LONG-TERM CHLORIDE PENETRATION RESISTANCE OF SILICA FUME CONCRETES BASED ON FIELD EXPOSURE

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Abstract

With support from the Silica Fume Association in the United States, cores were obtained in 2001 and 2002 from four concretes from bridge decks in New York State and one in Ohio. In addition, cores were taken from 4 parking garage decks located in Wisconsin, Utah, and 2 in Ohio. All concrete structures were between 6 and 15 years old when cored and which had been exposed to de-icing salts.

The cores were tested for chloride penetration profiles using mm profiling, chloride bulk diffusion by ASTM C 1556 (similar to Nordtest NT Build 443), rapid chloride penetration (ASTM C 1202), and the depth of cover was noted, where visible.

The results show that all of the silica fume concrete decks had high resistance to chloride penetration, with all full depth bridge decks having between 290 and 690 coulombs on average, while the portland cement concrete had 3900 coulombs. For parking decks, coulomb values ranged from 620 to 980. 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. In one case, portland cement concrete in an approach slab to a bridge deck was used as a control and 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 for the 3 new bridges and for allof the parking garage decks made with silica fume concrete.

1. INTRODUCTION

Due to premature corrosion of reinforcement due to ingress of deicer salts, highway agencies have taken a number of measures to improve durability and 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 and through use of supplementary

Hooton, R.D., Bentz, E.C., and Kojundic, T., "Long-Term Chloride Penetration Resistance of Silica Fume Concretes Based on Field Exposure", Proceedings, Service Life Design for Infrastructure RILEM PRO 70, 2010, Vol.1, pp.503-512.

cementing materials, such as silica fume. These measures have been shown to be effective, for example by Hooton et al [1] in laboratory tests, but there has not been much evaluation of long-term field performance. To address this, evaluation of field-exposed silica fume concretes is the topic of this contribution.

2. TEST PROGRAM

In 2001-2002, multiple cores were obtained from 5 bridge decks and 4 parking garage decks between 6 and 15 years old in New York State, Ohio, Utah, and Wisconsin as listed in Table 1. The Ohio bridge deck was 15 years old and made with silica fume concrete (477kg/m^3 cementitious materials with 14.3% silica fume, 0.33 w/cm) as previously described by Bunke [2]. The New York bridges included a 6 year old Portland cement concrete (0.42 w/c, 400kg/m^3), a 6 year old, 0.40 concrete with 20% F-fly ash and 6% silica fume (400kg/m^3), a 7 year old, 11% silica fume, 0.37 concrete (455kg/m^3), and a 12 year old silica fume concrete overlay (6% silica fume, 0.40, 400kg/m^3). The New York Route 78 bridge deck concrete has been detailed by Streeter [3]. The General Mitchell Airport parking deck was a 12 year old, 0.35 w/cm concrete (335kg/m^3) with 17.6% Class C fly ash, and 6.8% silica fume [4]. Cincinnati's Children's Hospital garage concrete was a 14 year old (0.37 w/cm, 390kg/m^3, 10% silica fume) concrete when cored. The Columbus Capitol South parking garage was a 12 year old structure when cored (363kg/m^3 cement, and 7.5% silica fume). The Salt Lake City Airport parking garage was a 14 year old garage when sampled (cement 363kg/m^3, 15% Class F fly ash, and 7.4% silica fume).

Table 1: Location of Structures, and Concrete Mixture Information

Location	Project	Code	Year Placed	W/CM	CM (kg/m^3)	SF (kg/m^3)	Fly Ash (kg/m^3)
Ohio	Bridge #161-0151	DOT	1987	0.33	417	60	0
New York	Overlay I-90 over Kraft Road	KR	1988	0.37	405	50	0
New York	Rt. 78 Class HP	78	1994	0.40	297	24	59
New York	Rt. 96 Class H- ref mix, approaches	FB-H	1996	0.42	400	0	0
New York	Rt. 96 Fall Brook Class HP	FB-HP	1996	0.40	297	24	59
Utah	Salt Lake Airport Garage	SL	1989	0.33	363	25	54
Ohio	Children's Hospital Garage	CH	1990	0.37	390	39	0
Ohio	Capital South COTA Garage	CS	1986	0.40	363	27	0
Wisconsin	General Mitchell Airport Garage	GM	1989	0.35	335	23	59 (Type C)

Cores were also obtained form five parking structures, but results are not included here. 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.

Slices from cores were tested for electrical conductance which integrated over a 6 hour test period (rapid chloride permeability) using ASTM C1202 (AASHTO T277), with results expressed in coulombs.

Some core slices 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 23^{o}C for 40 days. The samples were then profile ground, using a milling machine fitted with a 50mm 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 using a numeric solution to Fick's 2nd law [3].

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

3. RESULTS

Depths of carbonation, as determined by phenolphthalein indicator, were zero in all but one case. For the Route 78 bridge cores, carbonation was 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

SFC Project Cores	Code	Test 1	Test 2	Test 3	Average Charge (coulombs)	Chloride Ion Penetrability
General Mitchell Airport Parking, Milwaukee	GM	775	978		877	Very Low
Children's Hospital Parking, Cincinnati	CH	721	728	3674 (CH-3)	1711 (725 w/o CH-3)	Low (Very Low)
Capitol South (COTA Garage), Columbus	CS	938	979		959	Very Low
Ohio DOT Bridge # 161-0151	DOT	1061	323		692	Very Low
NY DOT, I-90 over Kraft Road	KR	1900	2819		2359	Moderate
NY DOT, Rt 78	78	333	252		293	Very Low
NY DOT, Rt 96 over Fall Brook, Class H	FB:1,4,5,8	4714	308		3899	Moderate
NY DOT, Rt 96 over Fall Brook, Class HP	FB:2,3,6,7	553	304		428	Very Low
Salt Lake City Airport Garage	SL	787	623	3032 (SL-5)	1481 (705 w/o SL-5)	Low (Very Low)

The non-silica fume, FB-Class H concrete had bulk diffusion coefficients about 10 times higher than the silica fume decks and a much average higher coulomb values as well. The Kraft Bridge (KR) silica fume overlay, which was the first trial of this type of concrete in New York State, was not as chloride resistant as the later silica fume decks, as measured by bulk diffusion or by coulombs.

Table 3: Chloride Bulk Diffusion Test Results

SFC Project Cores	**Core ID**	**Chloride Concentration**		**Diffusion Coefficient (10^{-12} m^2/s)**
		Surface (%)	Background (%)	
General Mitchell Airport Parking, Milwaukee	GM-2	0.94	0.07	3.76
	GM-4	1.00	0.07	6.37
Children's Hospital Parking, Cincinnati	CH-2	0.50	0.04	9.41
	CH-4	0.72	0.06	5.60
	CH-6	0.50	0.04	22.8
Capitol South (COTA Garage), Columbus	CS-2	0.65	0.03	7.15
	CS-4	0.66	0.05	12.8
Ohio DOT Bridge # 161-0151	DOT-1	0.69	0.04	3.54
	DOT-3	0.75	0.03	4.74
NY DOT, I-90 over Kraft Road	KR-1	0.79	0.02	8.15
	KR-3	0.86	0.02	5.70
NY DOT, Rt 78	78-2	0.74	0.03	2.45
	78-4	0.55	0.03	2.45
NY DOT, Rt 96 over Fall Brook, Class H	FB-1 (class H)	0.70	0.04	59.9
	FB-4 (class H)	0.73	0.04	53.3
NY DOT, Rt 96 over Fall Brook, Class HP	FB-3 (class HP)	0.70	0.07	2.08
	FB-6 (class HP)	0.80	0.07	1.63
Salt Lake City Airport Garage	SL-2	0.69	0.01	7.03
	SL-4	0.72	0.01	5.70
	SL-6	0.27*	0.14*	52.5*

* results do not appear to be valid

A set of surface chloride penetration curves for 6-year exposed NY Fall Brook Class HP deck are shown in Figure 1. Depths of reinforcement, where encountered in the various cores, were between 60 and 85mm.

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 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-

Table 4: Diffusion Values based on In-service Chloride Penetration

Core Information	Core ID	Chloride Concentration (% by mass of concrete)			Diffusion Coefficient (m^2/s)	
		Surface (Total)	Surface (Winter)	Background	Total	Winter
General Mitchell Airport Parking Milwaukee Constructed: Sept 1989-August 1990 Cored: Sept. 18, 2002	GM-1	0.698	0.688	0.0291	2.22E-13	5.02E-13
	GM-2	0.787	0.787	0.0341	1.52E-13	3.40E-13
	GM-3	0.738	0.728	0.0389	2.01E-13	4.51E-13
	GM-4	0.747	0.728	0.0372	2.21E-13	5.18E-13
	GM-5	0.470	0.460	0.0374	2.20E-13	5.20E-13
	GM-6	0.639	0.639	0.0309	2.19E-13	4.89E-13
Children's Hospital Parking Cincinnati Constructed: October 1990-June 1991 Cored: Feb 23, 2002	CH-1	0.548	0.555	0.0341	1.34E-13	3.25E-13
	CH-2	0.482	0.482	0.0288	1.95E-13	5.10E-13
	CH-3	0.536	0.536	0.0284	1.35E-13	3.25E-13
	CH-4	0.959	0.995	0.0359	1.20E-13	2.75E-13
	CH-5	0.545	0.545	0.0178	1.10E-13	2.78E-13
	CH-6	0.509	0.527	0.0382	7.03E-14	1.59E-13
Capitol South Garage Columbus Constructed: Sept1986-Sept 1987 Cored: Oct. 23, 2001	CS-1	0.235	0.245	0.0276	6.98E-14	1.89E-13
	CS-2	0.155	0.155	0.0263	5.56E-14	1.49E-13
	CS-3	0.573	0.573	0.0221	1.29E-13	3.67E-13
	CS-4	0.645	0.645	0.0213	2.09E-13	5.75E-13
	CS-5	0.956	0.956	0.0233	6.99E-14	1.79E-13
	CS-6	1.023	1.023	0.0199	2.09E-13	5.55E-13
Dept of Transportation Ohio, Bridge #161-0151 SF Deck placed: Aug. 14, 1987 Cored: May 1, 2002	DOT-1	0.736	0.736	0.0323	1.25E-13	2.85E-13
	DOT-2	0.704	0.704	0.0370	1.45E-13	3.45E-13
	DOT-3	0.728	0.728	0.0375	1.55E-13	3.65E-13
	DOT-4	0.744	0.744	0.0354	1.35E-13	3.25E-13
SFC Overlay I-90 Kraft Road, New York Constructed: 1989 Cored: Nov. 2001	KR-1	0.378	0.378	0.0070	5.70E-13	1.99E-12
	KR-2	0.292	0.292	0.0070	4.40E-13	1.43E-12
	KR-3	0.606	0.613	0.0070	3.69E-13	1.21E-12
	KR-4	0.412	0.417	0.0070	5.90E-13	1.88E-12
1st SFC full depth bridge Route 78, New York Placed: Oct. 13, 1994 Cored; Nov. 2001	78-1	0.639	0.609	0.0200	2.81E-13	9.91E-13
	78-2	0.774	0.819	0.0104	2.51E-13	6.15E-13
	78-3	0.744	0.729	0.0210	2.75E-13	8.75E-13
	78-4	0.879	0.894	0.0176	2.45E-13	6.45E-13
Class HP- Bridge Deck Route 96, over Fall Brook New York Aug. 8, 1995 Cored: Nov. 2001	FB-2	0.619	0.620	0.0502	6.50E-13	1.40E-12
	FB-3	0.649	0.656	0.04385	5.10E-13	1.03E-12
	FB-6	0.710	0.650	0.04385	3.82E-13	8.82E-13
	FB-7	0.670	0.660	0.04385	5.10E-13	9.91E-13
Class H - ref mix, approaches Route 96, over Fall Brook New York, Aug. 1995 Cored: Nov. 2001	FB-1	0.750	0.750	0.04385	1.45E-12	2.87E-12
	FB-4	0.591	0.591	0.04385	2.81E-12	5.59E-12
	FB-5	0.820	0.820	0.04385	1.84E-12	3.65E-12
	FB-8	0.452	0.434	0.04385	9.10E-13	2.00E-12

Table 4: Diffusion Values based on In-service Chloride Penetration (cont.)

Core Information	Core ID	Chloride Concentration (% by mass of concrete)			Diffusion Coefficient (m^2/s)	
		Surface (Total)	Surface (Winter)	Background	Total	Winter
Parking Garage Salt Lake City Constructed: Sept 1989-Dec 1990 Cored: Dec. 4, 2003	SL-1	1.455	1.455	0.0180	2.28E-13	4.95E-13
	SL-2	0.933	0.933	0.0170	1.85E-13	3.85E-13
	SL-3	0.861	0.861	0.0150	3.35E-13	7.15E-13
	SL-4	1.383	1.419	0.0134	3.79E-13	6.66E-13
	SL-5	0.333	0.333	0.0149	1.12E-14	2.47E-14
	SL-6	0.524	0.524	0.0122	3.60E-15	7.87E-15

surface chlorides out, but also allow most of the chlorides 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. While the "total" and "winter" analyses were fit to the same experimental data, the use of different assumed exposure times results in slight differences in the extrapolated surface levels as presented in the table.

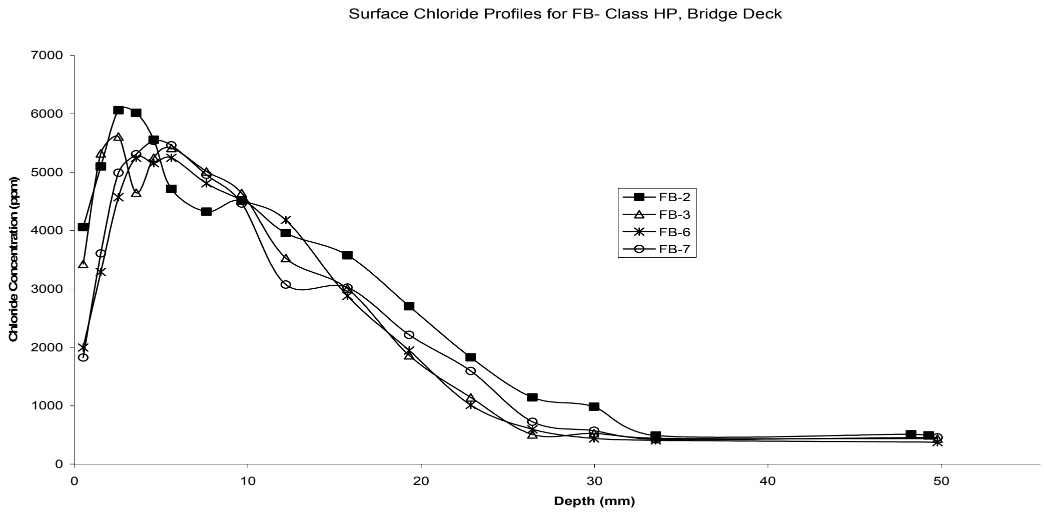

Figure 1: Typical In-service Chloride Penetrations (for the NY Fall Brook-Class HP Silica Fume Concrete Cores after 6 Years)

4. SERVICE LIFE PREDICTION

The remaining service life of the different structures was estimated using the program Conflux [4] which has the same basic calculation engine as the program Life-365 but 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:

- The diffusion rate calculated based on the surface profiles and “winter” time assumptions is a good estimate of the diffusion constant at the time of coring.
- The diffusion rate will decrease 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 felt to be important.
- The diffusion rate is constant with depth into the specimen.
- A qualitative average of the different measured chloride 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 residual service life prediction in Table 5).
- The surface chloride levels will remain constant for the remaining life of the structure. 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 50 mm (2 inches) 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 [3] 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.

Results from parking decks are much more variable, however. For the first three cases in Table 5, the predicted life based on the core data is dramatically longer than that which would be predicted by Life-365, by as much as a century. This may be, in large part, due to the fact that Life-365 assumes the same linear buildup of surface chloride content in parking garages as in bridges. However, in covered parking decks there is no de-icing salt deliberately applied to the decks, but chloride exposure occurs from chloride-laden snow and water dripping off of vehicles in the driving lanes, on the ramps, and non-uniformly in the parking spaces. Depending on locations of the cores and amounts of snow in any particular year, the surface loading may vary dramatically and the effective time of exposure will also vary. The extent of deck washing will also be more variable than bridge decks exposed to regular rain.

It can therefore be expected that there will be more variability in parking deck predictions than for bridge deck predictions, and this is what is observed in Table 5.

Table 5: Service-life predictions from extrapolation of surface chloride penetration profiles

Sample	State	D at start (m^2/s)	m	Surface Conc. (% conc)	Back. Conc. (% conc)	Assumed profile at start (% by mass of concrete) 5 mm	10 mm	15 mm	20 mm	25 mm	Time to initiate (years)	Prop-agate (years)	Time to 1st repair (years)
GM	WI	4.7E-13	0.32	0.67	0.035	0.50	0.35	0.22	0.15	0.07	165	6	**> 100**
CH	OH	3.1E-13	0.20	0.61	0.031	0.35	0.20	0.10	0.05	0.04	137	6	**> 100**
CS	OH	3.4E-13	0.20	0.60	0.023	0.50	0.35	0.20	0.10	0.02	107	6	**> 100**
DOT	OH	3.3E-13	0.20	0.73	0.036	0.55	0.38	0.20	0.08	0.04	93	6	**99**
KR	NY	1.6E-12	0.20	0.35	0.045	0.32	0.30	0.22	0.20	0.13	16	6	**22**
78	NY	7.8E-13	0.32	0.76	0.017	0.50	0.40	0.18	0.07	0.02	34	6	**40**
FB-H	NY	3.5E-12	0.20	0.65	0.044	0.50	0.50	0.50	0.40	0.30	now		**now**
FB-HP	NY	1.1E-12	0.32	0.65	0.044	0.55	0.45	0.35	0.20	0.10	57	6	**63**
SL	UT	5.7E-13	0.30	1.17	0.015	0.75	0.60	0.45	0.30	0.20	48	6	**54**

Table 6: Service-life predictions based on both chloride penetration profiles from cores and from initial Life-365 analysis

Project	Code	Estimated residual service life from cores (years)	Estimated Residual SL from Life-365 (years)	Error in Life-365 estimate (years)
Milwaukee General Mitchell Garage	GM	165 + 6 > 100	24 + 6 = 30	See Text
Children's Hospital Parking	CH	137 + 6 > 100	18 + 6 = 24	See Text
Capitol South Garage	CS	107 + 6 > 100	5 + 6 = 11	See Text
Ohio Bridge #161-0151	DOT	93 + 6 = 99	55 + 6 = 61	38 years conservative
NY Overlay, I-90 over Kraft Road	KR	16 + 6 = 22	30 + 6 = 36	14 years unconservative
NY Rt. 78 Class HP	78	34 + 6 = 40	24 + 6 = 30	10 years conservative
NY Rt. 96 Class H- ref mix, approaches	FB-H	0	0	
NY Rt. 96 Fall Brook Class HP	FB-HP	57 + 6 = 63	24 + 6 = 31	32 years conservative
Salt Lake Airport Garage	SL	48 + 6 = 54	23 + 6 = 29	25 years conservative

5. COMPARISON OF DATA TO LIFE-365 PREDICTIONS

Since the analyzed bridge decks and parking 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. The mix design properties in Table 1 and the location of the nearest large city in the Life-365 database were used to estimate surface chloride levels as well as an annual temperature history, Table 6 was created. 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 Table 6, 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. For the Kraft Road (KR) bridge, however, the results based on the core data suggest that the bridge will require repairs about 14 years earlier than an engineer would have estimated 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, and for the parking garages in the survey perhaps ever longer.

6. CONCLUSIONS

A series of concrete cores were obtained from 4 different parking garage decks, in Ohio (2), Utah, and Wisconsin, and 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, ASTM C1556 bulk diffusion, ASTM C1202 coulombs, and depth of carbonation. The following can be concluded:

1. 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) , 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 5 to 6 x 10^{-11} 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 chloride buildup with time will be slower and the concentration of chloride exposure is lower and intermittent over each year.
5. If one enters the existing chloride profile from each core into a predictive model, and uses the current bulk diffusion value as a constant value, the 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 a Life-365 analysis would indicate.
7. The 4 parking garage deck concretes exhibit even greater service-life expectancy than the bridge decks. These results are primarily due to the fact that parking decks are not typically directly exposed to precipitation and will tend to dry and reduce chloride transport abilities during that part of the year as compared to the Life-365 model which assumes constant steady-state diffusion as the primary chloride transport mechanism. As well, parking decks are not typically de-iced and are only exposed to salt from melting snow and ice falling from vehicles.

ACKNOWLEDGEMENTS

The financial support of the Silica Fume Association is gratefully appreciated. The project was administered by T. Holland. The laboratory work was performed by D. Castiglione, G. Haines, and N. Khakoo, and O. Perebatova.

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