Long-Term Chloride Penetration Resistance of Bridge Decks Made With Silica Fume Concretes

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Abstract

Cores were obtained in 2001 and 2002 from four concretes from bridge decks in New York State and one in Ohio and which had been exposed to de-icing salts. The Ohio bridge was 15 years old and made with silica fume concrete (804 pcy cementitious materials with 14.3% silica fume, 0.33 w/cm). The New York bridges included a 6 year old Portland cement concrete (0.42 w/c, 674 pcy), a 6 year old, 0.40 w/cm concrete with 20% F-fly ash and 6% silica fume (674 pcy), a 7 year old, 11% silica fume, 0.37 w/cm concrete (767 pcy), and a 12 year old silica fume concrete overlay (6% silica fume, 0.40 w/cm , 674 pcy).

The cores were tested for surface chloride penetration profiles using mm-layer profiling and the depths of cover were noted, where reinforcement was visible. Samples cut from below the depth of chloride penetration were tested for chloride bulk diffusion by ASTM C1556, rapid chloride penetration (ASTM C1202),

The results show that all of the silica fume concrete decks had high chloride penetration resistance, with all full depth decks having between 290 and 690 coulombs on average, while the portland cement concrete had 3900 coulombs. Predicted time-to-corrosion service life, using the Life-365 program, gave residual life estimates of between 30 and 61 years for the silica fume concretes. A portland cement concrete, used as a control, was found to be likely subject to corrosion at the time of coring. Predicted residual service lives based on extrapolation from existing chloride penetration profiles gave longer estimates by 10-years on average than the Life-365 initial predictions for the 3 new bridge decks made using silica fume concrete.

Introduction

Highway agencies have taken a number of measures to improve durability, reduce premature corrosion of reinforcement due to ingress of deicer salts, and to obtain longer service lives in bridge structures. One of these measures has been to reduce the rates of chloride penetration by use of concretes with lower water to cementitious materials ratios (w/cm) and through use of supplementary cementing materials, such as silica fume.

These measures have been shown to be effective, in laboratory tests (Hooton et al 1997), but there has not been much evaluation of long-term field performance. Evaluation of field-exposed silica fume concretes is the topic of this contribution.

Test Program

In 2001-2002, multiple cores were obtained from the 5 bridge structures between 7 and 15 years old in New York State and Ohio as listed in Table 1. The New York Route 78 bridge deck concrete has been detailed by Streeter (1996), and the Ohio bridge was described by Bunke (1988). Cores were visually examined, catalogued, and then cut for various tests to determine depth of carbonation and chloride penetration. Standard chloride resistance properties were also measured. Figure 1 shows a typical layout for slicing pairs of cores for the different tests.

Table 1. Location of Bridges, and Concrete Mixture Information

State	Bridge Project	Code	Year Placed	w/cm	Cementing Materials pcy (kg/m^3)	Silica Fume pcy (kg/m^3)	Fly Ash pcy (kg/m^3)
Ohio	Bridge #161-0151	DOT	1987	0.33	703 (417)	101 (60)	0
New York	Overlay I-90 over Kraft Road	KR	1988	0.37	683 (405)	84 (50)	0
New York	Rt. 78 Class HP	78	1994	0.40	500 (297)	40 (24)	99 (59)
New York	Rt. 96 Class H- ref mix, approaches	FB-H	1996	0.42	674 (400)	0	0
New York	Rt. 96 Fall Brook Class HP	FB-HP	1996	0.40	500 (297)	40 (24)	99 (59)

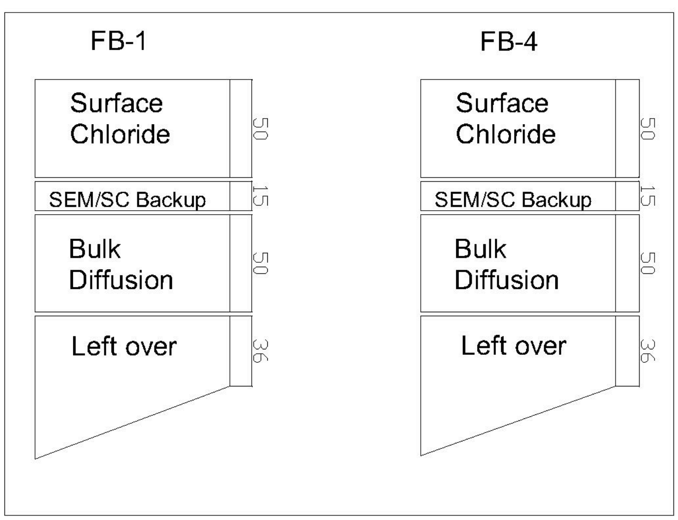

Figure 1. Typical arrangement of saw cuts on cores for testing (depths shown in mm) (Note: SEM/SC backup slices were reserved for microscopy, but were not tested)

Slices from cores were tested for electrical conductance (rapid chloride permeability) using ASTM C1202 (AASHTO T277), with results expressed in coulombs.

Some core slices, taken below the depth of chloride penetration, were tested using ASTM C1556, Chloride Bulk Diffusion. Samples were saturated and stored in lime water for one week, prior to being immersed in 2.8M NaCl solution at 73°F (23°C) for 40 days. The samples were then profile ground, using a Van Norman milling machine fitted with a 2 in. (50 mm) diameter diamond core bit, to obtain samples at approximately each mm of depth. The powder samples were then digested in acid as per ASTM C1152, filtered, and chloride analysis was performed using a Metrohm Titrino autotitrator. Surface chloride and bulk diffusion values were then fitted using Tablecurve software.

To determine the chloride penetration in service, the top 2 in. (50 mm) slices of selected cores were profile ground using a milling machine fitted with a 2 in. (50 mm) diameter diamond coring bit. Powder samples were taken for approximately each mm of depth and every second sample was digested in nitric acid, filtered, and then titrated using a potentiometric titrator.

Results

Depths of carbonation, as determined by phenolphthalein indicator, were zero in all but one case. For the Route 78 cores, carbonation was 1/16 in. (1.5mm). ASTM C1202 results are shown in Table 2. Bulk chloride diffusion results are shown in Table 3.

Table 2. ASTM C1202 Resistance to Chloride Ion Penetration Results

Project	Code	Avg. C1202 (coulombs)	Chloride Ion Penetrability
Bridge #161-0151	DOT	690	Very Low
Overlay, I-90 over Kraft Road	KR	2360	Moderate
Rt. 78 Class HP	78	290	Very Low
Rt. 96 Class H- ref mix, approaches	FB-H	3900	Moderate
Rt. 96 Fall Brook Class HP	FB-HP	430	Very Low

Table 3.Chloride Bulk Diffusion Test Results

Core ID	Chloride Concentration		Diffusion Coefficient	Average D
	Surface (%)	Background (%)	$10^{-12}(m^2/s)$	$10^{-12}(m^2/s)$
DOT-1	0.686	0.037	3.5	
DOT-3	0.749	0.029	4.7	4.1
KR-1	0.785	0.015	8.2	
KR-3	0.855	0.015	5.7	6.9
78-2	0.741	0.032	2.5	
78-4	0.546	0.034	2.5	2.5
FB-1 (class H)	0.702	0.040	59.9	

FB-4 (class H)	0.730	0.040	53.3	56.6
FB-3 (class HP)	0.695	0.070	2.1	
FB-6 (class HP)	0.799	0.065	1.6	1.9

The non-silica fume concrete, FB-Class H, had bulk diffusion coefficients about 10 times higher than the silica fume decks and a much average higher electrical conductance (coulomb value). The Kraft Bridge (KR) silica fume overlay, which was the first trial of this concrete in New York State, was not as chloride resistant as the later silica fume decks, as measured by bulk diffusion or by electrical conductance (coulombs). As discovered afterwards, apparently the NY DOT were conducting tests on other types of concrete mixtures on this overlay, and the core samples obtained may contain latex rather than silica fume.

A set of surface chloride penetration curves for 6-year exposed NY Fall Brook Class HP deck are shown in Figure 2. Depths of reinforcement, where encountered in the various cores, were between 2.4 and 3.4 in. (60 and 85 mm).

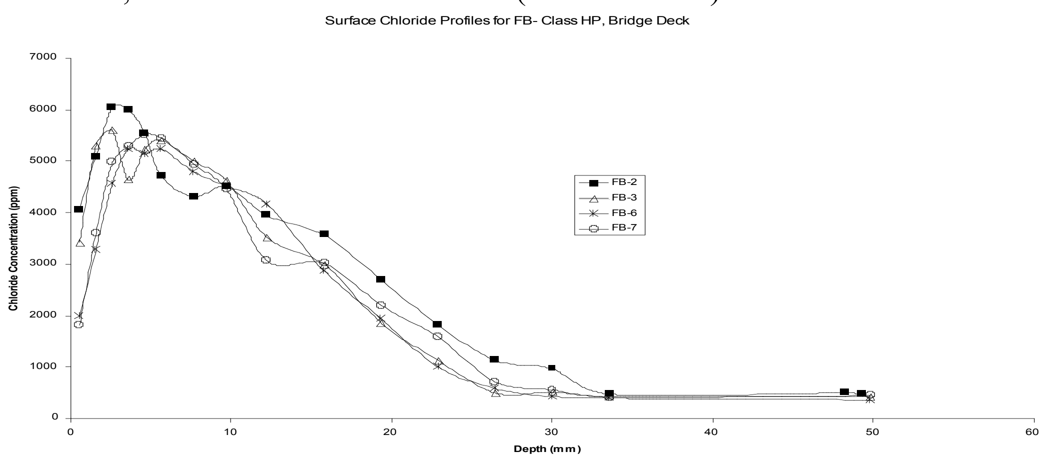

Figure 2. Typical In-service Chloride Penetration Profiles
(for 4 profiles from the NY Fall Brook-Class HP Silica Fume Concrete Cores after 6 Years exposure) (25.4 mm = 1.0 in.)

Two different pseudo-diffusion coefficients were fitted to the surface chloride profiles based on either the total time of service, or the time of service over which deicers were likely applied (based on weather records and first and last days of freezing temperatures). These are shown in Table 4.

The sets of calculated diffusion values are considered to approximately represent the possible upper and lower bound estimates of the actual in-situ effective diffusion coefficients. While chloride de-icers are only applied for part of the year, exposure to rain will both wash near-surface chlorides out (by counter diffusion), but also provide the moisture needed to allow the chlorides at depth to penetrate further during warmer parts of the year. The surface chloride contents listed in Table 4 are the surface level extrapolations from the best-fit Tablecurve analysis of the profiles. While the "total" and "winter" analyses were fit to the same experimental data, the use of different exposure times resulted in slight differences in the extrapolated surface levels as presented in the table.

Service Life Prediction

The remaining service life of the different structures was estimated using the program Conflux (Boddy, Bentz, Thomas and Hooton, 1999) which has the same basic finite-difference calculation engine used in the program Life-365 but it also allows initial concentration profiles to be applied (i.e. the surface chloride profiles as shown, for example, in Figure 1). The following assumptions were made:

Table 4. Diffusion Values based on In-service Chloride Penetration
(with different assumptions of exposure time)

		Chloride Concentration (% by mass of concrete)			**Diffusion Coefficient (m^2/s)**	
Core Information	**Core ID**	Surface (Total)	Surface (Winter)	Background	Total	Winter
Dept of Transportation	DOT-1	0.736	0.736	0.032	1.25E-13	2.85E-13
Ohio, Bridge #161-0151	DOT-2	0.704	0.704	0.037	1.45E-13	3.45E-13
SF Deck placed: Aug. 14, 1987	DOT-3	0.728	0.728	0.038	1.55E-13	3.65E-13
Cored: May 1, 2002	DOT-4	0.744	0.744	0.035	1.35E-13	3.25E-13
SFC Overlay I-90	KR-1	0.332	0.332	0.007	4.50E-13	1.56E-12
Kraft Road, New York	KR-2	0.292	0.292	0.007	4.40E-13	1.43E-12
Constructed: 1989	KR-3	0.352	0.349	0.007	4.18E-13	1.66E-12
Cored: Nov. 2001	KR-4	0.412	0.417	0.007	5.90E-13	1.88E-12
1st SFC full depth bridge	78-1	0.639	0.609	0.020	2.81E-13	9.91E-13
Route 78, New York	78-2	0.774	0.819	0.010	2.51E-13	6.15E-13
Placed: Oct. 13, 1994	78-3	0.744	0.729	0.021	2.75E-13	8.75E-13
Cored; Nov. 2001	78-4	0.879	0.894	0.018	2.45E-13	6.45E-13
Class HP- Bridge Deck	FB-2	0.619	0.620	0.050	6.50E-13	1.40E-12
Route 96, over Fall Brook	FB-3	0.649	0.656	0.044	5.10E-13	1.03E-12
New York Aug. 8, 1995	FB-6	0.71	0.650	0.044	3.82E-13	8.82E-13
Cored: Nov. 2001	FB-7	0.67	0.660	0.044	5.10E-13	9.91E-13
Class H - reference mix, bridge approaches	FB-1	0.75	0.750	0.044	1.45E-12	2.87E-12
Route 96, over Fall Brook	FB-4	0.591	0.591	0.044	2.81E-12	5.59E-12
New York, Aug. 1995	FB-5	0.82	0.820	0.044	1.84E-12	3.65E-12
Cored: Nov. 2001	FB-8	0.452	0.434	0.044	9.10E-13	2.00E-12

- The diffusion rate calculated based on the surface profiles and “winter” time assumptions is a reasonable estimate of the diffusion constant at the time of coring.
- The diffusion rate will decrease with time, due to increased hydration and chloride binding, using the parameter “m” as calculated by Life-365 (0.20 for the Portland and silica fume concretes, and 0.36 for the Fall Brook Class HP concrete with fly ash).
- No long-term lower bound to the diffusion rate is applied. As the “m” terms are relatively low for these specimens, this is not thought to be important.
- The diffusion rate is constant with depth into the specimen (ie. No curing effect).
- A qualitative average of the different measured chloride penetration profiles is used as the starting point of the diffusion analysis.

- The background chlorides are either bound or present in aggregates and thus have no effect on the time to corrosion.
- A chloride threshold level of 0.05% by mass of concrete is sufficient to depassivate the reinforcement.
- The time between depassivation and first repair is a constant 6 years for all structures (added to the residual service life prediction in Table 5).
- The surface chloride levels, are assumed to have reached their upper limit and will remain constant for the remaining life of the structure (This is considered reasonable based on Weyers, 1988). The value used is taken as the average from the curve fits to the surface chloride level to remove the effect of seasonal variations.
- The cover is 2 inches (50 mm) for all specimens. Information from cores was available for some specimens, that indicated higher depths of cover, but it was not clear if the depths obtained from the individual cores were representative of the remainder of the slab area or were necessarily from the top mat of steel.

Table 5 summarizes the results of the service life analysis. As can be seen, the concrete without silica fume (FB-H) is predicted to already have initiated corrosion. The Kraft Road overlay (KR) specimen shows much lower expected time to first repair compared to the other specimens, which is consistent with the relatively high RCPT values obtained from these samples. It should be noted that this structure was the first trial of such an overlay in New York state (Streeter, 1996) and it is thought that the procedures associated with placement of silica fume concrete overlays may have not been optimized.

The remaining structures are predicted not to require repairs due to chloride induced corrosion until 40-70 years from the date of coring.

Table 5. Predicted Residual Service Life Assuming a Constant Corrosion Propagation Period of 6 Years.

Project	Code	Estimated Residual Service Life (years)
Ohio Bridge #161-0151	DOT	65 + 6 = 71
NY Overlay, I-90 over Kraft Road	KR	16 + 6 = 22
NY Rt. 78 Class HP	78	34 + 6 = 40
NY Rt. 96 Class H- ref mix, approaches	FB-H	0
NY Rt. 96 Fall Brook Class HP	FB-HP	57 + 6 = 63

Comparison to Life-365 Predictions

As the analyzed bridge decks have known concrete mix designs and geographic locations, it is possible to perform a Life-365 calculation to see what would have been predicted by an engineer before construction began in terms of the expected service life. Table 6 was created using the mix design properties in Table 1 as inputs for Life-365 to calculate the default diffusion values and time-dependent changes in diffusion, and using the nearest large city in the Life-365 data base to estimate surface chloride levels as well as an annual temperature history. This table shows the expected number of years from the date of coring until the first repair without using any of the experimental results from the cores. As can be seen in the table, most predictions were conservative in that the service life prediction based on the experimental results from the cores produced a longer estimate of service life than the estimate which did not use the core data. However, for the Kraft Road (KR) bridge the results based on the core chloride penetration data suggest that the bridge will require repairs about 14 years earlier than would have estimated by Life-365 at the time of construction (if Life-365 had been available in 1988). On average, Table 6 suggests that bridge decks such as those in this paper that use silica fume can be expected to last perhaps 10 years longer on average than a Life-365 analysis would indicate.

Table 6. Predicted Residual Service Life from Life-365 Using No Experimental Results.

Project	Code	Estimated Residual SL from Life-365 (years)	Error in Life-365 Estimate (years)*
Ohio Bridge #161-0151	DOT	55 + 6 = 61	10 years conservative
NY Overlay, I-90 over Kraft Road	KR	30 + 6 = 36	14 years unconservative
NY Rt. 78 Class HP	78	24 + 6 = 30	10 years conservative
NY Rt. 96 Class H- ref mix, approaches	FB-H	0	-
NY Rt. 96 Fall Brook Class HP	FB-HP	24 + 6 = 31	32 years conservative

* Error relative to estimates shown in Table 5.

Conclusions

A series of concrete cores were obtained from 5 different bridge structures ranging in age from 7 to 15 years, in New York and Ohio. These were tested for chloride penetration resistance using surface chloride profiling and depths of carbonation. Lower sections of cores were tested for ASTM C1556 bulk diffusion and ASTM C1202 coulombs. The following can be concluded from the results:

1. As expected for bridge decks exposed to precipitation, depths of carbonation of all concretes after 7 to 15 years were nil to negligible.
2. Coulomb values, using ASTM C1202, were generally less than 1000 for all silica fume concretes (with the exception of the NY I 90 Kraft Road overlay cores which may or may not have contained silica fume), and over 3000 for the portland cement mixture.
3. Chloride bulk diffusion values, using ASTM C1556, were typically between 2 and 7 x 10^{-12} m^2/s for the silica fume concrete cores and 50 to 60 x 10^{-12} m^2/s for the portland cement concrete cores.
4. Diffusion values estimated from surface chloride penetration profiles were lower than those determined from the C1556 tests. This is due to the fact that the in-service chloride buildup with time will be slower and that the concentration of chloride exposure is lower and intermittent over each year.
5. If one enters the existing average chloride penetration profile from each set of cores into a predictive model, and uses the current bulk diffusion value as a

constant value, the residual time to corrosion can be estimated for an assumed depth of cover. The remaining service life for new full depth silica fume decks, with an assumed 50mm depth of cover, ranged from 40 to 71 years, while the full depth portland cement concrete has likely already started corroding.

6. Based on analysis of chloride penetration profiles obtained from 7 to 15 year old cores, bridge decks that use silica fume concrete can be expected to last perhaps 10 years longer on average than initial Life-365 analysis, using mix design information, would indicate.

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