SPECIAL REPORT

Durability Aspects of Precast Prestressed Concrete Part 2: Chloride Permeability Study

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A laboratory study was undertaken to investigate the good past performance of low water-cement ratio, heat-cured precast, prestressed concrete in highway bridges, parking garages, and other applications. The study included salt water ponding testing, AASHTO T 277 or ASTM C 1202 "coulomb" tests, compressive strength tests, and absorption and volume of permeable voids tests. Heat-cured, water-cured, and moist-cured concretes with water-cementitious ratio values of 0.46, 0.37 and 0.32 with and without silica fume were tested. Using the measured chloride contents, chloride diffusion coefficients were calculated and estimates of the time-to-corrosion were developed. The water-cement ratio was found to be the most important influence on the performance of the concrete, with low w/c, heat-cured conventional concretes having comparable performance to realistic silica fume concretes having 0.37 to 0.46 water-cementitious ratios. It was also found that the use of heat curing could reduce the permeability of AASHTO-grade, 0.46 w/c concrete by 40 to 50 percent. The addition of silica fume to concrete caused an increase in the absorption and volume of permeable voids in concrete, while heat curing was seen to decrease the absorption and volume of permeable voids in concrete.

The excellent durability of heat-cured, precast, prestressed concrete bridge and parking garage structures over the past 45 years, resulting from the use of water-cement ratios (w/c) between 0.30 and 0.40, is discussed in Part 1 of this report.[1]

In Part 1, a review of literature from 1960 to 1994 was performed to explain the history and past performance of precast, prestressed concrete highway, parking, and other structural concrete systems exposed to large amounts of chloride, and freezing and thawing. Essentially, all of these precast, prestressed concrete structural members were heat cured or steam cured without any in-plant supplemental moist curing following the overnight heat curing.

A 1987 Federal Highway Administration (FHWA) study[2] showed that the chloride permeabilities of heat-cured AASHTO-grade 0.44 w/c concretes with or without calcium nitrite were about 50 percent lower at the 1 in. (25 mm) depth, when compared to identical moist-cured conventional 0.44 w/c concrete after a severe 1-year cyclic salt water and air-drying test period on full-sized columns, beams, and bridge deck panels.

To verify this performance, the Precast/Prestressed Concrete Institute (PCI) funded this comprehensive 1-year laboratory study to answer questions relating to chloride permeability, water absorption, volume of permeable voids, compressive strength, coulomb values, diffusion coefficients, and times-to-corrosion for a wide range of heat-cured and moist-cured concretes.

The water-cement (w/c) values used for the conventional concretes were 0.46, 0.37, and 0.32, representative of typical AASHTO 0.45 w/c concrete, and of 0.37 to 0.32 w/c values commonly used in the precast concrete industry. Silica fume additions of 5.0 and 7.5 percent by mass of cement were also studied. The three conventional concretes were cured either in a water tank, under wetted burlap, or under wetted burlap in a heated chamber, while the silica fume concretes were cured under wetted burlap only.

While silica fume additions were used at all three water-cementitious materials ratios (w/cm), it is well recognized that silica fume concretes with 0.37 to 0.32 w/cm require more effort, experience, and knowledge to place and finish due to stickiness, slump loss, air loss, and a lack of bleed water, particularly when used for jobsite flatwork. In addition, if proper curing procedures are not followed, concretes containing silica fume with w/cm levels of less than 0.39 are more susceptible to cracking that has been ascribed to plastic shrinkage and self-desiccation.[3]

Field experience indicates that practical silica fume mixtures for cast-in-place concrete flatwork use w/cm values of about 0.40 to 0.45. Therefore, although this laboratory study used 0.32, 0.37, and 0.46 w/cm levels with both silica fume addition rates, the realistic corrosion performance comparisons should acknowledge that the lower 0.37 to 0.32 w/cm silica fume mixtures can be difficult to handle, consolidate and cure, especially with flatwork.

The main focus of the study was to determine chloride ingress of the various concretes subjected to salt water ponding. These tests were conducted using the AASHTO T 259 procedure,[4] except that the normal 90-day ponding period was increased to 365 days to provide more accurate chloride diffusion data. The 90-day period is too short to allow appreciable chloride ingress into these high quality concretes and to allow the calculation of diffusion coefficients. AASHTO T 277 or ASTM C 1202 "coulomb" tests,[5,6] ASTM C 32 compressive strength tests, and ASTM C 642 absorption and volume of permeable voids tests[7] were also performed.

MIXTURE PROPORTIONS AND SPECIMEN PREPARATION

Fifteen concrete conditions were tested to determine the influence of curing and silica fume additions on concrete permeability. When silica fume was used, the portland cement content was unchanged and silica fume solids were added to the constant cement contents at 5.0 and 7.5 percent by mass of cement. The testing matrix consisted of five groups of mixes, each tested at three different w/cm. These groups are:

- Conventional concrete — tank cure
- 5 percent silica fume concrete — burlap cure
- 7.5 percent silica fume concrete — burlap cure
- Conventional concrete — burlap cure
- Conventional concrete — heat cure

Materials

The same aggregate, sand, cement, and silica fume were used for all of the mixtures. The cement was LaFarge Type I. The high-range water-reducing admixture (HRWRA) was WRDA-19 and the air-entraining admixture (AEA) was Daravair. The coarse aggregate was a chloride-free river gravel from Eau Claire, Wisconsin, with a nominal maximum size of $^3/_4$ in. (19 mm). The fine aggregate was a river sand, also from Eau Claire, Wisconsin. The silica fume was Force-10,000, supplied in a densified powder form.

During batching, the silica fume was premixed with an equal mass of water using a high speed electric mixer to form a slurry. The slurry was slowly added to the concrete during mixing. The water mixed with the silica fume was accounted for in the batch quantities. The mixes were cast in groups, with all three w/cm concretes of a given group being cast during the same morning.

Mixture Proportions and Plastic Concrete Characteristics

The concrete proportions are shown in Table 1, as well as the measured slump, air, and unit weight. The aggregate moisture contents were determined immediately prior to casting. All quantities are the saturated surface-dry (SSD) quantities. The quantities have been corrected to account for the water present in the AEA dilution, but not for the water in the original AEA or HRWRA. All mixtures were proportioned to contain the same amount of coarse aggregate, compensating for changes in cement content by changing the amount of fine aggregate.

Table 1. Mixture proportions (SSD quantities lb per cu yd) and unhardened concrete properties.

Curing type	**Tank cure**			**5 percent silica fume burlap cure**			**7.5 percent silica fume burlap cure**			**Burlap cure**			**Heat cure**		
Mixture number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Cement	808	679	527	796	689	540	805	691	540	793	694	535	802	686	543
Silica fume	0	0	0	40	34	27	60	52	40	0	0	0	0	0	0
Water	253	248	241	273	271	263	284	275	268	251	254	245	254	252	251
Sand	1258	1331	1445	1161	1278	1426	1136	1247	1393	1235	1361	1475	1249	1345	1498
$^3/_4$ stone	586	575	570	577	583	588	584	586	588	575	588	582	582	581	591
$^1/_2$ stone	659	646	641	649	656	661	657	659	661	647	661	655	654	653	665
$^3/_8$ stone	416	408	404	409	414	417	414	415	417	408	417	413	413	412	419
AEA (oz/cwt)*	2.2	2.6	1.9	4.9	4.5	2.6	5.1	3.6	2.3	2.8	2.8	1.5	2.8	3.1	2.2
HRWRA (oz/cwt)*	25.6	15.1	13.9	22.8	16.7	12.9	29.2	25.2	9.9	19.8	14.8	7.6	11.5	15.0	16.2
w/cm	0.31	0.37	0.46	0.33	0.38	0.46	0.33	0.37	0.46	0.32	0.37	0.46	0.32	0.37	0.46
Air (percent)	5.25	6.00	6.30	5.60	5.80	6.00	6.00	6.10	6.00	7.20	5.50	6.30	6.20	6.60	5.60
Slump (in.)	5.75	5.50	6.50	2.75	3.00	3.25	5.00	5.75	5.75	6.25	4.00	4.25	6.25	6.25	4.75
Unit weight (lbs/cu ft)	147.4	143.9	141.7	144.6	145.4	145.2	146.0	145.4	144.7	144.7	147.3	144.6	146.4	145.5	147.0

Note: 1 in. = 25.4 mm; 1 lb per cu ft = 16.018 kg/m^3; 1 lb per cu yd = 0.593 kg/m^3; 1 oz/cwt = 65.198 mL/100 kg.
* Computed based on the mass of cement.

Table 2. Cement content for concrete mixtures without silica fume.

Average w/cm	**Coefficient of variation (CV) of w/cm (percent)**	**Portland cement content**		**CV of portland cement content (percent)**
		bags/cu yd	**kg/m^3**	
0.32	2.6	8.52	476	0.8
0.37	1.2	7.32	409	0.8
0.46	0.0	5.70	318	1.4

Table 3. Slump, air content and unit weight of concrete mixtures.

	Average	**Range**
Slump, in. (mm)	5.00 (127)	+1.25, -2.25 (+32, -57)
Air content, percent	6.03	+1.17, -0.78
Fresh unit weight, lb per cu ft (kg/m^3)	145.4 (2329)	+2.0, -3.7 (+32, -59)

The mixtures without silica fume were proportioned to have essentially the same water content while the cement contents varied according to the w/cm, as shown in Table 2.

The average water content of the mixtures and their coefficient of variation (CV) were as follows:

- Conventional = 30.0 gal per cu yd (149 liters/m^3), 1.8 percent CV
- 5 percent fume = 32.3 gal per cu yd (159 liters/m^3), 2.0 percent CV
- 7.5 percent fume = 33.1 gal per cu yd (164 liters/m^3), 2.9 percent CV

The air contents, slumps, and plastic unit weights were carefully controlled, as shown in Table 3.

Mixing

The concrete was mixed in a horizontal rotary-pan mixer using a mixing sequence of 3 minutes, followed by 3 minutes of rest, and an additional 2 minutes of mixing. After the second mixing period, the concrete was tested to determine the air content, unit weight, and slump. If necessary, the AEA and HRWRA dosages were adjusted and the concrete remixed and retested.

Three 12 x 12 x 5 in. (300 x 300 x 125 mm) slabs and four 4 x 8 in. (100 x 200 mm) cylinders were cast from each batch, and a sample of mortar was sieved and retained for the ASTM C 403 time of setting tests.[8] For the heat-cured mixtures, an additional four cylinders were cast to determine the effect of the heat curing on concrete strength. All test slabs and cylinders from this single batch were compacted on a table vibrator and finished with a wooden float.

Curing and Specimen Preparation

The lime-saturated water and wet burlap cure duration was selected as 7 days in accordance with the 1992 AASHTO requirements in Section 8.11[9] and in accordance with the 1995 ACI requirements given in Section 5.11 of ACI 318.[10]

The overnight heat cure, followed by no moist curing, was in accordance with the 1992 AASHTO Section 8.11.3.5 requirements, which do not require any moist curing after the overnight heat curing. This represents the typical heat curing that has taken place for decades in precast concrete plants. A supplemental 6-day moist curing was required in the 1989 AASHTO specification if the heat-cured concrete was to be eventually exposed to salt water; otherwise, no additional moist curing was required. The supplemental moist curing requirement in the 1989 specification was not previously required[11] and it has once again been eliminated in 1992.

For the first 24 hours after casting, the water tank-cured and burlap-cured specimens were left in forms and covered with wet burlap. When they were stripped, the burlap-cured slabs (including all of the silica fume mixtures) were wrapped in wet burlap and plastic and kept continuously wet until the concrete was 7 days old. The water tank-cured slabs were placed in lime saturated water for 3½ days after they were stripped. After 3½ days in the tank, they were removed and wrapped in wet burlap for another 2½ days.

After removing the burlap at 7 days, all of these slabs were transferred to a controlled climate room (CCR) held at 72°F (22°C) and 50 percent relative humidity until further testing. All of the cylinders for the water tank-cured and burlap-cured mixes were placed in the lime saturated water curing tank after they were stripped at an age of 1 day and remained in the tank until age 28 days, at which time they were tested or moved into the CCR until testing at 180 days.

In accordance with Section 3.4.2 of the PCI Manual for Quality Control,[12] the specimens to be heat cured were held under wet burlap and plastic sheeting at the laboratory temperature until the concrete had reached time-of-initial setting as defined in ASTM C 403. The waiting period ranged from 3.7 to 4.5 hours. The three slabs and four cylinders were then brought at a rate of 30°F per hour (17°C/hour) in a controlled-environment chamber to an air temperature of 145°F (63°C). The concrete was held at 145°F (63°C) for 7.5 hours, then allowed to cool to ambient temperature.

Twenty-four hours after they were cast, all of the heat-cured slabs and cylinders were moved into the CCR without any further moist curing. For direct comparison to the strength cylinders cast from the other mixtures, four cylinders from the heat-cured mixtures were allowed to cure at room temperature in their molds for 24 hours, after which they were placed into lime-saturated water, where they remained until age 28 days.

At 28 days, the slabs were lightly sandblasted to remove surface laitance. Acrylic plastic dikes were attached to the surfaces of two of the three slabs and their sides were coated with a two-part epoxy. At an age of 37 days, two 4 in. (102 mm) diameter by 5 in. (127 mm) long cores were removed from the third undiked slab for later use in the rapid chloride permeability testing (AASHTO T 277 or ASTM C 1202).

Table 4. Time of setting of concrete mixtures.

Cure and mixture type	Mixture number	As-mixed w/cm	Time of setting (hours)	
			Initial	Final
Tank cure	1	0.31	7.1	—
	2	0.37	7.7	—
	3	0.46	—	—
Burlap cure 5 percent silica fume	4	0.33	6.0	—
	5	0.38	4.7	—
	6	0.46	4.4	—
Burlap cure 7.5 percent silica fume	7	0.33	5.3	—
	8	0.37	4.7	—
	9	0.46	3.7	—
Burlap cure	10	0.32	7.3	—
	11	0.37	5.5	—
	12	0.46	4.7	—
Heat cure	13	0.32	4.5	5.7
	14	0.37	4.2	5.2
	15	0.46	3.7	4.6

TEST RESULTS

Tests performed on the unhardened and hardened concrete included time of setting, compressive strength, absorption and volume of permeable voids, AASHTO T 277 or ASTM C 1202 coulomb testing, and long-term chloride content at different depths.

Time of Setting

All concrete mixtures were tested according to ASTM C 403, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." Only the times of initial setting were generally determined, as shown in Table 4. The times of initial setting of Mixtures 13, 14, and 15 were considerably shorter than the companion mixes without silica fume. This was due to the higher ambient temperature that day. The times of initial setting for all of the 0.32 w/cm mixtures were significantly longer than the 0.37 or 0.46 w/cm concretes due to the use of larger dosages of HRWRA required to achieve the lowest w/cm.

Compressive Strength

Cylinders from all 15 mixtures were tested to determine their 28-day, water-cured compressive strengths, as well as their 180-day strengths. These 60 test cylinders were all cured in the lime water tank until a concrete age of 28 days, except for four extra heat-cured cylinders cast from each of Mixtures 13, 14, and 15 that were placed into the CCR immediately after being removed from the heat-curing chamber. These 12 heat-cured cylinders were tested to determine if the preset period was sufficient to prevent 28-day strength damage to the concrete due to the heating process. To properly

Table 5. Compressive strength test results.

Cure and mixture type	As-mixed w/cm	Average 28-day compressive strength (psi)		Average 180-day compressive strength (psi)	
		Tank cure	Heat cure	Tank cure	Heat cure
Tank cure	0.31	6960	—	9330	—
	0.37	6520	—	7640	—
	0.46	5170	—	5910	—
Burlap cure 5 percent silica fume	0.33	7280	—	9050	—
	0.38	5370	—	7160	—
	0.46	5250	—	6110	—
Burlap cure 7.5 percent silica fume	0.33	8060	—	8650	—
	0.37	7200	—	8190	—
	0.46	5270	—	5770	—
Burlap cure	0.32	6880	—	9150	—
	0.37	6960	—	6880	—
	0.46	5390	—	6260	—
Heat cure	0.32	6560	6050*	7880	6600
	0.37	6560	5630*	6320	6440
	0.46	5590	5090*	6560	5170

Note: 1000 psi = 6.895 MPa.

* 10 percent less than measured strength.

account for the dry condition of the heat-cured cylinders at the time of testing, the 28-day measured strengths have been reduced by 10 percent.[13] The test results are listed in Table 5.

All of the 28-day strengths were over 5000 psi (34.5 MPa), with the lower w/cm concretes having the higher strengths, as expected. The effects of the silica fume addition on the 28-day strengths were varied. As compared to the burlap-cured conventional concrete control specimens, the addition of 5 percent silica fume resulted in 28-day strength changes of 5.8, -22.8, and -2.6 percent for the 0.33, 0.38, and 0.46 w/cm concretes, respectively. The poor performance of the 0.38 w/cm 5 percent silica fume is unexpected and unusual. This mixture did not exhibit any similarly unexpected results in other tests conducted in the program.

The addition of 7.5 percent silica fume resulted in strength changes of 17, 3.5, and -2.2 percent for the 0.33, 0.37, and 0.46 w/cm concretes, as compared to the burlap-cured conventional concrete specimens. The negative effect of the silica fume addition to the 0.38 and 0.46 w/cm mixtures is interesting, because the addition of silica fume material is typically expected to increase the concrete strength. Possibly, the additional water added to these silica fume mixtures to maintain the w/cm with the added silica fume material offset the normally expected strength increase. The 28-day strengths of all of the conventional water-cured mixtures were within 6 percent of the burlap-cured conventional concrete.

All of the 180-day strengths were over 5700 psi (39.3 MPa), with the lower w/cm concretes having the higher strengths, as expected. The effects of the silica fume addition on the 180-day strengths were again varied. As compared to the burlap-cured conventional concrete specimens, the addition of 5 percent silica fume resulted in 180-day strength changes of -1.1, 4.1, and -2.4 percent for the 0.33, 0.38, and 0.46 w/cm concretes, respectively. The addition of 7.5 percent silica fume resulted in strength changes of -5.5, 19.1, and -7.9 percent for the 0.33, 0.37, and 0.46 w/cm concretes, respectively, as compared to the burlap-cured conventional concrete specimens.

The overall negative effect of the silica fume addition to the 0.33 and 0.46 w/cm mixtures is again interesting, because the additional silica fume is typically expected to increase the concrete strength, especially at later concrete ages. The 180-day strengths of the tank-cured cylinders of the conventional concrete mixtures were within 11 percent of the nominally identical burlap-cured conventional concrete. This is a larger variation than was seen for the 28-day strengths.

The effect of heat curing was investigated by comparing the compressive strength test results from the heat-cured cylinders to the tank-cured cylinders from the same batch. Because normal weight concrete stored at 10 to 75 percent relative humidity after 7 days of initial moist curing can have 28-day compressive strengths about 10 percent higher than continuously moist-cured concrete,[13] the 28-day strengths of the heat-cured cylinder were reduced by 10 percent to account for the 27 days of air drying at 50 percent relative humidity following the overnight heat curing.

The 28-day strengths of the heat-cured cylinders (after 10 percent reduction) were 92, 86, and 91 percent of the companion tank-cured cylinders for the 0.32, 0.37, and 0.46 w/c concretes, respectively. The heat curing created no significant strength loss at 28 days and indicates that the preset period was appropriate. However, the 180-day strengths of the heat-cured specimens were 83, 102, and 79 percent of the tank-cured control concrete specimens for the 0.32, 0.37, and 0.46 w/c concretes, respectively.

Apparently, the tank-cured specimens continued to gain strength after being removed from the water curing tank at an age of 28 days, while the heat-cured specimens, when stored for 179 days in the controlled climate room drying environment at 73°F (22°C) and 50 percent relative humidity, remained at a nearly constant strength, with 180-day strengths 98, 103, and 92 percent of their 28-day strengths for the 0.32, 0.37, and 0.46 w/c concretes, respectively. Such long-term constant drying at 50 percent relative humidity would not occur outdoors and, therefore, these 180-day strengths are not typical as related to outdoor conditions.

Absorption and Volume of Permeable Voids

All 15 mixtures were tested according to ASTM C 642, "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete" to determine the water absorption after immersion, water absorption after immersion and boiling, and the volume of permeable voids in the concrete. This test was chosen to serve as an indicator of the short-term absorption characteristics of the concrete, as opposed to the long-term diffusion predominantly measured by the AASHTO T 259 long-term ponding tests. The test is performed by oven-drying the concrete specimen, immersing it in water for 48 hours, and finally testing it in water that is raised to boiling and held for 5 hours, weighing the specimen after each step. At the conclusion of the testing, the specimen is weighed while suspended in water.

The tests were conducted on two specimens for each mixture at a concrete age of 42 days. The test specimens consisted of the lower 3 in. (75 mm) portion of the 4 in. (100 mm) diameter cores taken from the unponded 5 in. (125 mm) test slab for conducting the rapid chloride permeability test. The results are listed in Table 6.

Table 6. Average concrete absorptions and permeable void volumes, sorted in order of decreasing boiling absorption.

Cure and mixture type	As-mixed w/cm	Absorption after immersion (percent)	Absorption after immersion and boiling (percent)	Volume of permeable voids (percent)	Slump (in.)
Burlap cure 5 percent silica fume	0.46	4.9	6.5	14.7	3 1/4
Burlap cure 5 percent silica fume	0.38	4.6	6.4	14.4	3
Burlap cure 5 percent silica fume	0.33	3.9	5.5	12.5	2 3/4
Burlap cure 7.5 percent silica fume	0.46	5.0	5.3	11.7	5 3/4
Burlap cure	0.46	4.5	4.7	10.7	4 1/4
Tank cure	0.46	4.1	4.4	9.9	6 1/2
Burlap cure 7.5 percent silica fume	0.37	4.2	4.3	9.9	5 3/4
Burlap cure	0.37	4.0	4.2	9.8	4
Burlap cure 7.5 percent silica fume	0.33	4.0	4.2	9.6	5
Burlap cure	0.32	3.8	4.0	9.3	6 1/4
Tank cure	0.37	3.6	3.9	8.9	5 1/2
Tank cure	0.31	3.4	3.7	8.5	5 3/4
Heat cure	0.46	3.2	3.5	8.0	6 1/4
Heat cure	0.37	2.7	2.9	6.8	6 1/4
Heat cure	0.32	2.3	2.5	5.8	4 3/4

Note: 1 in. = 25.4 mm.

Very low absorptions and permeable void volumes of the heat-cured specimens were observed. The three heat-cured conventional concretes at all three w/c levels had lower absorptions and volumes of permeable voids than all the other 12 moist-cured mixtures, including all six of the moist-cured silica fume mixtures. The heat-cured specimens had absorptions and permeable void volumes 25 to 40 percent lower than the companion burlap-cured mixes, indicating that heat curing reduces the absorption and permeable void volume at all three w/c levels.

A 1994 paper by Gillott and Czarnecki[14] may help explain the absorption differences between these burlap-cured or tank-cured and heat-cured concretes. Their research determined that the microcracking of the 28-day fog-cured 0.35, 0.40, and 0.45 w/c conventional concretes was always greater than 28-day-old concrete that was fog-cured to 28 days after overnight heating to 185°F (85°C). The crack counts in their continuously fog-cured concretes during petrographic studies were about 135, 50, and 80 percent greater than the accelerated heat-cured concretes for the 0.35, 0.40, and 0.45 w/c concretes, respectively.

The 5 and 7.5 percent silica fume mixtures had average volume of permeable voids that were about 100 and 50 percent greater, respectively, than the heat-cured mixtures, irrespective of their w/cm. The higher absorption and volume of permeable voids may be related to the higher susceptibility to cracking of low w/cm conventional and silica fume concretes.[3,14,15,16] Within each concrete mixture group, the absorptions and permeable void volumes were seen to be increasing with increasing w/cm, as would be expected. This observation serves to discount the effect of slump on the test results, because within each group the absorptions and permeable void volume increased in order of decreasing w/cm, regardless of slump.

AASHTO T 277 or ASTM C 1202 Testing

At a concrete age of 42 days, two specimens were tested according to AASHTO T 277 "Rapid Determination of the Chloride Permeability of Concrete" or ASTM C 1202 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." To provide the best indication of the in-service condition of the concrete, the test specimens consisted of the top 2 in. (50 mm) portion of 4 in. (100 mm) diameter cores removed from the center portion of the unponded 5 in. (125 mm) test slab. The lower 3 in. (75 mm) portion of the core was tested to determine the absorption and permeable void volume, as previously described.

The average test results are summarized in Table 7 and ranged from 637 to 3410 coulombs, in the range expected. At a given w/cm, the heat-cured slabs exhibited the highest coulomb values, while the silica fume concretes exhibited the lowest. There were no substantial or consistent differences in coulombs between the 5 and 7.5 percent silica fume addition rates. The 5 percent silica fume concrete had the lower coulomb value for the 0.33 and 0.46 w/cm mixtures and

Table 7. Average AASHTO T 277 or ASTM C 1202 test results.

Cure and mixture type	As-mixed w/cm	42-day coulomb value
Tank cure	0.31	1431
	0.37	2004
	0.46	2909
Burlap cure 5 percent silica fume	0.33	637
	0.38	943
	0.46	1484
Burlap cure 7.5 percent silica fume	0.33	678
	0.37	726
	0.46	1696
Burlap cure	0.32	1411
	0.37	1965
	0.46	3041
Heat cure	0.32	1841
	0.37	2794
	0.46	3410

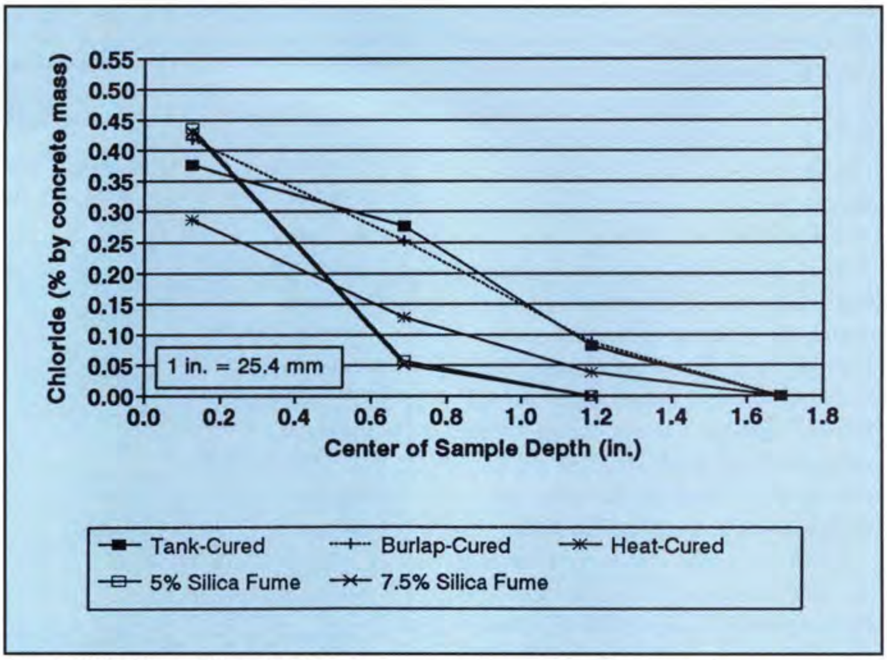

Fig. 2. Chloride profiles of 0.46 water-cementitious ratio concretes.

Fig. 1. Slab after coring to remove chloride samples.

the 7.5 percent silica fume concrete had the lower coulomb value for the 0.37 w/cm mixture.

The effect of curing can be observed by comparing the three conventional concrete mixtures. The tank-cured and burlap-cured specimens had essentially the same coulomb values, while the heat-cured specimens had somewhat higher coulomb values. Apparently, the early rapid curing of the heat-cured concrete, followed by a period of limited hydration while stored in air for 41 days in the CCR, resulted in a concrete with a lower electrical resistance and higher coulomb value than the identically proportioned 7-day water tank-cured and burlap-cured conventional concretes.

Note also that many of these low w/c concretes had higher coulomb values than would have been anticipated, based on Table 1 featured in the AASHTO T 277 or ASTM C 1202 specifications describing concretes as having high, moderate, low, very low,

Table 8. One-year concrete chloride content (percent by concrete mass).

Cure and mixture type	As-mixed w/cm	0 to $^1/_4$ in. depth			$^1/_2$ to $^7/_8$ in. depth			1 to $1^3/_8$ in. depth		
		Slab A	Slab B	Average	Slab A	Slab B	Average	Slab A	Slab B	Average
Tank cure	0.31	0.394	0.558	0.476	< 0.007	0.010	0.009	< 0.007	< 0.007	< 0.007
	0.37	0.417	0.522	0.469	0.106	0.091	0.099	< 0.007	< 0.007	< 0.007
	0.46	0.416	0.337	0.377	0.262	0.291	0.277	0.075	0.089	0.082
Burlap cure 5 percent silica fume	0.33	0.464	0.379	0.422	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007
	0.38	0.393	0.563	0.478	0.010	< 0.007	0.009	< 0.007	< 0.007	< 0.007
	0.46	0.450	0.422	0.436	0.047	0.068	0.058	< 0.007	< 0.007	< 0.007
Burlap cure 7.5 percent silica fume	0.33	0.337	0.372	0.355	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007
	0.37	0.398	0.300	0.349	0.010	0.010	0.010	< 0.007	< 0.007	< 0.007
	0.46	0.439	0.420	0.430	0.054	0.050	0.052	< 0.007	< 0.007	< 0.007
Burlap cure	0.32	—	—	0.506	0.013	0.025	0.019	< 0.007	< 0.007	< 0.007
	0.37	—	—	0.457	0.045	0.046	0.046	< 0.007	< 0.007	< 0.007
	0.46	0.445	0.392	0.419	0.244	0.262	0.253	0.074	0.102	0.088
Heat cure	0.32	0.421	0.392	0.407	0.008	0.030	0.019	< 0.007	< 0.007	< 0.007
	0.37	—	—	0.364	0.073	0.052	0.063	< 0.007	< 0.007	< 0.007
	0.46	—	—	0.287	0.146	0.113	0.130	0.039	0.038	0.039

Note: 1 in. = 25.4 mm.

or negligible chloride penetrability, as also observed in other research.[1,17,18]

Chloride Content Testing

One year after the continuous ponding started, the two slabs for each mixture were cored and tested to determine the chloride content in the following depth regions: $^1/_2$ to $^7/_8$ in., 1 to $1^3/_8$ in., and $1^1/_2$ to $1^7/_8$ in. (13 to 22 mm, 25 to 35 mm, and 38 to 48 mm). To reduce variability due to the sample size or aggregate concentrations, two 3 in. (75 mm) diameter cores were removed from the center of each slab and sliced into the depth increments described above.

After the two cores were sliced, the slices taken from the same depth region were pulverized, combined and analyzed using an acid-digestion potentiometric titration technique to determine acid-soluble chloride content essentially according to ASTM C 1152.[19] Following this testing, further work was performed to determine the chloride content in the uppermost $^1/_4$ in. (6 mm) of the concrete slabs. For this testing, a 4 in. (100 mm) diameter core was removed from each slab, sliced, ground, and analyzed. A slab after all the sampling is shown in Fig. 1.

For the initial portion of this additional work (Mixtures 10, 11, 14, and 15), one core was removed from each pair of slabs, and the two slices were interground to form a single sample. For the subsequent testing, the two slices were analyzed separately. Using this technique, the lower limit of detectable chloride was 0.007 percent by concrete mass. None of the 15 mixtures had measurable chloride in the $1^1/_2$ to $1^7/_8$ in. (38 to 48 mm) depth increment. The testing generally produced two measured chloride contents for each mixture, which were then averaged as listed in Table 8.

The results for the five different 0.46 w/cm concretes are shown in Fig. 2. The chloride profiles for the two silica fume concretes are clearly different than the three conventional concretes. Despite having chloride contents approximately 20 percent of the tank-cured or burlap-cured conventional concretes in the $^1/_2$ to $^7/_8$ in. (13 to 22 mm) depth interval, the silica fume mixtures had similar or higher chloride contents in the 0 to $^1/_4$ in. (0 to 6 mm) depth interval. This may be explained by the significantly higher absorption and volume of permeable voids of the 0.46 w/cm ratio silica fume concretes, as previously discussed. Apparently, the improved chloride resistance associated with the addition of silica fume does not apply to the uppermost portion of the concrete, where absorption dominates over the slower diffusion process.

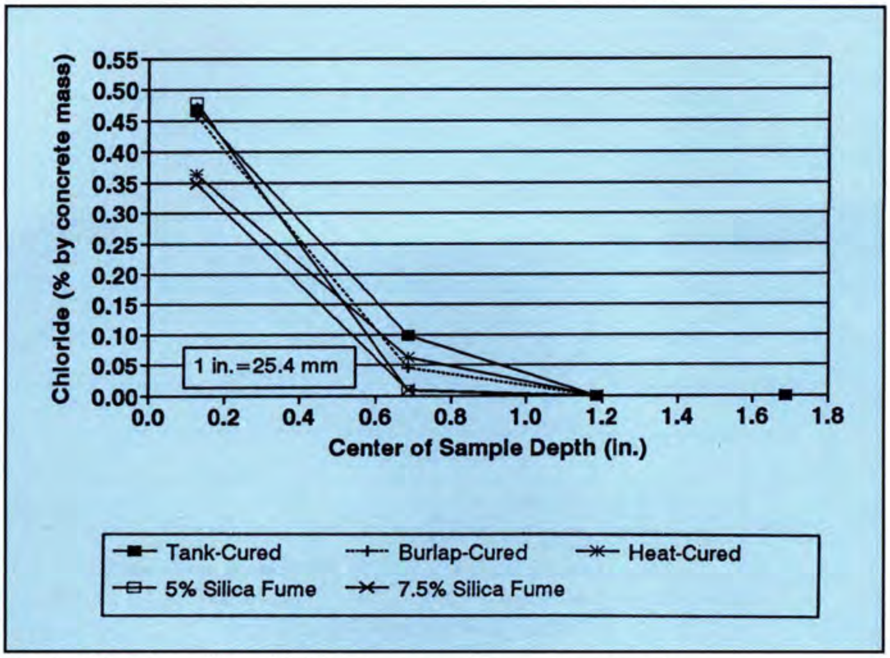

Fig. 3. Chloride profiles of 0.37 water-cementitious ratio concretes.

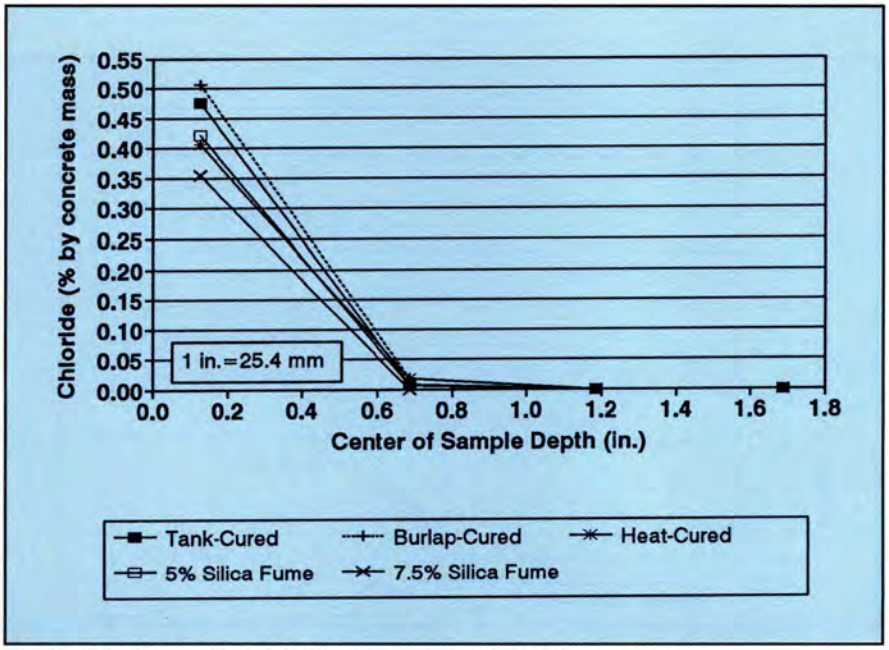

Fig. 4. Chloride profiles of 0.32 water-cementitious ratio concretes.

The chloride content in the 0 to $^1/_4$ in. (0 to 6 mm) depth interval for the heat-cured conventional concrete was the lowest of all five 0.46 w/cm mixtures, and about 35 percent lower than the two silica fume mixtures. The heat-cured conventional concrete had 50 percent reductions in chloride content, as compared to the water tank-cured and burlap-cured conventional concretes at the $^3/_4$ to $1^1/_2$ in. (19 to 38 mm) depth levels. This confirms the

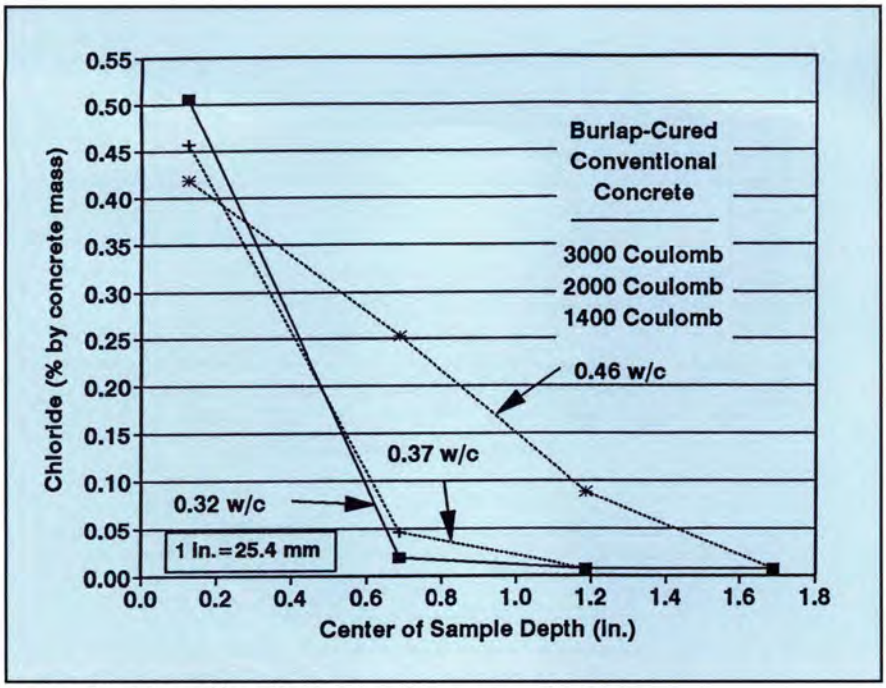

Fig. 5. Chloride profiles of burlap-cured conventional concretes.

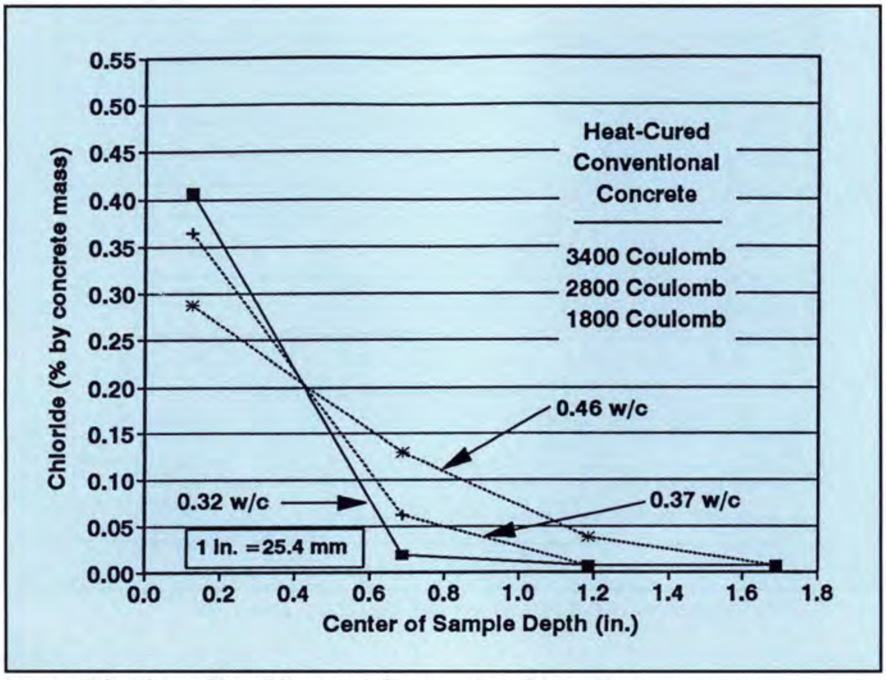

Fig. 6. Chloride profiles of heat-cured conventional concretes.

earlier work performed as part of the 1987 FHWA "Protective Systems for New Prestressed and Substructure Concrete" study[2] where similar 30 to 50 percent reductions in chloride intrusion into heat-cured AASHTO-grade concrete were observed, when compared to 3-day moist-cured, AASHTO-grade concrete.

At the 0.37 w/cm, the performances of the five different concretes were more similar, as shown by the similar shapes of the chloride profiles in Fig. 3. All concretes exhibited a significant drop in chloride content between the uppermost two-depth intervals, an observation only seen with the silica fume-modified concretes at the 0.46 w/cm.

As before, the two silica fume concretes had lower chloride contents than the other three conventional concretes, but the apparent improvement was dramatically less than with the 0.46 w/cm concretes. The heat-cured concrete had lower chloride contents than the burlap-cured concrete in the uppermost portion of the slab, but essentially identical chloride contents in the lower portion of the slabs.

For these five concretes, the 5 percent silica fume concrete had the same chloride content in the 0 to $^1/_4$ in. depth interval as the tank-cured and burlap-cured control concretes, while the 7.5 percent silica fume concrete and the heat-cured concrete had significantly lower chloride content in the uppermost concrete level. The heat-cured concrete had a similar chloride level in the uppermost portion of the concrete to the 7.5 percent silica fume concrete.

At the 0.32 w/cm, all concretes had similar chloride profiles, as shown in Fig. 4. The only appreciable differences were the chloride concentrations in the near-surface region In this surface region, the 7.5 percent silica fume concrete had the lowest chloride content, followed by the heat-cured concrete and the 5 percent silica fume concrete. The burlap-cured and tank-cured conventional concretes had the highest near-surface chloride contents.

The dramatic change in the chloride profiles between the five different concretes from the 0.46 to the 0.37 and 0.32 w/cm ratio shows the overpowering effect of w/cm. At the lowest w/cm values, the beneficial effects of silica fume and heat curing of conventional concrete could not be seen due to the major reduction in chloride penetration caused solely by the decrease in the w/cm to 0.32.

The effect of the w/cm was pronounced, with the chloride contents of the 0.32 w/c and w/cm concretes at least 85 percent less than those of the comparable 0.46 w/c and w/cm concrete mixtures at the $^1/_2$ to $^7/_8$ in. (13 to 22 mm) depth. This can be clearly seen in Figs. 5, 6, and 7, which show the chloride profiles for the burlap-cured conventional concretes, heat-cured conventional concretes, and burlap-cured 7.5 percent silica fume concretes, respectively.

Note that in Figs. 5 and 6 for the burlap-cured and heat-cured conventional concretes, there is a reversal of relative chloride contents in the near-surface region of the slab, with the concretes with less chloride at depth having higher chloride contents near the surface. The reason for this is not known, but it probably relates to poorer surface characteristics of the lower w/cm concretes or more microcracks due to shrinkage of the higher cement content, lower w/cm concretes, as previously discussed. All 15 concretes had very high near-surface chlorides, ranging from about 11 to 20 lbs per cu yd (6.6 to 12 kg/m^3).

Chloride Diffusion Coefficient Calculations

A least-squares curve fitting technique was used to calculate the chloride diffusion coefficients and the salt water exposed surface chloride concentration. The calculation was performed assuming Fick's law of diffusion[20,21] according to the following equation:

$$C\left(x,t,C_o,D_{eff}\right)=C_o\left[1-\operatorname{erf}\left(\frac{x}{2\sqrt{tD_{eff}}}\right)\right]$$

where

x = sample depth
t = time
D_{eff} = effective diffusion coefficient
C_o = surface chloride concentration
erf = error function

During the curve fitting, the measured chloride concentrations at the four tested depths, x, were used to determine a least-squares fit for the effective diffusion coefficient, D_{eff}, and the surface chloride concentration, C_o, at a time, t, of 1 year. For Mixtures 4 and 7, the undetectable chloride in the $^1/_2$ to $^7/_8$ in. (13 to 22 mm) depth interval was assumed to be zero.

The surface chloride concentration reflects the chloride concentration C_o at the exterior surface of the concrete. The diffusion coefficient indicates the permeability of the concrete, with a smaller number indicating a less permeable concrete. The results of the calculations are shown in Table 9.

As shown in Table 9, the calcula-

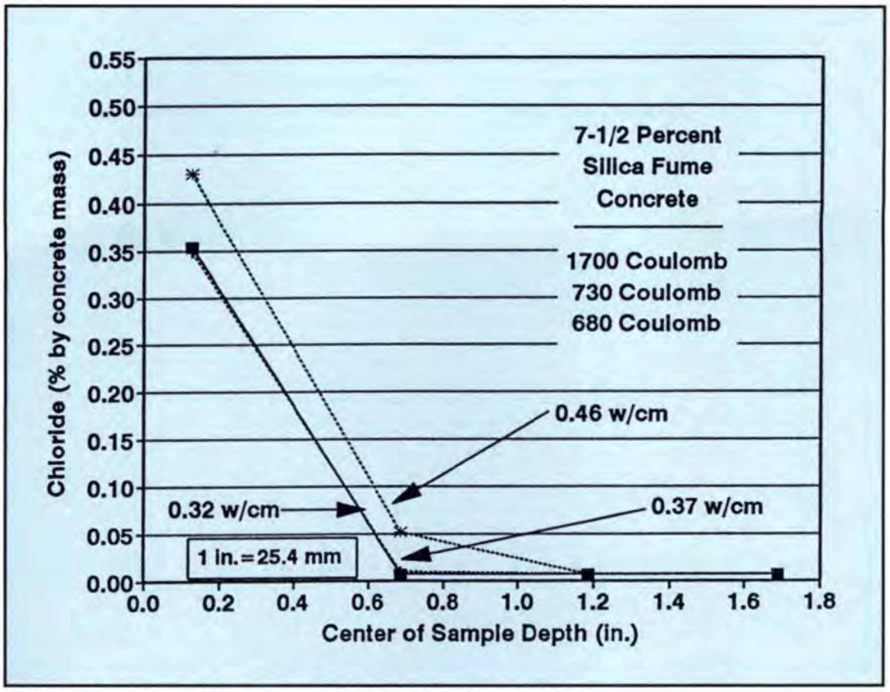

Fig. 7. Chloride profiles of 7.5 percent silica fume concretes.

Table 9. Calculated diffusion coefficients and surface chloride concentration.

Cure and mixture type	Mixture number	Diffusion coefficient ($mm^2/s \times 10^{-6}$)	Surface chloride concentration (percent by concrete mass)
Tank cure	1	0.77	0.734
	2	2.51	0.586
	3	10.9	0.444
Burlap cure 5.5 percent silica fume	4	0.74	0.657
	5	0.77	0.737
	6	1.81	0.569
Burlap cure 7.5 percent silica fume	7	0.56	0.600*
	8	0.88	0.521
	9	1.69	0.567
Burlap cure	10	0.97	0.739
	11	1.52	0.613
	12	8.79	0.483
Heat cure	13	1.06	0.583
	14	2.15	0.464
	15	6.19	0.331

* A surface chloride of 0.600 was assumed for Mixture 7 to allow a reasonable curve-fit to be performed despite a lack of chloride data at and below the $^1/_2$ in. (13 mm) depth interval.

Table 10. Calculated average surface concentration for given w/cm.

w/cm	Cure type	Average chloride content at surface, C_o		
		lb per cu yd	kg/m^3	Coefficient of variation (percent)
0.32	Burlap and tank* Heat	27.8 22.8	16.5 13.5	6.5 —
0.37	Burlap and tank* Heat	24.0 18.2	14.2 10.8	14.7 —
0.46	Burlap and tank* Heat	20.2 13.0	12.0 7.7	12.1 —

* Conventional and silica fume mixtures, three or four mixtures.

Table 11. Estimated time-to-corrosion for continuously ponded specimens with 2 in. (50 mm) cover.

w/cm	Cure type, percent silica fume	Mixture number	Time-to-corrosion (year)
0.46	Tank — 0	3	1
0.46	Burlap — 0	12	1
0.46	Heat — 0	15	2
0.37	Tank — 0	2	4
0.46	Burlap — 5	6	5
0.37	Heat — 0	14	5
0.46	Burlap — 7.5	9	6
0.37	Burlap — 0	11	6
0.32	Heat — 0	13	9
0.32	Burlap — 0	10	9
0.32	Tank — 0	1	11
0.37	Burlap — 7.5	8	11
0.37	Burlap — 5	5	11
0.32	Burlap — 5	4	12
0.32	Burlap — 7.5	7	17

Table 12. Estimated time-to-corrosion for continuously ponded specimens with 3 in. (75 mm) cover.

w/cm	Cure type, percent silica fume	Mixture number	Time-to-corrosion (year)
0.46	Tank — 0	3	2
0.46	Burlap — 0	12	3
0.46	Heat — 0	15	4
0.37	Tank — 0	2	9
0.37	Heat — 0	14	11
0.46	Burlap — 5	6	12
0.46	Burlap — 7.5	9	13
0.37	Burlap — 0	11	14
0.32	Burlap — 0	10	20
0.32	Heat — 0	13	20
0.37	Burlap — 7.5	8	25
0.37	Burlap — 5	5	25
0.32	Tank — 0	1	26
0.32	Burlap — 5	4	28
0.32	Burlap — 7.5	7	38

tions indicate that the heat-cured concretes have between 18 and 36 percent less surface chloride than the average water tank-cured and burlap-cured conventional and silica fume concretes. Tables 9 and 10 further show that the low w/cm concretes generally have higher surface chloride concentrations than the higher w/cm mixtures, and that the coefficients of variation of the surface chlorides of burlap-cured and tank-cured conventional and silica fume concretes are low at 6 to 15 percent. All of these surface concentrations are less than the 30 lbs per cu yd (17.8 kg/m^3) discussed and used in other corrosion-related documents.[18,21,22,23]

Time-to-Corrosion Calculations

The Fick's law diffusion model was used to compare the relative permeability of the different concretes. This method is superior to earlier methods such as computing an "integral chloride,"[17] or comparing chloride contents at specific depth intervals,[17] as the diffusion equation serves to appropriately characterize the different chloride contents. Using Fick's law and the surface chloride concentrations and diffusion coefficients determined during the curve fitting, the chloride diffusion over periods longer than 1 year can be estimated.

The calculation assumes that the C_o surface concentration calculated after the 1-year ponding period will remain constant and that the diffusion coefficient does not change with time as the concrete matures. These assumptions are valid over short time periods, but very little research has investigated the time dependence of the diffusion parameters, so the long-term indications should be applied with care.

A $1\frac{1}{2}$ and 2 in. (38 and 50 mm) cover is recommended by the 1995 ACI 318-95R[10] for precast concrete for walls and slabs, and for other members, respectively, when exposed to corrosive environments. These ACI recommended values are 2 and $2\frac{1}{2}$ in. (50 and 62 mm) for cast-in-place concrete walls and slabs, and for other members, respectively, for the same environment.

The 1992 AASHTO[9] minimum cover for deck slabs exposed to deicing salts that have no positive corrosion protection is $2\frac{1}{2}$ in. (64 mm) for top reinforcement and 1 in. (25 mm) for bottom reinforcement. For prestressed concrete, the AASHTO minimum cover for prestressing steel and mild reinforcing steel is 2 in. (50 mm) for top of slab when deicers are used. AASHTO also states that when deicers are used, and where constant deicer contact cannot be avoided with the girders, or in locations where members are exposed to salt water, salt spray, or chemical vapor, additional cover should be provided.

AASHTO[9] also requires in Section 8.6.6 in Division II — Construction that cast-in-place concrete when exposed to salt water should have a 4 in. (100 mm) clear cover, unless indicated otherwise on the plans. AASHTO Sections 4.5.16.7 and

4.5.17.8 in Division I — Design call for 3 in. (76 mm) clear cover for precast piles and cast-in-place concrete piles when in a corrosive or marine environment or in alkali soils.

The time-to-corrosion for each of the 15 mixes was computed assuming a 2 and 3 in. (50 and 75 mm) cover over the reinforcing bars and a corrosion threshold of 0.022 percent acid-soluble chloride ion by concrete mass. The results are shown in Tables 11 and 12. Note that these times-to-corrosion are for continuously ponded specimens and are expected to be conservative estimates for parking garages, bridge decks, bridge substructures, and other structures that receive intermittent exposure to chloride.

The estimated time-to-corrosion calculations for 2 in. (50 mm) cover ranges from 1 to 17 years. The time-to-corrosion for all AASHTO-grade 0.46 w/cm concretes including the silica fume concretes are very low, ranging from 1 to 6 years. The benefits of using low w/cm concretes (0.37 to 0.32) with and without silica fume is easily seen with 7 of the 10 lower w/cm mixtures having time-to-corrosion of 9 to 17 years.

The time-to-corrosion estimates for the 0.46 and 0.37 w/cm silica fume concretes used in the construction of parking garages, bridge decks, and other members, were about 5 and 11 years, respectively. These values are much greater than the 1 year for the water tank-cured and burlap-cured AASHTO-grade 0.46 w/c conventional concretes.

The heat-cured conventional concretes with 0.37 and 0.32 w/c had estimated values of 5 and 9 years, respectively. These values are equivalent to the 5 to 11 years for the 0.46 to 0.37 w/cm silica fume concretes and essentially equal for 0.45 to 0.40 w/cm silica fume concretes typically used on current construction projects. Although the 12- to 17-year estimates for the 0.32 w/cm with the 5 and 7.5 percent silica fume mixtures were the longest computed time-to-corrosion estimates, these two concretes would be very difficult to use in typical construction projects where cast-in-place concrete operations and significant flatwork are required.

Table 13. Increase in time-to-corrosion.

w/cm	Cure type, percent silica fume	Mixture number	Increase in time-to-corrosion (years) 2 in. (50 mm) vs. 1 in. (25 mm)	Increase in time-to-corrosion (years) 3 in. (75 mm) vs. 2 in. (50 mm)
0.46	Tank — 0	3	1	1
0.46	Burlap — 0	12	1	2
0.46	Heat — 0	15	2	2
0.37	Tank — 0	2	3	5
0.37	Heat — 0	14	4	6
0.46	Burlap — 5	6	4	7
0.46	Burlap — 7.5	9	4	7
0.37	Burlap — 0	11	5	8
0.32	Burlap — 0	10	7	11
0.32	Heat — 0	13	7	11
0.37	Burlap — 7.5	8	9	14
0.38	Burlap — 5	5	9	14
0.31	Tank — 0	1	9	15
0.33	Burlap — 5	4	9	16
0.33	Burlap — 7.5	7	13	21

For more severe exposure, such as precast piles in salt water or alkali soils, or cast-in-place concrete in a corrosive or marine environment, AASHTO[9] requires the use of 3 to 4 in. (75 to 100 mm) of cover. The estimated time-to-corrosion for 3 in. (75 mm) cover ranges from 2 to 38 years. The conventional AASHTO-quality 0.46 w/c concretes with tank cure, burlap cure, or heat cure had time-to-corrosion estimates of 2 to 4 years. All of the 12 other concretes performed better, with estimates ranging from 9 to 38 years.

The 5 and 7.5 percent silica fume mixtures with w/cm of 0.46 to 0.37 have estimates of 12 to 25 years, essentially equal to the 11 to 20 years of the heat-cured 0.37 to 0.32 w/c conventional concretes. Among the other mixes, the 0.37 to 0.32 w/c burlap-cured conventional concretes had estimates of 14 to 20 years, and the 0.32 w/c tank-cured conventional concrete had an estimate of 26 years. These are about the same as the silica fume and heat-cured concretes already discussed. The 0.32 w/cm silica fume mixtures with 5 and 7.5 percent silica fume have the longest estimates of 28 to 38 years.

The benefits of using 2 in. (50 mm) cover vs. 1 in. (25 mm), or 3 in. (75 mm) cover vs. 2 in. (50 mm) cover in time-to-corrosion are shown in Table 13. The dramatic increase in the calculated times-to-corrosion illustrate that the time-to-corrosion of AASHTO-grade burlap-cured 0.46 w/c concrete is only marginally increased by 1 to 2 years when the cover is increased from 1 to 2 in. (25 to 50 mm) or from 2 to 3 in. (50 to 75 mm).

With commonly used 0.37 to 0.32 w/c heat-cured conventional concretes, the increases are about 5 to 10 times greater for the same cover increases. With 0.46 to 0.37 w/cm silica fume mixtures, the increases are about 6 to 12 times greater for the same cover increases. These data indicate that if increasing cover is to be used to increase the time-to-corrosion, it will be most effective when used with a low w/cm heat-cured conventional concrete or burlap-cured silica-fume concrete.

DISCUSSION OF TEST RESULTS

In this section, the effects of water-cementitious materials ratio, heat curing and silica fume together with comparable end-use concretes and validity of AASHTO and ASTM specifications are discussed.

Table 14. Comparison of chloride content reductions due to lowered water-cement ratios (FHWA[2] and present investigations).

Study	Change in w/c	Reduction in chloride at 1 in. (25 mm) depth (percent)
1987 FHWA	0.51 to 0.40	80
Present	0.46 to 0.37	80
1987 FHWA	0.51 to 0.28	95
Present	0.46 to 0.32	94

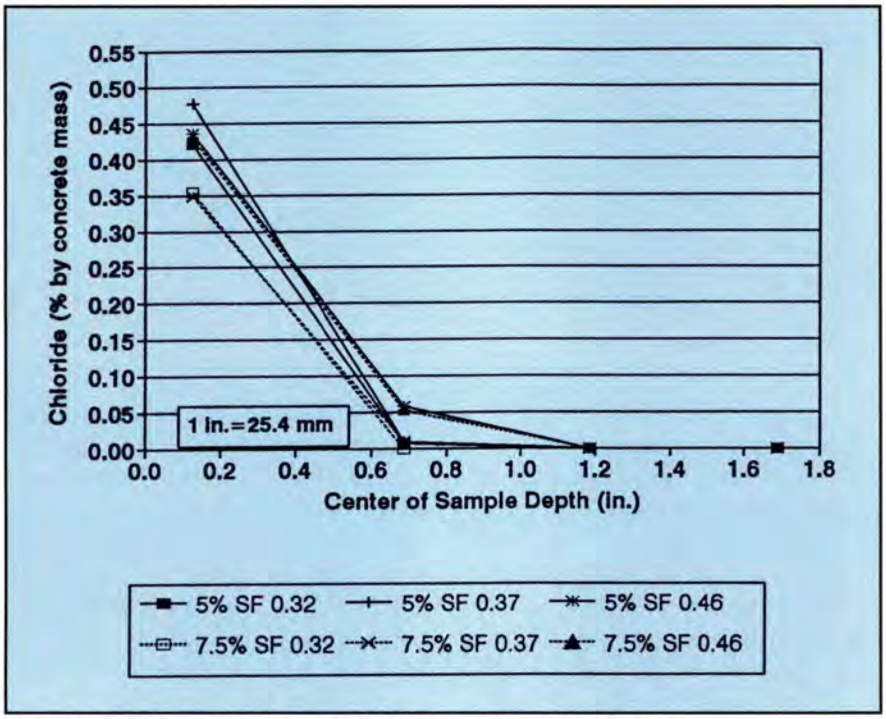

Fig. 8. Comparison of concretes with different silica fume dosages.

Effect of Water-Cementitious Materials Ratio

The most important conclusion gained from this work is the effectiveness of a low w/c or w/cm in decreasing the chloride permeability of concrete. As shown in Fig. 4, all five mixtures using a 0.32 w/cm had very low chloride contents of less than 0.020 percent by concrete mass in the $^1/_2$ to $^7/_8$ in. (13 to 22 mm) depth region.

In addition, all five mixtures produced using a w/cm of 0.37 had significantly lower chloride contents than their companion mixtures produced at a w/cm of 0.46, as shown in Figs. 2 and 3. The effect of low w/cm can also be seen in the very low chloride content in the 1 to 1$^3/_8$ in. (25 to 35 mm) depth for all 10 mixtures with 0.32 and 0.37 w/cm, as shown in Table 8.

The overwhelming evidence of improved performance through lowering the w/c matches conclusions reached by Pfeifer et al., in a 1987 FHWA study.[2] A comparison of the chloride content reductions due to lowered w/c in that study and in the present study is shown in Table 14.

Effect of Heat Curing

The results show that the heat-cured conventional concretes at 0.32, 0.37, and 0.46 w/c produced water absorptions and volume of permeable voids that were much lower than the 12 moist- and tank-cured mixtures that contained 0, 5, and 7.5 percent silica fume and were moist-cured for 7 days. In fact, at all w/cm, the silica fume concretes had volume of permeable voids that were, on average, 100 and 50 percent greater than the heat-cured conventional concretes for the 5 and 7.5 percent silica fume addition rates, respectively.

The highest volume of permeable voids for heat-cured conventional concrete was only 8.0 percent, a value 17 percent lower than the 9.6 percent voids of the best performing silica fume mixture (0.33 w/cm with 7.5 percent silica fume), and 46 percent lower than the 14.70 percent voids of the worst performing silica fume concrete (0.46 w/cm with 5.0 percent silica fume). These high absorption values for all of the silica fume concretes may explain the high surface chloride concentrations for these silica fume concretes observed during the long-term ponding tests.

The long-term ponding tests showed that the AASHTO-grade 0.46 w/c heat-cured concrete had the lowest near-surface chloride concentration when compared to the 0.46 w/cm moist-cured concretes, including the 5.0 and 7.5 percent silica fume mixtures. These surface chlorides for the 0.46 w/c heat-cured concrete averaged about 36 percent less than the four other moist-cured 0.46 w/cm concretes with or without silica fume.

The long-term ponding tests also indicate that the heat-cured conventional concretes at 0.32, 0.37, and 0.46 w/c had lower or essentially equal chloride contents at all measured depths when compared to the burlap-cured or water tank-cured conventional concretes at the same w/c.

These current observations confirm similar conclusions about the beneficial effects of heat curing on chloride profiles in 0.44 w/c AASHTO-grade concrete studied in the 1987 FHWA study of heat-cured vs. moist-cured 0.44 w/c concrete.[2] This current study also showed that the 28-day compressive strength of properly heat-cured concrete was not significantly lowered by heat curing, even when the cylinders did not receive any supplemental wet or moist curing after the initial overnight heat curing.

This conclusion, in conjunction with the lower water and chloride absorption, lower volume of permeable voids, lower 1-year chloride content profiles, and comparable estimated time-to-corrosion values, indicates that heat-cured conventional concretes are far more impervious to water and chloride ingress than the same moist-cured

AASHTO-grade 0.46 w/c concretes. The 0.37 and 0.32 w/c heat-cured conventional concretes also had equal or greater resistance to water and chloride ingress than moist-cured conventional concretes with equal w/c levels.

The observations from these two major studies indicate that the removal of the AASHTO requirement for 6 days of supplemental moist curing of heat-cured concrete in 1992 was justifiable and appropriate.

Effect of Silica Fume

The addition of silica fume to the 0.46 w/cm specimens was seen to be highly beneficial in reducing chloride ingress. After the long-term ponding test, the chloride at $^1/_2$ to $^7/_8$ in. (13 to 22 mm) in these concretes were at least 78 percent lower than that in the conventional 0.46 w/c concrete. The addition of the silica fume prevented the measurable ingress of chloride to the 1 to $1^3/_8$ in. (25 to 35 mm) depth region.

The benefits of the silica fume were also apparent in the 0.37 w/cm mixes, where the 5 and 7.5 percent silica fume concrete had 75 to 80 percent less chloride than the companion burlap-cured conventional concrete in the $^1/_2$ to $^7/_8$ in. (13 to 22 mm) depth interval. The benefits of the silica fume were difficult to determine in the 0.32 w/cm mixes, because all of the 0.32 w/c and w/cm mixes had extremely low chlorides at all depths, except the near-surface region.

As shown in Fig. 8, chloride concentrations after ponding for the 5 and 7.5 percent silica fume mixes were similar for each w/cm. The 7.5 percent silica fume concretes also required higher admixture dosages, although they did have slightly higher slumps than the 5 percent silica fume mixtures. The compressive strength and coulombs values for the 7.5 percent silica fume mixes were not always better than the 5 percent silica fume mixes.

Table 15. Measured and calculated concrete properties of four different mixtures.

Mixture number	w/cm	Coulombs	Diffusion coefficient $\text{mm}^2\text{/s} \times 10^{-6}$	Volume of permeable voids (percent)	Calculated surface chloride concentration (percent)	Time-to-corrosion (years) Cover 2 in.	Time-to-corrosion (years) Cover 3 in.
12	0.46	3040	8.8	10.7	0.48	1	3
6*	0.46	1484	1.8	14.7	0.57	5	12
9†	0.46	1690	1.7	9.3	0.57	6	13
14	0.37	2794	2.2	6.8	0.46	5	11

Note: 1 in. = 25.4 mm.

* 5 percent silica fume.

† 7.5 percent silica fume.

0.46 w/c conventional concrete (Mixture 12) with 7 days of burlap cure.

0.46 w/cm silica fume concretes (Mixtures 6 and 9) with 7 days of burlap cure.

0.37 w/c conventional concrete (Mixture 14) with overnight heat curing and no supplemental moist curing.

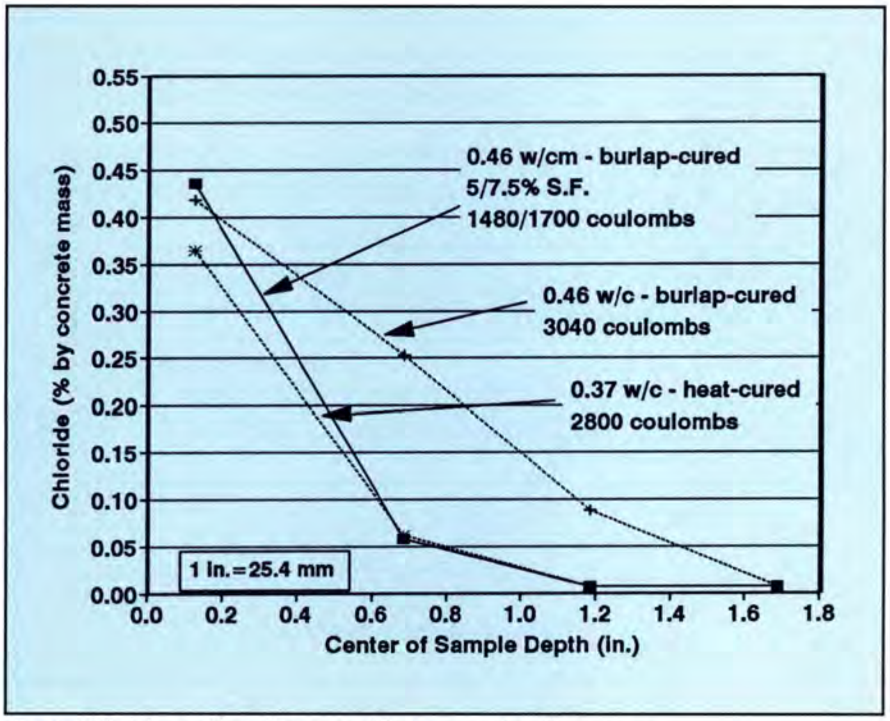

Fig. 9. Chloride profiles of comparable "conventional" systems.

Comparable End-Use Concretes

The dramatic and overpowering effect of the w/c on the chloride permeability of concrete requires that the potential advantages of so-called "high performance" concretes, such as low w/c heat-cured concretes or those containing admixtures such as silica fume, be examined using realistic w/cm values for project application.

When comparing heat-cured precast concrete to moist-cured, cast-in-place concrete, it must be recognized that precast concrete typically must have a lower w/cm due to the need to strip and recycle the forms in short time periods. Two examples are given here; others could be constructed, keeping in mind the project requirements.

One such comparison would be of a conventional parking garage or bridge with only a minimal emphasis on corrosion protection for which no specialty contractors, extra effort, or materials would be required. Such structures are currently being built and require few changes in construction or production methods. The comparable concrete systems used in this hypothetical bridge or garage are: 0.46 w/c burlap-cured conventional concrete, 0.46 w/cm burlap-cured concrete with 5 or 7.5 percent silica fume, and a 0.37 w/c heat-cured conventional precast concrete. The measured and calculated properties of these four concretes are shown in Table 15.

The chloride profiles for these more easily constructed systems, along with

Table 16. Measured and calculated concrete properties of four different mixtures.

Mixture number	w/cm	Coulombs	Diffusion coefficient mm²/s × 10^{-6}	Volume of permeable voids (percent)	Calculated surface chloride concentration (percent)	Time-to-corrosion (years) Cover 2 in.	3 in.
11	0.37	1965	1.5	9.8	0.61	6	14
5*	0.37	943	0.8	14.4	0.74	11	25
8†	0.37	726	0.9	9.9	0.52	11	25
13	0.32	1841	1.1	5.8	0.58	9	20

Note: 1 in. = 25.4 mm.

* 5 percent silica fume.

† 7.5 percent silica fume.

0.37 w/c conventional concrete (Mixture 11) with 7 days of burlap cure.

0.37 w/cm silica fume concretes (Mixtures 5 and 8) with 7 days of burlap cure.

0.32 w/c conventional concrete (Mixture 13) with overnight heat curing and no supplemental moist curing.

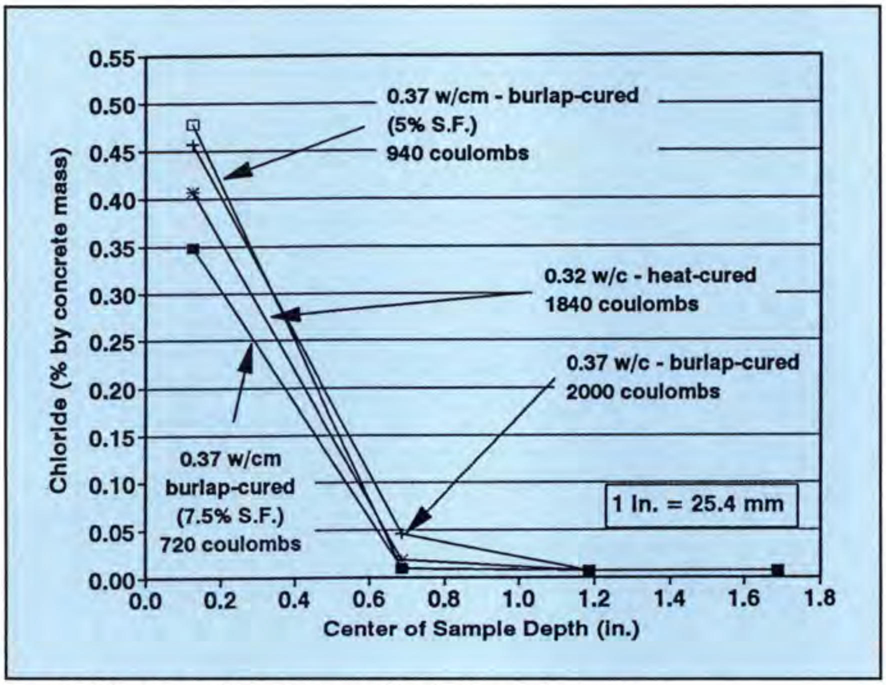

Fig. 10. Chloride profiles of comparable "higher quality" systems.

their coulomb values, are shown in Fig. 9. The silica fume and heat-cured precast concrete have essentially identical diffusion coefficients and times-to-corrosion, and both offer a substantial advantage over the conventional 0.46 w/c concrete.

Any of these three higher performance concretes with low diffusion coefficients of about 2.0×10^{-6} mm²/s would be a good choice for prolonging the life of the concrete structure. This is true despite the 1200-coulomb difference between 2800-coulomb value for the heat-cured conventional concrete and the average 1600-coulomb value from the two silica fume concretes.

As another comparison, consider the concretes specified for significantly improved corrosion protection, shown in Table 16, that could be placed with more effort on the part of the concrete material suppliers and the contractor's workers. These concretes would include a 0.37 w/c burlap-cured conventional concrete, a 0.37 w/cm burlap-cured concrete containing 5 or 7.5 percent silica fume, or a heat-cured conventional concrete with a w/c of 0.32.

The resulting chloride profiles for these concretes are shown in Fig. 10. Either the addition of silica fume or the use of low 0.32 w/c heat-cured concrete results in substantially improved diffusion coefficients of about 1×10^{-6} mm²/s and times-to-corrosion. This similar and substantial reduction in chloride penetration occurs despite a two-fold difference (830 vs. 1840) in the coulomb values of these concretes.

The increases in the time-to-corrosion were not reflected by these coulomb values. In fact, this low-permeability 0.32 w/c heat-cured concrete, with a coulomb value of 1840, would not have passed the 1000-coulomb cutoff used sometimes in project specifications.

Accuracy and Validity of AASHTO T 277 or ASTM C 1202 Testing

Comparison of the AASHTO T 277 or ASTM C 1202 coulomb values, the 1-year ponding test results, the diffusion coefficients, the surface chloride concentration C_o, and the calculated times-to-corrosion raises a number of serious questions regarding the accuracy of the T 277 or ASTM C 1202 tests and the permeability correlations presented in Table 1 of T 277 and C 1202, currently used in concrete specifications in an effort to ensure low-permeability concrete. The use of the T 277 or C 1202 test in an attempt to ensure long-term service life assumes incorrectly that the coulomb value is directly related to the long-term diffusion properties and the surface chloride concentration C_o, which in turn control Fick's law of diffusion of chloride through concrete.

The data in Tables 7 and 10 clearly indicate that there is no correlation between coulomb value and surface chloride concentration C_o.

The relationship between the calculated diffusion coefficient and the measured coulomb value for the 15 concretes tested during this study is shown in Fig. 11. Although there is an apparent relationship with lower coulomb values and lower diffusion coefficients, there is a large amount of scatter in the data and an apparent extreme sensitivity of the diffusion coefficient to the coulomb value. This is shown by Mixtures 1, 4, 5, 7, 8, 10, and 13, which have essentially the same very low diffusion coefficients ranging from 0.6 to 1.1 × 10^{-6} mm²/s and coulomb values ranging from 600 to 1800 coulombs.

Similarly, Mixtures 6 and 9 (0.46 w/cm with silica fume contents of 5 and 7.5 percent, respectively) have essentially the same diffusion coefficient as Mixture 14 (0.37 w/c conventional heat-cured), of about 1.7 to 2.1 × 10^{-6} mm²/s, yet there is a difference of 1200 coulombs.

A similar difference occurs between Mixture 4 (0.32 w/cm and 5 percent silica fume) and Mixture 1 (0.32 w/c conventional water tank-cured), with both mixes having the same very low diffusion coefficient of 0.75 × 10^{-6} mm²/s and an 800 coulomb difference. These cumulative data show that there can be an 800 to 1200 coulomb decrease when silica fume is added and that essentially equal diffusion coefficients for 0.32 and 0.37 w/c conventional concretes can be obtained despite this 800 to 1200 coulomb difference. This same observation has been made in other research studies.[17]

To expand this lack of correlation, the data from these 15 concretes were combined with the data from a 1988 chloride diffusion study[18] of nine concretes with and without calcium nitrite with w/cm values ranging from 0.38 to 0.48 and silica fume contents of 0, 7.5, and 15 percent, as shown in Fig. 12. Four concretes with very high silica fume contents of 15 percent had coulomb values of only 75 to 253. The one concrete with 7.5 percent silica fume had a very low coulomb value of 380. The other four concretes contained no silica fume.

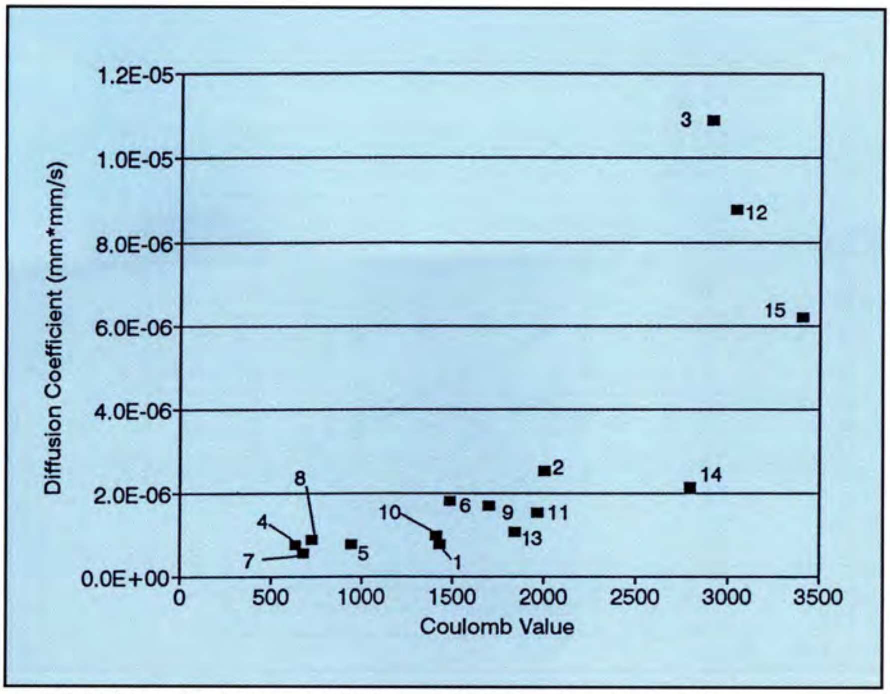

Fig. 11. Relationship between diffusion coefficient and coulomb value.

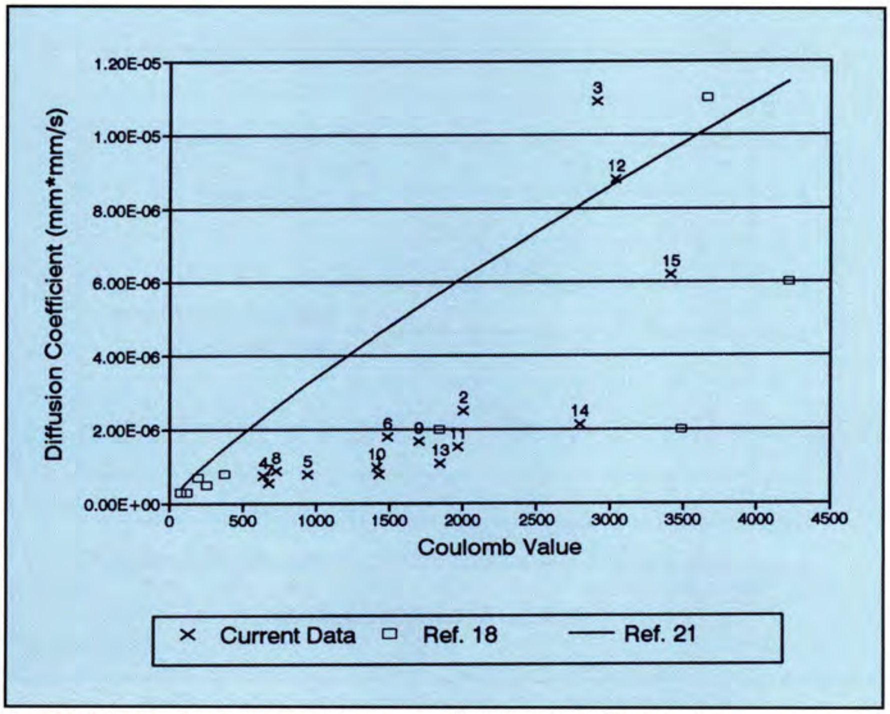

Fig. 12. Relationship between diffusion coefficient and coulomb value.

The data from these 24 concretes in Fig. 12 show that there is a dramatic change in the relationship at a coulomb level of about 2500 to 3000, not at 1000 coulomb as implied by Table 1 in the AASHTO T 277 and ASTM C 1202 specifications. In both studies, very low diffusion coefficients of 2.0 to 1.0 × 10^{-6} mm²/s were achieved using practical concretes with coulomb values less than 3500, with the majority less than 2000 coulombs.

These very low diffusion coefficients of 2 to 1 × 10^{-6} mm²/s are 80 to 90 percent lower than the 11 × 10^{-6} mm²/s diffusion coefficients of the 0.46 to 0.48 w/c conventional moist-cured concretes used as controls in these two studies. Yet, two of these 14 practical concretes, one from each study, had coulomb values of 2800 to 3500 with very low diffusion coefficients of 2 × 10^{-6} mm²/s.

The approximate relationship between the coulomb value and time-to-corrosion [assuming a 2 in. (50 mm) cover] results from the lack of correlation of the surface chloride concentration C_o to the coulomb value and the high sensitivity of the time-to-corrosion to the diffusion coefficient, shown in Fig. 13.

Because of these two factors, the small scatter in the data shown in Fig.

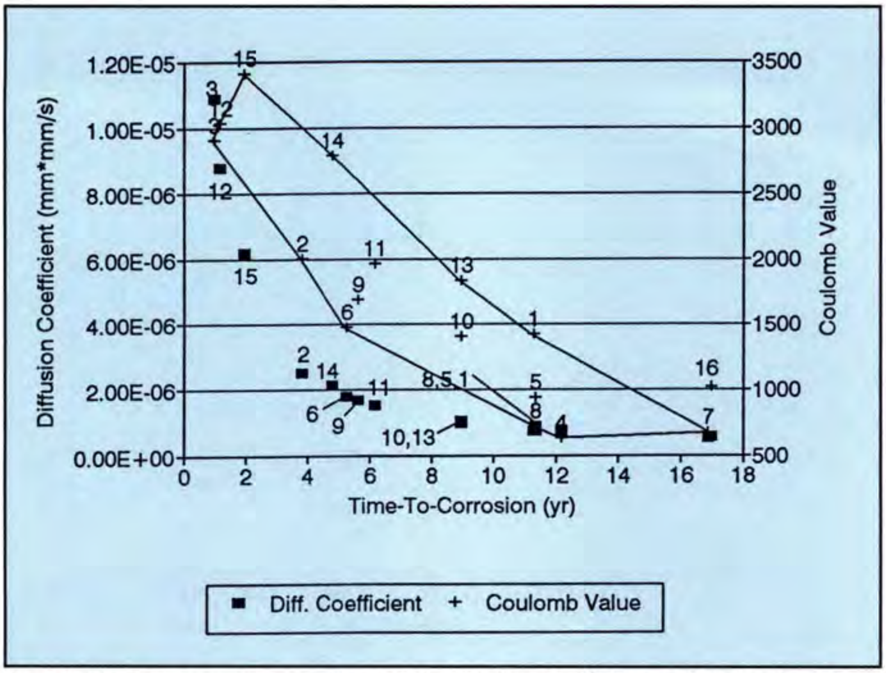

Fig. 13. Time-to-corrosion as estimated by diffusion coefficient and coulomb value.

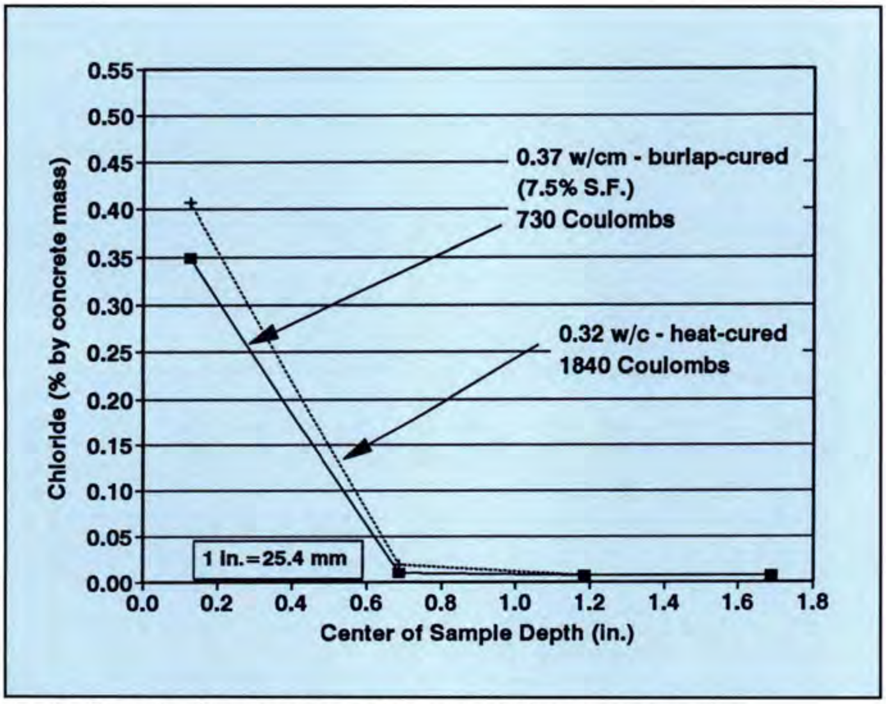

Fig. 14. Example of comparable concretes with different coulomb values.

11 is increased when the time-to-corrosion is calculated, resulting in the large scatter in the bounded area shown in Fig. 13. As a result, the calculated time-to-corrosion when using a coulomb-based estimate of the diffusion coefficient can cover a range of approximately 3 to 5 years for coulomb values of 500, 1000, and 2000. Conversely, given a constant time-to-corrosion, the estimated coulomb values can vary by 700 to 1200 coulombs.

As shown in Fig. 12, the combined data from these 24 concretes from these two studies do not appear to be correctly represented by the correlation equation developed from data from the 1988 paper[18] and presented in a 1994 paper.[21]

This sensitivity of calculated time-to-corrosion indicates that the diffusion coefficients and C_o factors should be determined using long-term ponding studies, rather than coulomb-based estimates, which determine neither of these two factors. An example of the error arising from using coulomb values to attempt to predict long-term performance is shown in Fig. 14. The 0.37 w/cm concrete with 7.5 percent silica fume and the 0.32 w/c heat-cured concrete had essentially identical chloride profiles, yet had more than a 1000 coulomb difference.

In addition to similarly performing concretes having very different coulomb values, some differently performing concretes can have very similar coulomb values. Another example of this error is shown in Fig. 15, where the 0.46 w/c burlap-cured concrete has a very similar coulomb value of 3000 to a 0.37 w/c heat-cured concrete with a coulomb value of 2800, yet their chloride profiles and their diffusion coefficients were vastly different, and their C_o values were essentially equal. Had the coulomb value been solely relied upon to indicate the relative permeability of the concrete and time-to-corrosion, grossly incorrect conclusions would have been reached, with the heat-cured 0.37 w/c conventional concrete being improperly classified.

These cumulative data from two studies illustrate that the 1000-coulomb cutoff level for discriminating between "real world" concrete diffusion coefficient, surface chloride concentrations and time-to-corrosion is unjustified and inappropriate. It is important to note that numerous concrete projects in the past with specified coulombs of 600 to 1000 have created jobsite construction problems and cracking, based on the authors' experience.

Based on this extensive study and the requirement for "constructable" projects with minimal concrete finishing, curing, cracking, and permeability problems, it is clear that concrete with coulomb levels of 1000 to 3000 can produce low permeability concretes. In fact, for concretes with coulombs below 3000, both studies discussed above show diffusion coefficients that are at least 80 percent lower than the 0.46 w/c AASHTO-quality conventional concrete Mixture 3 used in this study and the 0.48 w/c conventional concrete used in the other referenced study,[18,21] which both had coulomb values of 2900 to 3700 for these AASHTO-quality concretes.

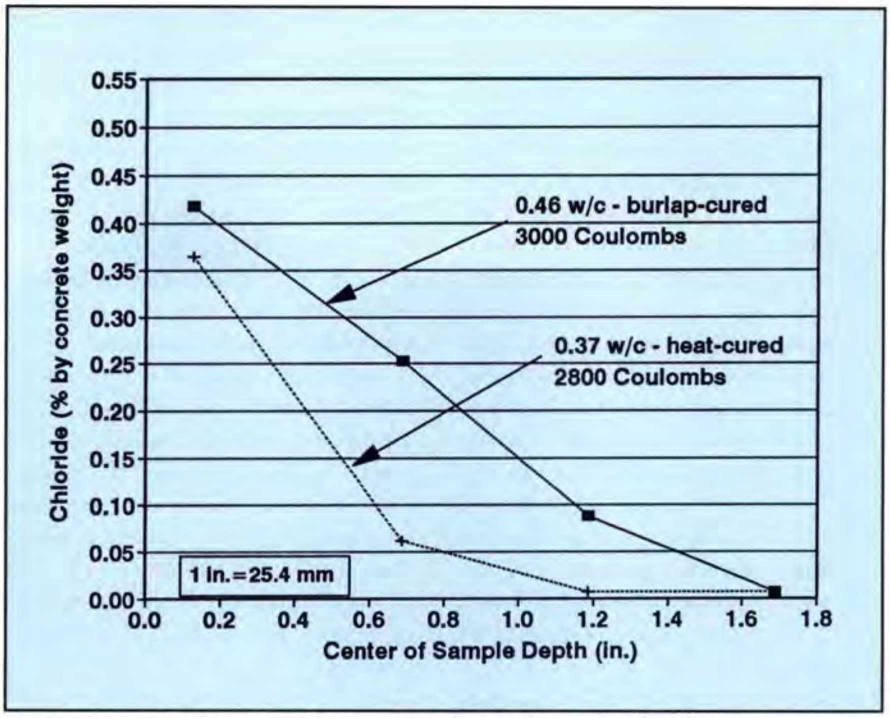

Fig. 15. Example of comparable concrete with similar coulomb values.

CONCLUDING REMARKS

The major conclusions, observations, recommendations, and concerns from this time-to-corrosion and chloride permeability study are as follows:

1. The low 0.32 w/cm mixtures had longer times of initial setting, probably related to the higher HRWRA requirements to achieve this very low w/cm value. This increase could range from about 1 hour to 1.5 hours when compared to the 0.46 w/cm mixtures. This setting time increase influences jobsite construction and finishing operations and heat curing preset periods for precasting plants.

2. The four 0.46 and 0.37 w/cm silica fume mixtures produced 28- and 180-day compressive strengths that essentially equaled the 28- and 180-day strengths of equal w/c ratio, conventional concretes.

3. The 28-day strength of heat-cured conventional concretes with no supplemental moist curing after the overnight heat curing averaged 90 percent of their companion 28-day water tank-cured cylinders for the three w/c levels. Therefore, proper heat curing created no significant strength loss at 28 days at all three w/c levels.

4. The three heat-cured conventional concrete mixtures had the lowest water absorptions and volume of permeable voids when compared to the 12 water tank-cured or burlap-cured concretes with or without silica fume. The concretes with 5 and 7.5 percent silica fume additions had average volumes of permeable voids that were about 100 and 50 percent greater, respectively, than the heat-cured conventional concretes.

5. All 15 concrete mixtures produced very high near-surface chloride concentrations after the 365-day ponding. The lowest w/cm mixtures produced on average the highest calculated C_o surface chloride concentrations, and the highest w/cm mixtures produced the lowest calculated C_o surface chloride concentrations.

6. The heat-cured concretes had the lowest water absorptions and volume of permeable voids at age 42 days. The 365-day long-term ponding tests also indicate that the heat-cured slabs generally had 18 to 36 percent lower near-surface chloride concentration than the overall average of the burlap-cured and water tank-cured concretes with and without silica fume, at all w/cm levels.

7. The surface chloride concentrations of 13 to 23 lbs per cu yd (7.7 to 13.6 kg/m^3) for the heat-cured concretes are significantly lower than the 30 lbs per cu yd (17.8 kg/m^3) assumed in other published corrosion research studies pertaining to long-term life estimates.

8. This present study and a 1987 FHWA study indicate that the concrete w/c ratio is the dominant factor in reducing chloride permeability. When the w/c is reduced from AASHTO-quality 0.46 to 0.51 w/c levels to 0.37 to 0.40 levels, the chloride reduction at the 1 in. (25 mm) depth level after severe 1-year salt water exposure testing was about 80 percent. When the w/c is reduced further to 0.28 to 0.32 levels, the chloride reductions were about 95 percent of the AASHTO-quality 0.46 to 0.51 w/c concrete.

9. The 5 and 7.5 percent burlap-cured silica fume mixtures with 0.46 to 0.37 w/cm have estimated times-to-corrosion similar to those of heat-cured 0.37 to 0.32 w/c conventional concretes. These four silica fume mixtures produced very low diffusion coefficients of 0.8 to 1.8×10^{-6} mm^2/s, and the two heat-cured conventional concretes produced similar diffusion coefficients of 1.1 to 2.2×10^{-6} mm^2/s. Typical burlap-cured AASHTO-grade 0.46 w/c conventional concrete produced a high diffusion coefficient of 8.8×10^{-6} mm^2/s, a value 4 to 10 times greater than the six low-permeability concretes discussed above. The lowest average diffusion coefficient of 0.65×10^{-6} mm^2/s was from the 0.32 w/cm silica fume concretes with 5 and 7.5 percent fume. The typical AASHTO-grade 0.46 w/c conventional burlap-cured concrete diffusion coefficient is about 14 times this lowest coefficient measured on this difficult to use 0.32 w/cm concrete.

10. An increase in cover to improve corrosion performance is significantly more effective when low w/c concretes are used.

11. This investigation of the AASHTO T 277 and the ASTM C 1202 test methods revealed that significant and serious questions remain regarding their appropriateness for use in concrete qualification and project specifications. The correlation between long-term chloride diffusion, the surface chloride concentration C_o, the time-to-corrosion and the coulomb test recommended in the ASTM C 1202 test appears to be highly variable and requires individual correlations between these two types of tests for every concrete mixture. The widely used 1000 coulomb cut-off limit was found to be arbitrary and misleading for many concretes, due to the widely different chloride permeabilities and C_o factors observed for concretes both meeting and failing such a coulomb limit-based specification. The C_o chloride surface concentration did not correlate to the coulomb value. The use of heat curing was found in this study to increase the coulomb values of concrete without increasing its actual chloride permeability.

12. When similar end-use concretes are compared using estimated time-to-corrosion and long-term chloride ingress, low w/c heat-cured conventional concrete performs as well as practical w/cm concretes containing silica fume.

13. The best way to improve current concrete is to specify lower w/c concretes and enforce the specification requirements. Concrete should be specified to have a low chloride diffusion coefficient and a low C_o surface chloride concentration, as determined by long-term ponding tests. The 6-hour AASHTO T 277 and ASTM C 1202 tests for determining coulomb values only should not be used for specification purposes due to the variable effects of curing and other factors on the coulomb value. The test must only be used when proper correlations between coulomb values and long-term ponding test results have been established for the individual concretes under test, as already required in the ASTM C 1202.

14. To meet these new demands, materials suppliers, the precast concrete industry, and all other suppliers to the concrete industry should carry out long-term ponding tests (with at least 1 year of ponding) to demonstrate the performance of their specific materials and end product to the purchaser. By taking a long-term view of the concrete performance, the durability of all structures can be increased, lessening the need for repair and maintaining concrete as a state-of-the-art building material of choice for the transportation and construction industry.

During the testing described in this report, certain inconsistencies and weaknesses in the standardized tests were noted and reported by others.[24] The following recommendations and concerns to users of the test procedures have been provided in an effort to improve future specifications and testing of similar high performance concretes.

AASHTO Section 8.11 Curing Specifications

Except for top slabs of structures serving as finished pavements, the 1992 AASHTO specifications permit the moist curing to be terminated in less than 7 days, once the field-cured cylinders reach 70 percent of their design strength. With today's cement and lower w/c values, this permits the termination of moist curing from piers, columns, beams, parapets, walls, median barriers, and sound barriers, and other components that will be exposed to salt water during their life after as little as 1 to 3 days, based on the authors' experience. This procedure could result in improper moist curing for a number of highway structures that receive deicers.

AASHTO T 259 Ponding Test

Modifications to the AASHTO T 259 test procedures are required to enable the performance of high quality concretes to be differentiated. These modifications include:

1. Provision of a more realistic curing period. The T 259 recommended 14-day moist curing is unrealistic; a 7-day period is realistic because both ACI and AASHTO utilize this 7-day period.

2. Use of a higher chloride concentration for the ponding solution. The recommended 3 percent NaCl solution models sea water; however, it does not accurately model deicing salt solutions that frequently have significantly higher chloride concentrations. If a 15 percent salt solution is used, the measured chloride in the slabs will be greater, providing increased accuracy in the determination of the chloride contents and improved diffusion modeling.

3. Increase the ponding period. The 90-day test is only appropriate for distinguishing relatively porous and permeable concretes. A minimum test period of 365 days is recommended. As the test does not require extensive supervision or work during the ponding period, this extended period will have little impact on the cost of the tests.

4. Use of an increased number of chloride samples. The test procedure recommends only two chloride measurements to be made at depths $^1/_{16}$ to $^1/_2$ in. (1.6 to 13 mm) and at $^1/_2$ to 1 in. (13 to 25 mm). Two data points are totally insufficient to determine diffusion coefficients required for prediction of chloride concentrations during the life of the structure, and at least four depths should be used.

5. Use of core samples, rather than drilled samples. It is significantly better to use large samples cored from the slabs than to use small drilled powder samples that are usually subjected to errors from contamination and inaccurate drilling depths.

AASHTO T 277

This test method should be replaced with the newly revised ASTM C 1202 test method in order to specifically require correlation to long-term ponding data and to eliminate the misleading interpretation of Table 1.

ASTM C 1202

A number of changes should be made to reflect the changing state-of-the-knowledge reflected by this Part 2 paper and other papers on this controversial test method. These changes are:

1. The age of the concrete for conducting the coulomb tests should be specified when laboratory produced concrete mixtures are being evaluated and correlated to long-term ponding tests.

2. All laboratory produced specimens for coulomb testing and long-term ponding should have realistic moist curing of no longer than 7 days, as per ACI and AASHTO specifications for construction sites. Continuous moist curing to ages of 28 to 90 days prior to coulomb testing or ponding should be prohibited.

3. The long-term ponding used to correlate the material-specific performance of the concrete should be specified in ASTM C 1202 to be at least 365 days and should use a salt water solution of 15 percent, in order to obtain more accurate diffusion coefficients and surface chloride concentrations.

4. Table 1 showing correlation of coulombs to permeability should be removed.

General Concern

The authors of this paper are concerned about specifications that require the ASTM C 1202 or AASHTO T 277 "coulomb test" for the concrete acceptance for a project, yet which also prohibit the use of the "coulomb test" on drilled cores from the project to determine if the Owner actually obtained his specified "coulomb value." This reluctance to test the jobsite concrete is undoubtedly based on concerns about jobsite concrete consolidation and curing factors.

ACKNOWLEDGMENT

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