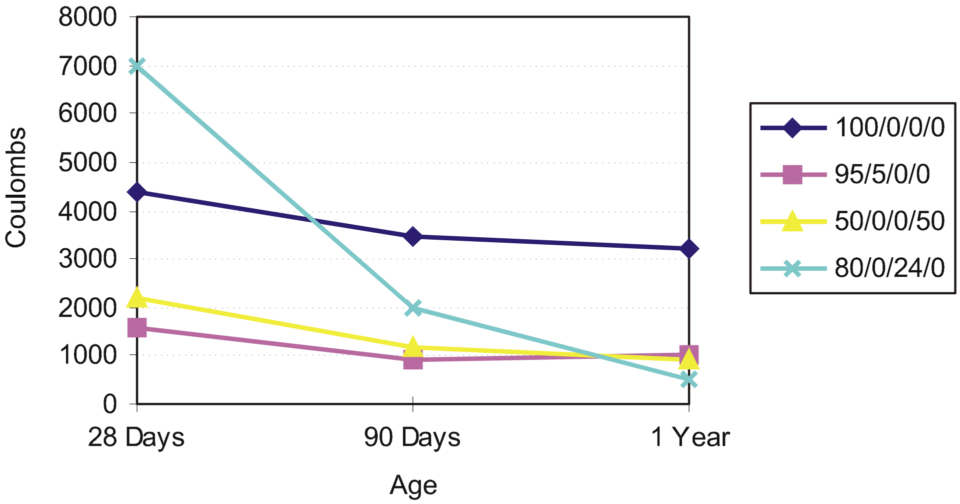

Figure 7. Reduction in Permeability with Time for Concretes with a W/CM of 0.45

Ponding Test

The chloride contents obtained at two depths after ponding for 4 months for concretes with a W/CM of 0.40 are given in Table 5. The chloride contents at four depths after ponding for 15 and 30 months are also given in Tables 5 and 6, respectively. The test results at 9 months are omitted because the data were inconclusive. Results varied widely, especially at the top two depths, and included values higher than at 15 months. This was attributed to sampling error. It is believed that the chloride-contaminated concrete on top was inadvertently mixed with powdered concrete in the lower depth through shaving of the top surface layer. To correct the problem, a larger hole, 50 mm in diameter, was drilled on the surface to discard the top 6 mm of concrete, and then the regular bit, 29 mm in diameter, was used to drill to avoid shavings from the top heavily salted layer. The results indicate that at 4 months, when tested with standard cure, all concretes had chloride contents exceeding the corrosion threshold value of 0.77 kg/m^3 at the upper average depth of 13 mm. The control concrete had the highest chloride value of 2.39 kg/m^3 at the 13-mm depth. The corrosion threshold value is the concentration of chlorides sufficient to initiate corrosion of the reinforcing steel and is about 0.77 kg/m^3 for bridge deck concretes used in Virginia.[7] At the second depth of 25 mm, all the concretes had chloride contents below the corrosion threshold as expected. The ponding period of 4 months was not long enough to discern differences with depth.

The 15-month results indicate that all the concretes with a W/CM of 0.40 subjected to three curing periods of 7 days, 42 days, and 90 days had a high chloride content exceeding the threshold value at the top 13-mm layer. At the 25-mm layer, control concretes had values exceeding the threshold value, but all pozzolanic systems except one had values below the threshold. At a W/CM of 0.45, only the standard 42-day curing was used. All concretes had high chloride contents at the 13-mm depth. At the 25-mm depth, the control concrete had a chloride content almost 5 times the corrosion threshold value whereas all of the concretes with pozzolans or slag had very low or negligible values less than the threshold value. At the lower depths of 38 and 51 mm, low or negligible chloride content values were obtained except that the control concrete had a value closer

Table 5. Chloride Values (kg/m^3)

Mix	Core Depth (mm)	4 months (w/c = 0.40)	15 months (w/c = 0.35)	15 months (w/c = 0.40)			15 months (w/c = 0.45)
		42d	42d	7d	42d	90d	42d
Batch 1	13	2.39	2.58	5.41	7.62	5.03	10.99
100/0/0/0	25	0.18	0.28	1.79	2.36	0.87	3.72
	38		0.00	0.06	0.28	0.01	0.59
	51		0.00	0.00	0.02	0.00	0.05
Batch 2	13	1.34	0.87	5.80	3.55	4.31	3.67
95/0/0/5	25	0.09	0.00	0.32	0.23	0.36	0.30
	38		0.00	0.00	0.07	0.00	0.00
	51		0.00	0.04	0.03	0.04	0.00
Batch 3	13	0.91	0.91	7.06	6.33	1.28	6.98
65/35/0/0	25	0.03	0.00	0.41	0.07	0.00	0.18
	38		0.00	0.00	0.00	0.16	0.00
	51		0.00	0.00	0.00	0.00	0.00
Batch 4	13	1.02	1.42	4.00	5.14	5.18	6.91
50/50/0/0	25	0.00	0.00	0.47	0.15	0.00	0.15
	38		0.00	0.00	0.03	0.06	0.00
	51		0.00	0.00	0.03	0.00	0.00
Batch 5	13	1.67	4.26	8.02	7.12	2.55	9.14
80/0/24/0	25	0.08	0.05	0.82	0.28	0.08	0.59
	38		0.00	0.00	0.10	0.00	0.07
	51		0.05	0.00	0.00	0.00	0.05
Batch 6	13	1.84	3.60	5.32	3.42	2.49	5.41
79/0/31/0	25	0.21	0.20	0.28	0.12	0.04	0.27
	38		0.08	0.00	0.08	0.00	0.00
	51		0.08	0.00	0.04	0.01	0.00
Batch 7	13	1.24	0.71	6.37	4.72	3.95	6.55
62/35/0/3	25	0.10	0.03	0.28	0.06	0.18	0.18
	38		0.00	0.00	0.03	0.04	0.00
	51		0.00	0.01	0.07	0.05	0.01
Batch 8	13	1.24	2.79	5.81	4.31	2.40	5.20
77/0/24/3	25	0.11	0.00	0.15	0.28	0.14	0.29
	38		0.07	0.00	0.08	0.03	0.00
	51		0.00	0.00	0.11	0.00	0.07

Table 6. Chloride Values (kg/m^3)

Mix	Core Depth (mm)	30 months (W/CM = 0.35)	30 months (W/CM = 0.40)			30 months (W/CM = 0.45)
		42d	7d	42d	90d	42d
Batch 1	13	1.57	4.45	7.38	3.03	9.10
100/0/0/0	25	0.00	2.47	3.85	1.20	5.36
	38	0.00	0.39	1.75	0.00	2.47
	51	0.00	0.00	0.00	0.00	0.67
Batch 2	13	0.67	4.05	3.69	3.79	5.68
95/0/0/5	25	0.00	0.28	0.00	0.22	1.67
	38	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	0.00	0.00
Batch 3	13	0.91	4.81	6.18	2.55	5.69
65/35/0/0	25	0.00	0.00	0.00	0.00	0.50
	38	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	0.00	0.00
Batch 4	13	1.02	4.54	3.50	5.41	9.64
50/50/0/0	25	0.00	0.00	0.00	0.00	0.44
	38	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	0.00	0.00
Batch 5	13	5.63	5.92	5.45	2.11	11.67
80/0/24/0	25	0.00	0.42	0.00	0.00	1.69
	38	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	0.00	0.00
Batch 6	13	4.49	6.27	2.59	1.64	10.99
79/0/31/0	25	0.00	0.00	0.00	0.00	0.69
	38	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	0.00	0.00
Batch 7	13	0.21	4.20	4.70	7.58	11.48
62/35/0/3	25	0.00	0.00	0.00	0.00	1.37
	38	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	0.00	0.00
Batch 8	13	3.75	6.41	6.14	3.22	7.04
77/0/24/3	25	0.10	0.30	0.17	0.00	0.54
	38	0.00	0.00	0.00	0.00	0.00
	51	0.00	0.00	0.00	0.00	0.00

to the threshold value at the 38-mm depth. Concretes with a W/CM of 0.35 also had the standard 42-day cure. At the 13-mm depth, chloride contents were above the threshold value except for the fly ash and silica fume combination. The values were lower than those obtained for higher W/CM. At lower depths, all the values were low or negligible.

At 30 months of ponding, results similar to the 15-month ponding were obtained. At a W/CM of 0.40, again the control had high chloride values at the 25-mm depth and even the 38-mm depth for the standard cure, and the concretes with pozzolans or slag had very low or negligible values. At the W/CM of 0.45, control had high chloride contents at the 25-mm and 38-mm depth. Some of the concretes with the pozzolans or slag had high chloride contents (above the threshold) at the 25 mm depth, but the values were lower than the controls and at 38 mm all pozzolanic systems had very low or negligible values. At the W/CM of 0.35 concretes had negligible values at the 25 mm and lower depths.

Ponding Test (Diffusion Coefficients) versus Rapid Permeability Test (Coulomb Values)

Many concretes had negligible (basically zero) chloride content at depths below the top 13-mm depth. The validity of diffusion coefficients in the presence of one value is questionable. Further, the properties of concretes at the top 13-mm depth are affected largely by finishing and curing and would affect the chloride content. Therefore, a quantitative relationship between the diffusion coefficients and the coulomb values was not pursued. However, the absence of any chlorides with depth after a long period of ponding in the concretes with pozzolans and slag and in control concretes at a W/CM of 0.35 indicates that these concretes have a high resistance to penetration. Similarly, these concretes had low or very low coulomb values, indicating high resistance to penetration. The ability of the concretes with a lower W/C ratio and those with pozzolanic material to have lower coulomb values was used in the development of VDOT’s low-permeability specification.

Drying Shrinkage

The drying shrinkage values are given in Table 7 at 4, 8, 32, and 64 weeks, and the 64-week data are displayed in Figure 8. The values ranged from 0.0465 to 0.0670 percent at 64 weeks, with higher values corresponding to concretes having higher W/CM or water contents. Control concretes and some concretes with fly ash that had high cementitious material or paste contents (batches 5 and 6) had higher shrinkage.

CONCLUSIONS

- The strength of concrete increases with age and with a reduction in W/CM.

- The permeability of concrete decreases with time.

- Concretes with pozzolans or slag have a higher resistance to chloride penetration than the controls. For a W/CM of 0.35, differences are not apparent and longer ponding periods are needed to discern between different concretes.

- Shrinkage is greater in control concretes and in some concretes with a higher W/CM and water and paste content.

Table 7. Shrinkage

Batch	**Mixture**	**W/CM**	**Length Change (%)**			
	(% PC/S/FA/SF)		**4 weeks**	**8 weeks**	**32 weeks**	**64 weeks**
1A	100/0/0/0	0.35	0.0375	0.0455	0.0525	0.0525
1B		0.40	0.0410	0.0495	0.0630	0.0670
1C		0.45	0.0305	0.0435	0.0595	0.0650
2A	95/0/0/5	0.35	0.0285	0.0335	0.0430	0.0470
2B		0.40	0.0330	0.0385	0.0490	0.0515
2C		0.45	0.0330	0.0410	0.0540	0.0595
3A	65/35/0/0	0.35	0.0300	0.0370	0.0435	0.0470
3B		0.40	0.0330	0.0440	0.0550	0.0590
3C		0.45	0.0295	0.0390	0.0505	0.0550
4A	50/50/0/0	0.35	0.0335	0.0405	0.0480	0.0465
4B		0.40	0.0290	0.0350	0.0440	0.0465
4C		0.45	0.0310	0.0390	0.0500	0.0505
5A	80/0/24/0	0.35	0.0450	0.0500	0.0555	0.0565
5B		0.40	0.0485	0.0545	0.0620	0.0635
5C		0.45	0.0420	0.0515	0.0610	0.0635
6A	79/0/31/0	0.35	0.0430	0.0505	0.0505	0.0505
6B		0.40	0.0505	0.0600	0.0625	0.0630
6C		0.45	0.0460	0.0540	0.0655	0.0670
7A	62/35/0/3	0.35	0.0260	0.0405	0.0435	0.0400
7B		0.40	0.0335	0.0460	0.0510	0.0490
7C		0.45	0.0300	0.0440	0.0505	0.0510
8A	77/0/24/3	0.35	0.0335	0.0390	0.0460	0.0460
8B		0.40	0.0345	0.0400	0.0495	0.0495
8C		0.45	0.0325	0.0415	0.0550	0.0550

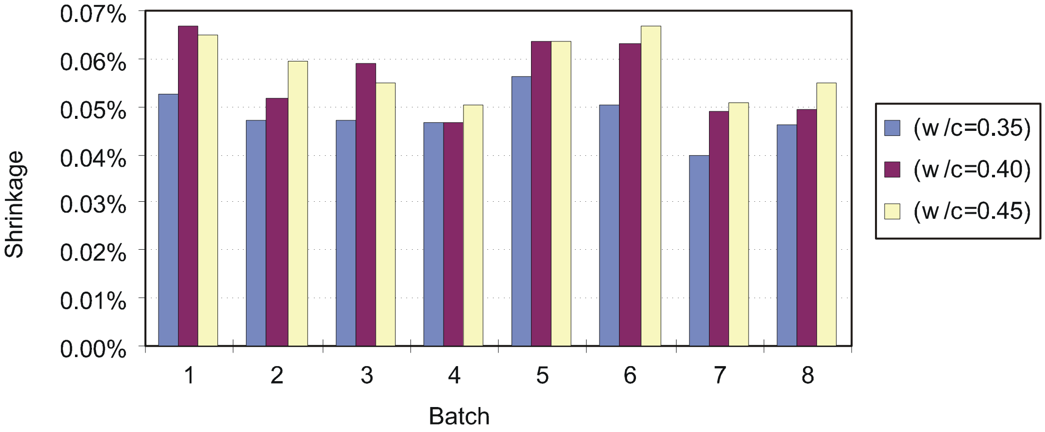

Figure 8. Shrinkage at 64 Weeks

RECOMMENDATIONS

- For durable concretes, use pozzolans or slag.
- Test concretes for permeability using the rapid permeability test because it provides useful information in a short time regarding the resistance of concretes to the penetration of harmful solutions.
- Include VDOT's low-permeability specification in future projects.
- Conduct further work with increased ponding times and/or testing for chloride content in thin layers (possibly 1-mm thick) for more discernable data points to enable the determination of diffusion coefficients.

REFERENCES

1. Ozyildirim, C. 1993. Durability of concrete bridges in Virginia. *ASCE Structures Congress XI Proceedings: Structural engineering in natural hazards mitigation.* New York: American Society of Civil Engineers, pp. 996-1001.

2. American Concrete Institute. *ACI 201, Guide to durable concrete.* Farmington Hills, Mich.

3. Ozyildirim, C. 1994. Resistance to penetration of chlorides into concretes containing latex, fly ash, slag, and silica fume. *ACI SP-145, Concrete durability*, pp. 503-513. Farmington Hills, Mich.: American Concrete Institute.

4. Whiting, D. 1981. *Rapid determination of the chloride permeability of concrete*. FHWA/RD-81/119. Washington, D.C.: Federal Highway Administration.

5. Weyers, R.E., and Cady, P.D. 1987. Deterioration of concrete bridge decks from corrosion of reinforcing steel. *Concrete international: Design and construction*, Vol. 9, No. 1, pp. 15-20.

6. Sherman, M.R., McDonald, D.B., and Pfeifer, D.W. 1996. Durability aspects of precast prestressed concrete. Part 1: Historical review, and Part 2: Chloride permeability study. *PCI Journal,* July-August, pp. 62-95.

7. Clear, K.C. 1976. *Time-to-corrosion of reinforcing steel in concrete slabs: Vol. 3*. FHWA-RD-76-70. Washington, D.C.: Federal Highway Administration.

APPENDIX

CHEMICAL AND PHYSICAL ANALYSIS OF CEMENT, SLAG, FLY ASH, AND SILICA FUME

Table A-1. Chemical and Physical Analyses of Cement, Slag, Fly Ash, and Silica Fume

Analyses	Cement	Slag	Fly Ash	Silica Fume
Chemical (%)				
SiO_2	21l8	35.2	53.0	94.6
Al_2O_3	4.5	10.7	31.3	0.3
Fe_2O_3	2.9	1.0	5.6	0.1
CaO	63.0	37.9	1.0	0.5
MgO	3.0	13.0	0.5	0.4
SO_3	2.7	0.8	0.5	0.0
Na_2O equivalents (total alkalies)	0.69	0.28	1.36	0.52
Physical fineness (-325)		98.2%		99.5%
Blaine (m2/kg)	372	494		