PENNDOT RESEARCH
AGREEMENT E03134

100 YEAR SERVICE LIFE STUDY

CHLORIDE MIGRATION COEFFICIENT EVALUATION

By

Clay Naito, Ph.D., P.E.
Liyang Ma
Amirali Shojaeiandivkolaei
Paolo Bocchini, Ph.D.
John Fox, Ph.D.
Aman Karamlou

June 2016

ATLSS REPORT NO. 16-04

ATLSS is a National Center for Engineering Research on Advanced Technology for Large Structural Systems

117 ATLSS Drive

Bethlehem, PA 18015-4729

Phone: (610)758-3525
Fax: (610)758-5902

www.atlss.lehigh.edu
Email: inatl@lehigh.edu

ABSTRACT

A research study sponsored by Pennsylvania Department of Transportation is conducted to examine the chloride resistance of concrete commercially produced in Pennsylvania. Concrete produced by ready mix suppliers and precast and prestressed concrete producers were examined. PennDOT certified concrete class A, AA, and AAAP, and precast SCC and HES mixes were procured from suppliers in the form of 4x8 in. cylinders and evaluated in accordance with Nordtest Method NT Build 492. The test determines the chloride migration coefficient from non-steady-state migration experiments. Experiments were conducted on concrete cured to 28, 56 and 112 days. Across all ages the study resulted in an average non-steady-state migration coefficient of 9.9E-12 m^2/s for class A, 8.3E-12 m^2/s for class AA, 6.1E-12 m^2/s for class AAAP, 7.6E-12 m^2/s for HES and 1.0E-12 m^2/s for SCC. The test procedure, methods, computation method, results and discussion are included in this report. In general SCC performed the best followed by AAAP, HES, AA, and A. Correlation was observed between increased design mix strength reduced and migration coefficient. There was minimal correlation between migration coefficient and concrete water/cement ratio, design slump, admixtures, and unit weight. High migration values were observed for concretes containing coarse aggregate with a GL classification and an absorption of 1.99. A probabilistic analysis of the results indicate that he majority of concretes evaluated will not provide satisfactory resistance to chlorides when used in standard bridge structures with a 100 year design life.

TABLE OF CONTENTS

LIST OF FIGURES

OVERVIEW

This report details chloride migration evaluation of class A, AA, AAAP, High Early Strength (HES), and Self-Consolidating Concrete (SCC) produced in Pennsylvania for PennDOT construction. The concretes were produced by ready mix suppliers and precast bridge producers throughout the state, delivered to Lehigh University, and tested at ages ranging from 28 to 113 days. The concrete was tested in accordance with Nordtest Method NT Build 492:

NT Build 492, (1999), "Nordtest Method Concrete, Mortar and Cement-Based Repair Materials: Chloride Migration Coefficient from Non-Steady-State Migration Experiments," Nordic Council of Ministers, Espoo, Finland.

The study is conducted to assess the variability of chloride resistance of concrete produced in the state of Pennsylvania. The migration coefficient is used as a metric of chloride resistance which in turn is used as an input parameter for FIB 34 to determine the expected service life of components fabricated from the concrete.

FIB 34 Task Group 5.6. "Model Code for Service Life Design." Tech. no. Bulletin 34. Lausanne: International Federation for Structural Concrete, 2006.

In a natural environment the process of chloride penetration is measured in years. The traditional accelerated methods such as diffusion cells or solution immersion are time-consuming to obtain results (Luping and Nilsson, 1992a, b). To address these limitations the Nordtest Method NT Build 492 was developed by Luping and Nilsson (1992a, b). The method imparts an electrical field to a concrete sample to accelerate chloride migration and provides a mathematical model to determine the ion diffusion as a result of the applied electrical field.

The NT Build 492 method has been used by researchers around the world to investigate the chloride migration coefficient of concrete and its relationship with the other concrete properties. For example, the correlation of chloride migration coefficient and concrete maturity was studied by Li, Dong, and Xiong (2014). The study suggested a strong correlation between chloride diffusion coefficient with curing ages and curing temperature. More comprehensive tests investigating temperature effects and concrete strength with various admixtures have been conducted by Presuel-Moreno, Liu, Wu, and Arias (2013). The migration coefficient was found to be dependent on many factors in the concrete composition such as the cement type, amount of water and admixtures.

Research Program

This study is the first phase of a research effort funded by the Pennsylvania Department of Transportation to assess the design life of concrete bridge structures produced in the state. Included are all concrete types used for standard production of substructure and superstructure components. These concretes are designated as HES, SCC, A, AA, and AAAP. The PennDOT (2016) required mechanical properties for each class of concrete and their usage are summarized in Table 1. A self-consolidating concrete mix with properties similar to HES (High Early Strength) was also included. One sample of HPC was also acquired, since the properties are the same as that of AAAP it is herein classified as AAAP.

Table 1: PennDOT Concrete Class Properties [PennDOT 2016]

Class	Use	Cement Factor lbs/cyd		Max W/C ratio	Min. Mix Design Compressive Strength [psi]			Proportion of Coarse Aggregate to Solid Volume [cft/cyd]	28 day design compressive strength [psi]
		Min	Max		3d	7d	28d		
AAAP	Bridge Deck	560	690	0.45	-	3000	4000	-	4000
HPC	Bridge Deck	560	690	0.45	-	3000	4000	-	4000
HES	Structures and Misc.	752	846	0.40	3000	-	3750	9.10 – 12.00	3500
A	Structures and Misc.	564	752	0.50	-	2750	3300	10.18 – 13.43	3000
AA	Structures and Misc.	587.5	752	0.47	-	3000	3750	9.93 – 13.10	3500
AA	Paving	587.5	752	0.47	-	3000	3750	9.93 – 13.10	3500
AA	Slip Form Paving	587.5	752	0.47	-	3000	3750	11.00 – 13.10	3500
AAA	Other	634.5	752	0.43	-	3600	4500	-	4000

Concrete specimens procured from nine companies. The concrete cylinders were fabricated by the companies, shipped to Lehigh University and cured in water in accordance with ASTM C31. The cylinders were kept moist until the NT Build 492 test was initiated. Five different mix types were procured. The types along with their ages are listed Table 2. Company names are eliminated to protect the identity of the various groups. Each company is represented by a code from A to I. Concrete types were tested at multiple ages ranging from 28 days to 113 days as noted. Producers from six of the PennDOT districts participated. Figure 1 presents the company locations relative to each PennDOT district in Pennsylvania.

Table 2: Company List

Mix Type	Company Code	Age at NT-492 test (days)
A	F	28
A	H	28
A	B	54
A	D	56
A	F	56
A	H	58
A	I	59
A	D	111
A	F	112
A	H	112
A	I	112
AA	F	27
AA	A	44
AA	A	52
AA	B	55
AA	F	55
AA	D	57
AA	C	65
AA	I	70
AA	B	112

Table 2: Company List		
Mix Type	Company Code	Age at NT-492 test (days)
	D	113
	I	113
	F	111
	H	113
AAAP	H	29
	G	54
	B	55
	D	55
	F	56
	H	59
	B	112
	D	112
	F	112
HES	E	53
SCC	E	57
	E	112

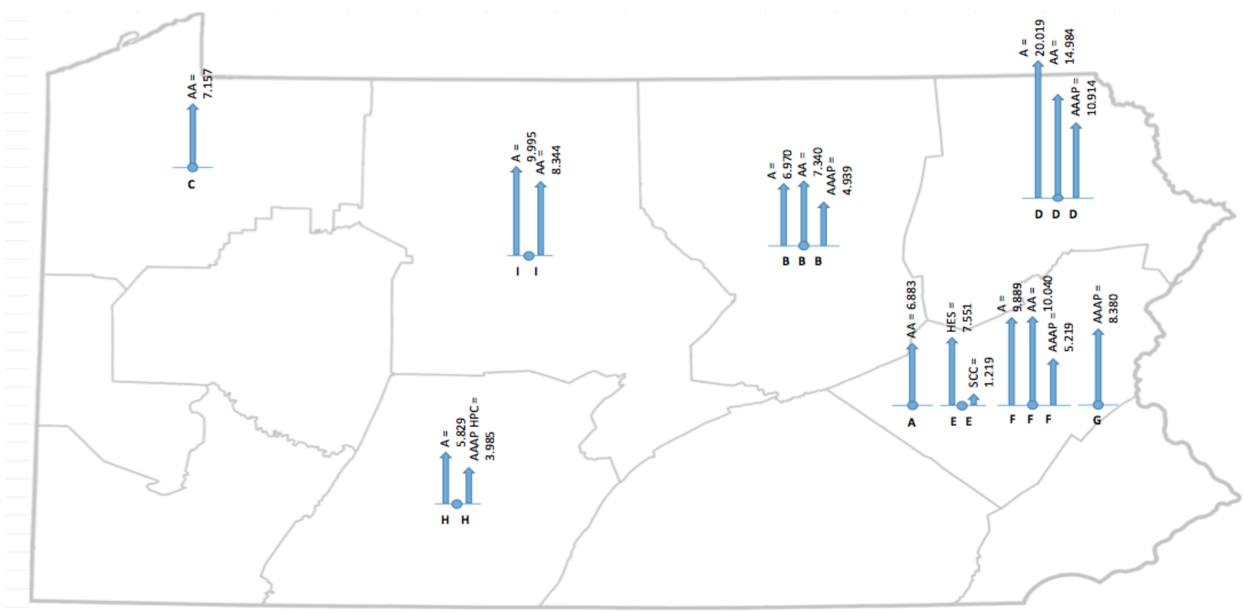


Figure 1: Company location map relative to PennDOT districts

NT BUILD 492 TEST METHOD

The concrete samples were evaluated in accordance with NT Build 492. The testing method is summarized in this section.

Test Schedule and Design

Concrete were procured from seven ready mix and two precast concrete producers. Some companies provided multiple types of concrete (i.e., A, AA, AAAP). Due to the date of fabrication and the delivery of the mixes the experiments were conducted over a period ranging from December 22 to March 25. A total of 105 migration tests were conducted on 40 concrete samples. For each sample one to five migration tests were conducted. For the majority of cases three specimens were cut from two concrete cylinders of each material type. The concretes were examined around an age of 28 days, 56 days and 112 days to evaluate the change of variation of migration coefficient over time (Table 3). Due to the limited number of samples and the time at which they were received not all concrete types were tested at every age.

Table 3: Test schedule

Specimen ID	Sample Type	Number of Specimens	Cylinders	Casting Date	Age
A-2A	AA	3	3	3-Nov	52
A-2A	AA	2	2	3-Nov	53
B-2A	AA	3	2	10-Nov	55
B-2A	AA	3	2	10-Nov	112
B-3A	AAA Opt	3	2	9-Nov	55
B-3A	AAA Opt	3	2	9-Nov	112
B-A	A	1	1	3-Nov	53
B-A	A	3	3	3-Nov	54
C-2A	AA w/Slag	3	2	10-Nov	57
C-2A	AA w/Slag	3	2	10-Nov	65
D-2A	AA	3	2	11-Nov	57
D-2A	AA	3	2	11-Nov	113
D-3A	AAA Opt	3	2	10-Nov	55
D-3A	AAA Opt	3	2	10-Nov	112
D-A	A	3	2	16-Nov	56
D-A	A	3	2	16-Nov	111
E-HES	HES	2	2	6-Nov	53
E-SCC	SCC	3	3	16-Nov	57
E-SCC	SCC	3	2	16-Nov	112
F-2A	AA	3	2	3-Dec	27
F-2A	AA	3	1.5	3-Dec	55
F-2A	AA	1	0.5	3-Dec	111
F-3A	AAAP	3	2	13-Nov	56
F-3A	AAAP	3	2	13-Nov	112
F-A	A	3	2	24-Nov	28
F-A	A	3	1.5	24-Nov	56

Table 3: Test schedule					
Specimen ID	Sample Type	Number of Specimens	Cylinders	Casting Date	Age
F-A	A	1	0.5	24-Nov	112
G-3A	AAAP	3	3	4-Nov	54
G-3A	AAAP	1	1	4-Nov	55
H-3A	AAA HPC	3	1.5	3-Dec	29
H-3A	AAA HPC	3	1.5	3-Dec	59
H-3A	AAA HPC	2	1	3-Dec	113
H-A	A	3	1.5	3-Dec	28
H-A	A	3	1.5	3-Dec	58
H-A	A	2	1	3-Dec	112
I-2A	AA	3	2	20-Nov	70
I-2A	AA	3	2	20-Nov	113
I-A	A	3	2	20-Nov	69
I-A	A	3	2	20-Nov	112

Sample Preparation

Migration coefficient specimen samples were made from the 4 x 8 in. cylinders. Each sample was cut into 50 ± 2 mm thick segments as showed in Figure 2. A water-cooled diamond saw was used to saw the concrete cylinder perpendicularly to its axis. As recommended by NT Build 492, *the end surface that is nearer to the first cut (the middle surface) was exposed to the chloride solution (catholyte)*.

Figure 2: 50 mm concrete sample

Preconditioning

After sawing the concrete cylinder, the specimens were brushed and washed. The surfaces of the specimen were wiped remove excess water. When the specimens were surface-dry, they were placed in the vacuum container for vacuum treatment. The absolute pressure in the vacuum container was reduced to less than 50 mbar (5 kPa) within a few minutes. Since an absolute pressure is defined the chamber must be capable of providing a vacuum in the range of -100 to -96 kPa. The vacuum was maintained for 3 hours and then, with both the end surfaces exposed and pump still running, the container was filled with saturated $Ca(OH)_2$ solution. The $Ca(OH)_2$ solution was made by 5.37 g Calcium hydroxide with 3100 ml pure water. The specimens were immersed in $Ca(OH)_2$ solution under vacuum for an additional hour and then depressurized to standard room pressure (i.e., 101 kPa). The specimens were kept in solution for 18 ± 2 hours. Figure 3 shows three specimens under vacuum treatment.

Figure 3: Vacuum container with three specimens

Migration Test

According to NT Build 492, the principle of the test is to apply an external electrical potential axially across the specimen and force the chloride ions outside to migrate into the specimen. The setup is illustrated in Figure 4. In the laboratory, three parallel setups are established numbered 1 to 3 so that the three specimens can be tested in parallel. Steps of the testing procedure and the testing setups are illustrated in Figure 5.

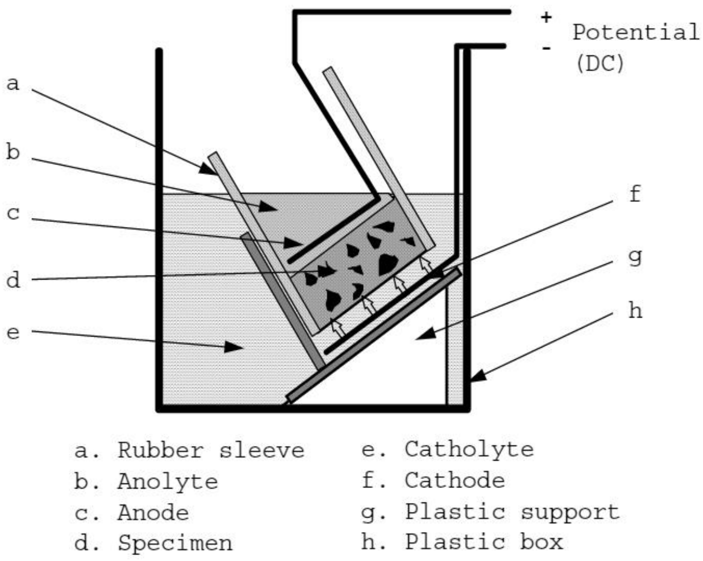


Figure 4: One arrangement of the migration test setup [NT Build 1999]

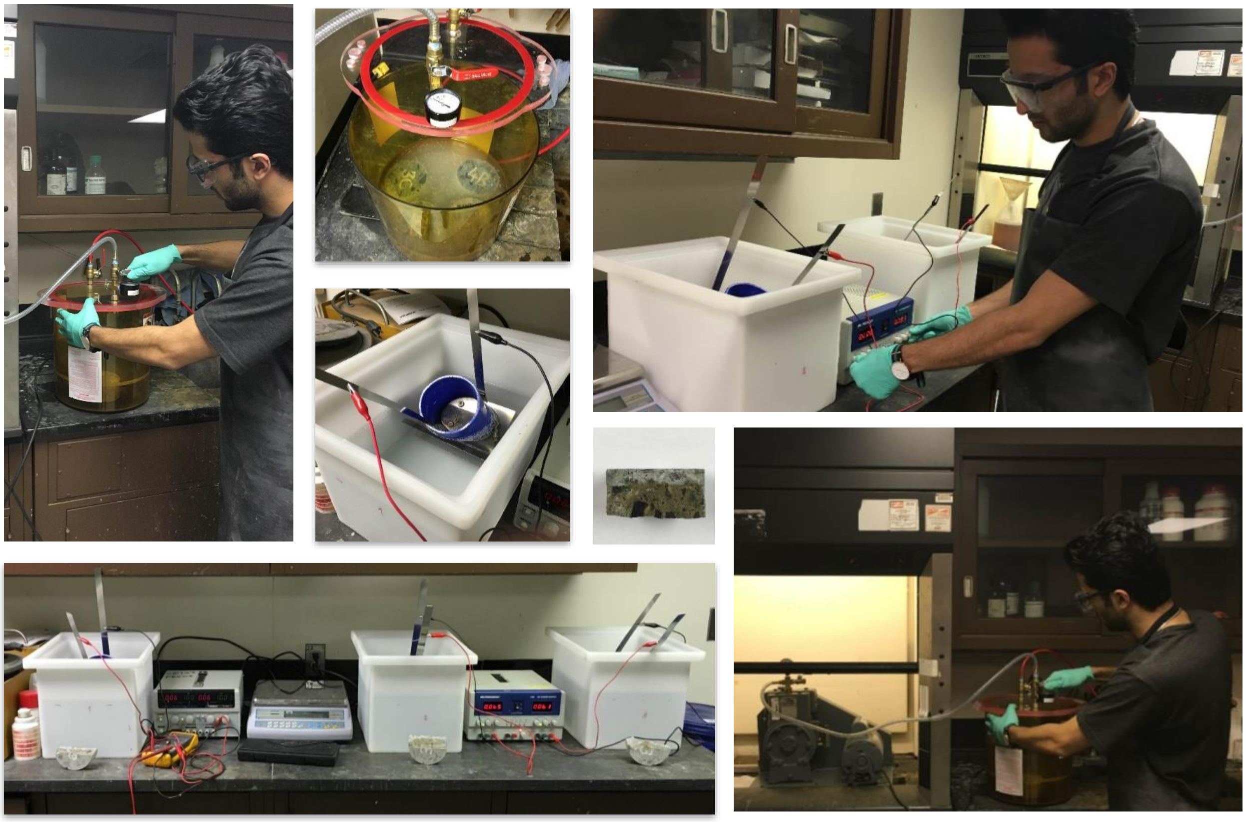


Figure 5: Migration set-up and test in the lab

Each specimen is subjected to an initial voltage of 30 V. The initial current through each specimen is recorded. Based on the initial current when subject to 30 V, the voltage applied is adjusted in accordance with the recommendations in Table 4. Initial temperature in each anolyte solution is recorded. As noted in Table 4 test duration is 24 hours for the majority of the cases but could range from 6 hours for high initial current and up to 96 hours for low initial current.

Table 4: Test voltage and duration for concrete specimen [NT Build 1999]

Initial current I_{30V} (with 30 V) (mA)	Applied voltage U (after adjustment) (V)	Possible new initial current I_0 (mA)	Test duration t (hour)
$I_0 < 5$	60	$I_0 < 10$	96
$5 \le I_0 < 10$	60	$10 \le I_0 < 20$	48
$10 \le I_0 < 15$	60	$20 \le I_0 < 30$	24
$15 \le I_0 < 20$	50	$25 \le I_0 < 35$	24
$20 \le I_0 < 30$	40	$25 \le I_0 < 40$	24
$30 \le I_0 < 40$	35	$35 \le I_0 < 50$	24
$40 \le I_0 < 60$	30	$40 \le I_0 < 60$	24
$60 \le I_0 < 90$	25	$50 \le I_0 < 75$	24
$90 \le I_0 < 120$	20	$60 \le I_0 < 80$	24
$120 \le I_0 < 180$	15	$60 \le I_0 < 90$	24
$180 \le I_0 < 360$	10	$60 \le I_0 < 120$	24
$I_0 \ge 360$	10	$I_0 \ge 120$	6

The procedure of the test is illustrated using flow chart in Figure 6.

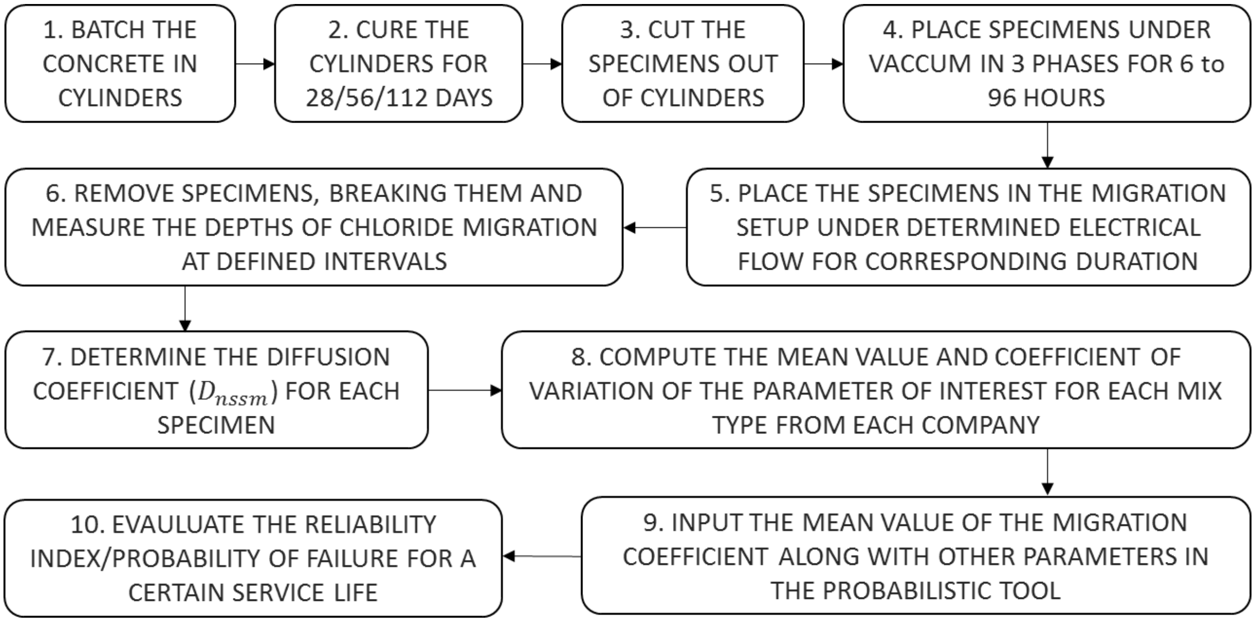


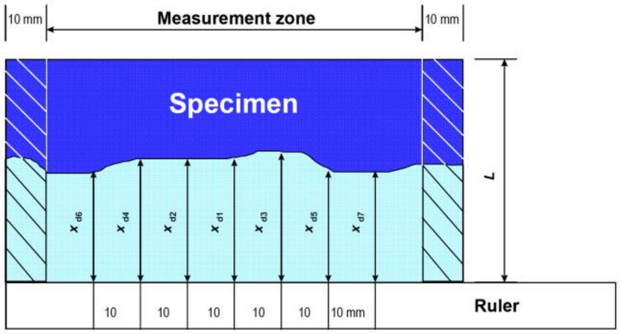
Figure 6: Flowchart of the test procedure

Measurement of Chloride Penetration Depth

After the test, the specimen is axially split and 0.1 M silver nitrate solution was sprayed on to one of the freshly split sections. After 15 minutes, the chloride penetration depth can then be measured from the visible white silver chloride precipitation, after which the chloride migration coefficient can be calculated from this penetration depth. Figure 7 shows the split specimens with silver nitrate solution sprayed on the surface.

Figure 7: Split specimens with silver nitrate solution

A caliper is used to measure the penetration depth from the center to both edges at intervals of 10 mm with accuracy of 0.01 mm. Seven penetration depths were measured as in Figure 8. Depth measurements within 10 mm from the edge were ignored due to edge effects that can occur during the test. When the penetration front was blocked by the presence of an aggregate, the depth at that point was ignored as long as there are more than five valid depths. If there was a significant defect, such as a void, in the specimen resulting in penetration depth significantly larger than the average value, the depth at that point was eliminated. All discrepancies identified are noted in the summary test data presented in the Appendix.

a) 

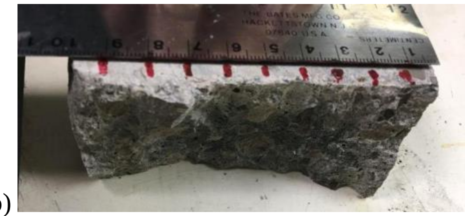
b) 

Figure 8: Measurement of penetration depths (a) NT Build 492 [1999] (b) on Specimen

Determination of Non-Steady State Migration Coefficient

Chloride migration coefficient is a parameter used to quantify the resistance of concrete to the transport of chlorides. There are two methods currently used to determine the coefficient. The first utilizes steady state experiments such as diffusion or a migration cell, and the other utilizes non-steady state experiments [Andrade, Castellote, Alonso, and Gonzalez 2000]. Steady state evaluation is a time consuming process that can take months or years to conduct. Non-steady state or non-stationary methods can be completed in an accelerated manner and in the case of the NT Build 492 consists of a 24 to 96 hour test. In addition to the relatively short duration the non-stationary methods also assesses the binding of chlorides with the cement paste and the ionic transport. Steady state methods only do the later [Castellote, Andrade, and Alonso 2001].

The NT Build 492 Method determines the Non-Steady State Migration Coefficient, D_{nssm}. The measurement is typically designated in 10^{-12} m^2/s. A higher value is indicative of a faster diffusion of chlorides and a shorter design life for the structure in which it is utilized. Henceforth the terminology migration coefficient will be used to refer to the non-steady state migration coefficient as determined using NT Build 492 [1999].

Determination of D_{nssm}

The following equation is used to calculate the non-steady-state migration coefficient:

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right)$$

Equation 1

Where:

D_{nssm} : non-steady-state migration coefficient, $\times 10^{-12} m^2/s$

U: absolute value of the applied voltage, V;

T: $(T_1+T_2)/2$ = average value of the initial and final temperatures in the anolyte solution, ℃;

L: thickness of the specimen, mm;

x_d: average value of the penetration depths, mm;

t: test duration, hour

Sample Calculations

As an example the chloride penetration depths data along with other input variables are summarized for two materials with three samples each in Table 5.

Table 5: Sample calculation input

	Measurement of the chloride penetration depth (mm)							T	L	U	T_1	T_2
ID	x2	x3	x4	x5	x6	x7	x8	(hr)	(cm)	(V)	(°C)	(°C)
F-A-1	23.22	24.66	23.92	21.72	22.44	21.52	23.55	24	5	30.00	22.5	21.6
F-A-2	15.53	-	22.43	22.82	23.23	15.46	15.20	24	5	25.00	22.1	21.8
F-A-3	19.21	22.60	20.27	20.77	15.62	17.60	16.41	24	5	30.04	21.7	21.9
A-2A-1	22.06	14.67	14.40	11.88	14.68	13.12	11.32	24	5	30.00	23.4	21.2
A-2A-2	16.07	16.02	15.90	17.18	18.38	17.37	18.82	24	5	30.00	23.2	21.2
A-2A-3	20.09	16.35	14.75	18.66	16.49	16.13	18.60	24	5	35.00	23.2	21.2

[1] AGG = Aggregate present and data omitted

The non-steady-state migration coefficient is calculated from the values in Table 5 using Equation 1. Average value of the three samples is calculated along with the coefficient of variation to evaluate the accuracy of the test. Table 6 shows the non-steady-state migration coefficient calculated using the input from Table 6.

Table 6: Migration coefficient with mean, coefficient of variation and age

Sample Code	D_{nssm} Migration Coefficient (E-12 m^2/s)	Average	COV	Age(days)
F-A-1	10.695	9.960	11.3%	28
F-A-2	10.521			
F-A-3	8.665			
A-2A-1	6.565	7.043	9.3%	52
A-2A-2	7.793			
A-2A-3	6.771			

Coefficient of variation is computed when at least three samples are evaluated from the same material at the same age. Figure 9 shows the variation of coefficient relative to the age of the concrete. As illustrated the coefficient of variation ranges considerably (1.5% to 35.9%). This is on par with the NT Build method which notes in section 6.6.2 "*The coefficient of variation of reproducibility is 13 % for Portland cement concrete or for concrete mixed with silica fume, and 24 % for concrete mixed with slag cement, according to the results from the Nordic round-robin test between six laboratories*."

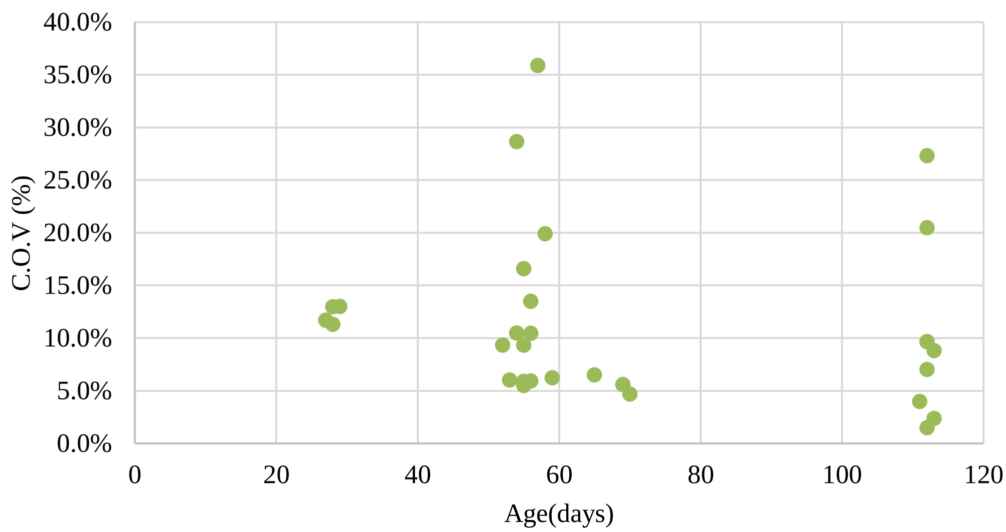


Figure 9: Variation of C.O.V with age of concrete

EXPERIMENTAL RESULTS AND DISCUSSION

As mentioned previously, concrete were procured from seven ready mix and two precast concrete producers. Some companies provided multiple types of concrete (i.e., A, AA, AAAP). A total of nine concrete producers are involved in the test. Some of the producers provide 3 types of concrete while some of them provide only 1 type of concrete. A total of 105 migration tests were conducted on 40 concrete samples. For each sample one to five migration tests were conducted. For the majority of cases three specimens were cut from two concrete cylinders of each material type. The concretes were examined around an age of 28 days, 56 days and 112 days to evaluate the change of variation of migration coefficient over time.

Table 7 presents the summary non-steady state migration coefficient along with its mix type, company code, COV and age for all tests conducted.

Table 7: Migration coefficient data

Mix Type	Company Code	Average	COV	Age
A	F	9.960	11.30%	28
	B	6.970	10.48%	54
	H	7.288	12.97%	28
	D	20.019	13.50%	56
	F	9.889	10.47%	56
	I	9.995	5.60%	69
	H	5.828	19.89%	58
	D	17.601	3.99%	111
	I	8.569	9.66%	112
	F	7.867	-	112
	H	5.207	-	112
AA	A	6.005	-	44
	A	7.043	9.34%	52
	F	10.375	11.70%	27
	B	7.340	16.58%	55
	D	14.984	13.14%	57
	C	7.157	6.49%	65
	F	10.040	9.33%	55
	I	8.344	4.68%	70
	B	7.075	20.48%	112
	D	13.682	8.81%	113
	I	7.567	2.39%	113
	H	2.843	-	113
	F	5.466	-	111
AAAP	G	8.380	28.67%	54
	H	4.849	13.02%	29
	B	4.939	5.50%	55
	D	10.914	5.88%	55
	F	5.219	5.94%	56
	H	3.985	6.24%	59
	B	4.798	1.51%	112

Table 7: Migration coefficient data				
Mix Type	Company Code	Average	COV	Age
	D	6.649	9.65%	112
	F	5.240	7.01%	112
HES	E	7.551	6.02%	53
SCC	E	1.219	35.88%	57
SCC	E	0.858	27.31%	112

The influence of concrete mix type, w/c ratio, unit weight, slump and strength on migration coefficient is evaluated.

Influence of Concrete Type

From the limited data examined there appears to be limited correlation between concrete type and migration coefficient. The average data for concrete tested at an age of approximately 56 days is presented in Figure 10. While the sample size is too small to draw any firm conclusion, it is noted that migration coefficient is reduced with better concrete. Across all ages the study resulted in an average non-steady-state migration coefficient of 9.9E-12 m^2/s for class A, 8.3E-12 m^2/s for class AA, 6.1E-12 m^2/s for class AAAP, 7.6E-12 m^2/s for HES and 1.0E-12 m^2/s for SCC. It should be noted that the one SCC sample tested had the highest strength among all the others and it has the lowest migration coefficient.

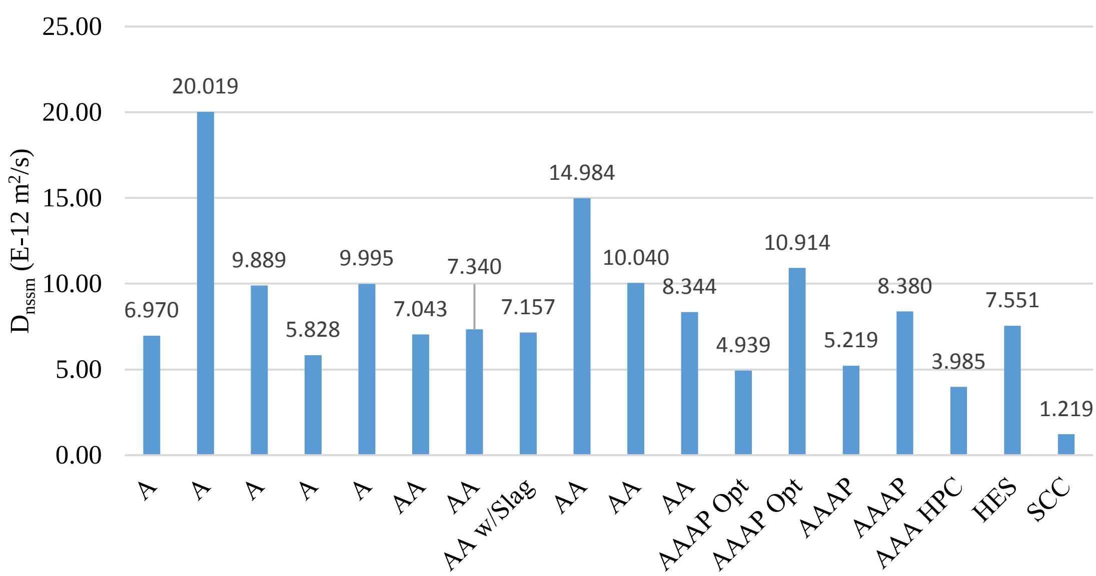


Figure 10: Variation of 56-days migration coefficient with mix type

Influence of Concrete Strength

In a general sense the migration coefficient decreases with increase in concrete compressive strength. The 7-day and 28-day compressive strengths for a number of mix designs were provided by the concrete producers and are compared to the migration coefficient measured at an age of 56-days as shown in Figure 11 and Figure 12. As shown higher strength concretes are observed to produce a lower migration coefficient.

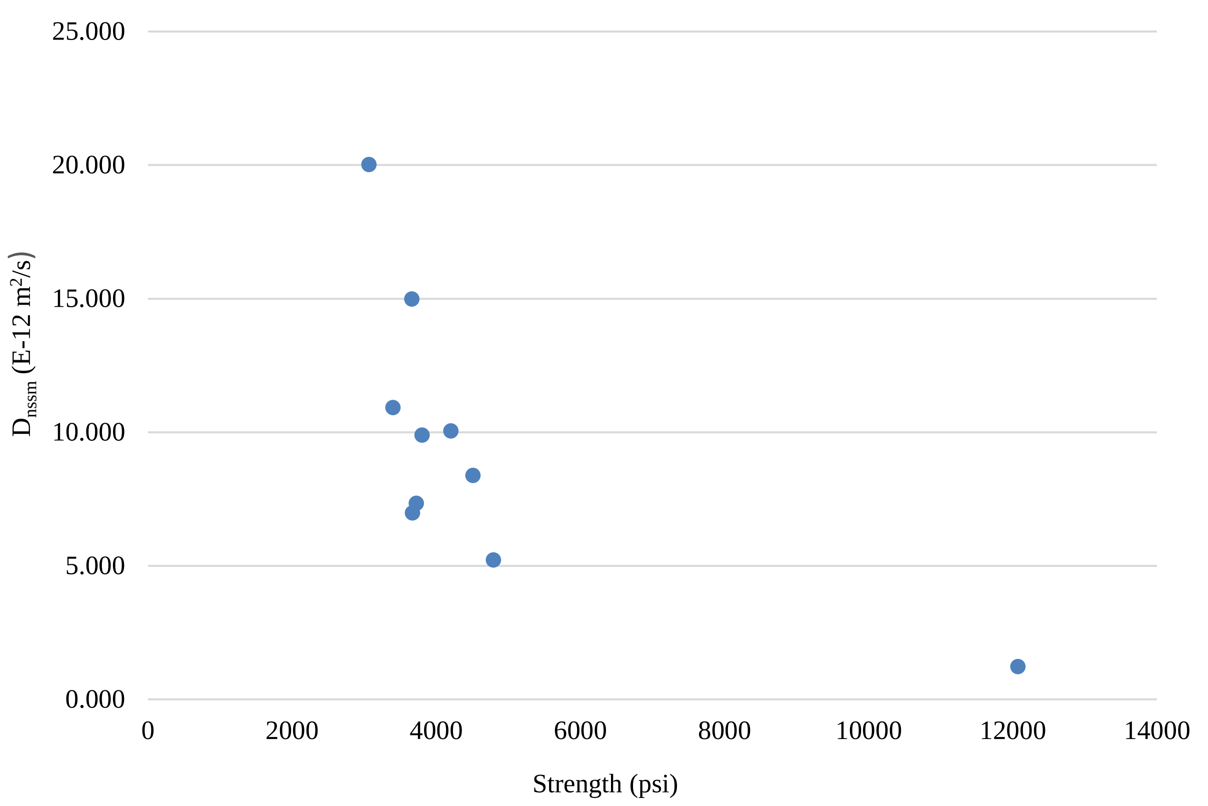


Figure 11: Variation of migration coefficient at 56-days with concrete 7-day compressive strength

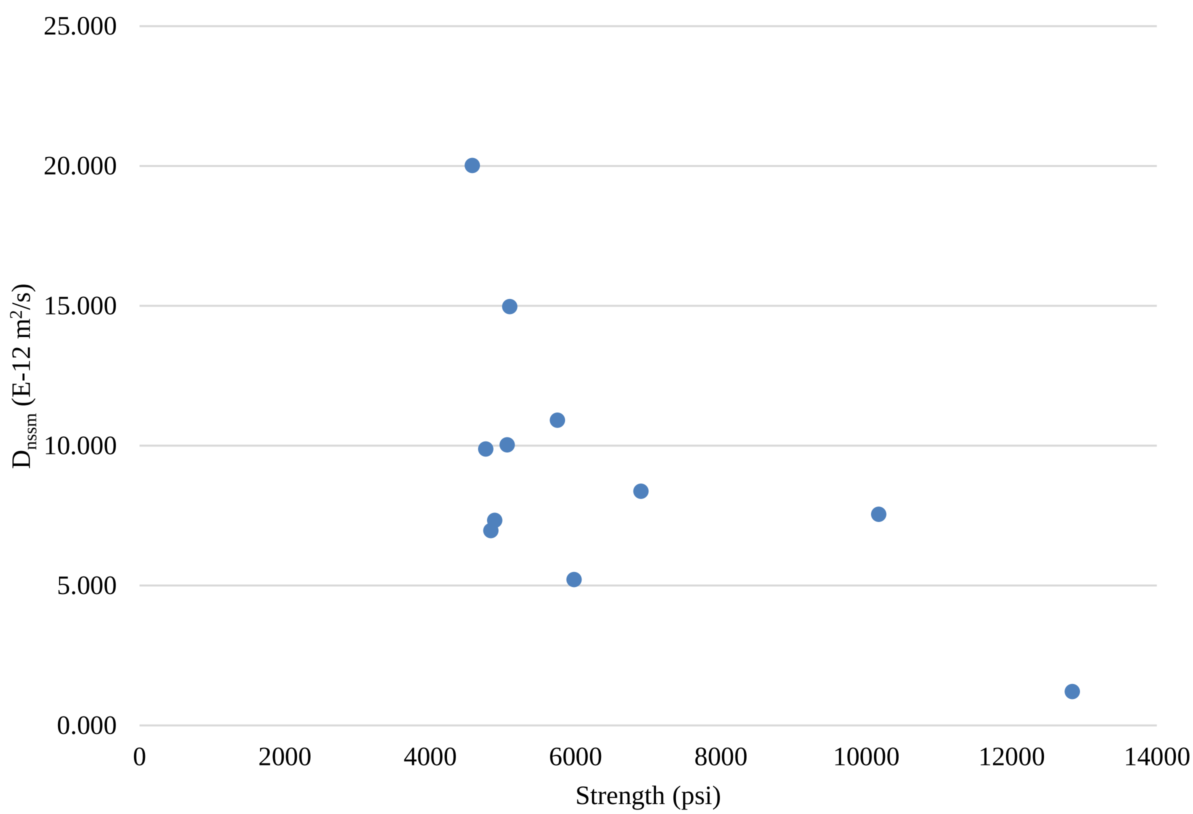


Figure 12: Variation of migration coefficient at 56-days with 28-day compression strength

Influence of water to cement ratio

The water to cement ratio was determined based on the mix design tags provided with each sample of concrete tested. Minimal correlation is observed between the water to cement ratio and the migration coefficient as shown in Figure 13.

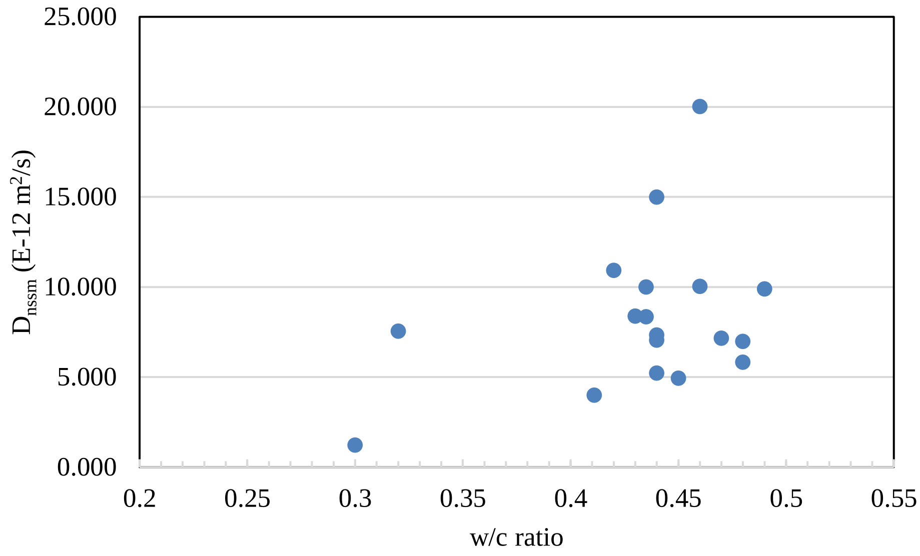


Figure 13: Variation of 56-day migration coefficient with w/c ratio

Influence of Unit Weight

The unit weight of each mix type was determined from the mix design and batch tags provided with each concrete sample received. There is minimal correlation between unit weight and migration coefficient for the data studied as shown in Figure 14.

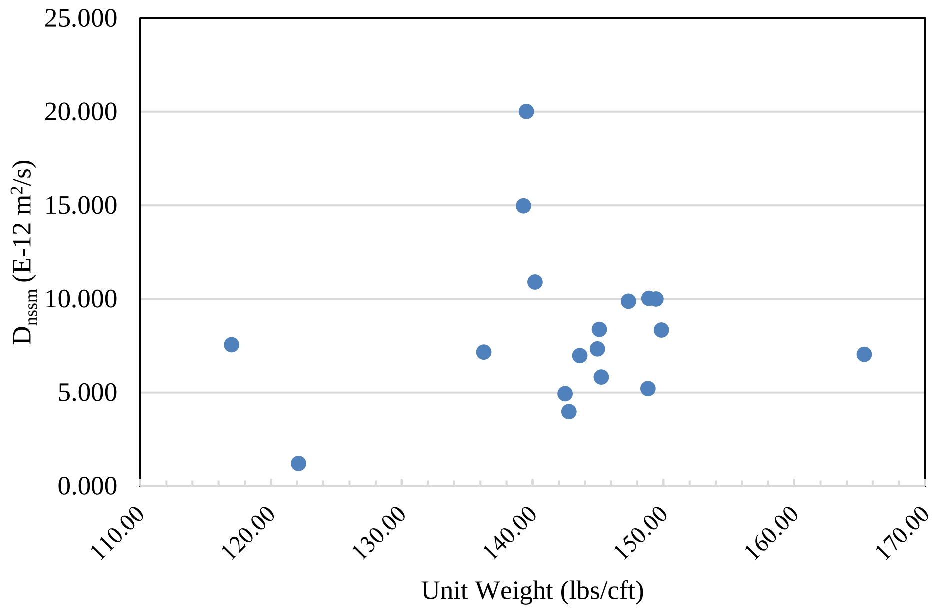


Figure 14: Variation of 56-day migration coefficient with unit weight

Influence of Slump

The slump of each mix type was determined from the mix design and batch tags provided with each concrete sample received. Minimal correlation between the plastic slump and the migration coefficient was observed as shown in Figure 15.

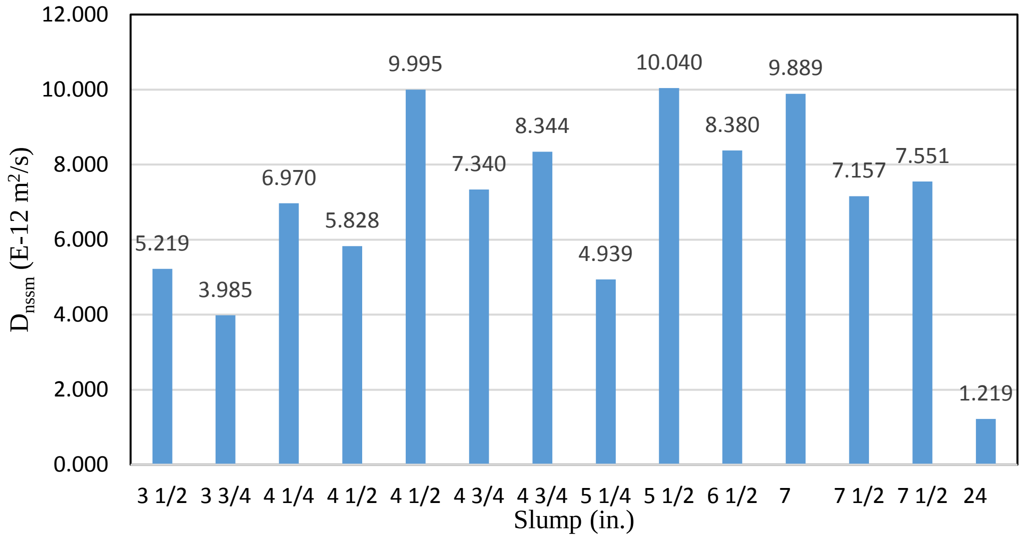


Figure 15: Variation of 56-day migration coefficient with slump

Influence of Concrete Age

The migration coefficient for the concrete tested tends to decrease with age. The migration coefficient tests were conducted at approximately 28, 56, and 112 days of age. Not all concretes were tested at each age and due to similar concrete fabrication dates the test date varied around the target as illustrated in Figure 16. The migration coefficients consistently decrease as the age of the concrete increases from 28 days to 56 and 112 days. The test results are agreement with other studies of the chloride penetration behavior in laboratory tests and real structures, where a clear time dependency of the migration coefficient is observed.

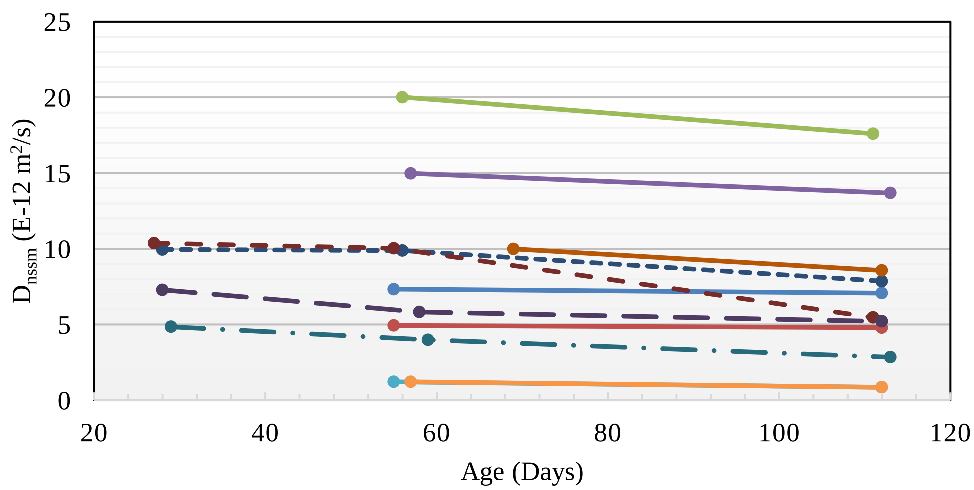


Figure 16: Variation of migration coefficient with concrete age

Influence of Coarse Aggregate

The coarse aggregate absorption and type were examined for each of the samples provided. The aggregate types were identified from the PennDOT Concrete Mix Design Form (TR-4221A) which identified the coarse aggregate producer and supplier code. The coarse aggregate properties were determined from PennDOT Bulletin 14 Publication 34 - Aggregate Producers. The specific gravity, absorption, sodium sulfate soundness and rock composition is provided. No correlation was observed between either the specific gravity or soundness and the migration coefficient. One concrete sample produced very high migration coefficient values. This material was produced from one aggregate type and was present in three mixes D-A, D-2A and D-3A. As illustrated in the three outliers in Figure 17 and the Sandstone – GL types in Figure 18 the concretes containing these aggregates had a very high migration coefficient. This may be attributed to the high absorption of the aggregate (1.99) or the fact that the material is a sandstone gravel (GL).

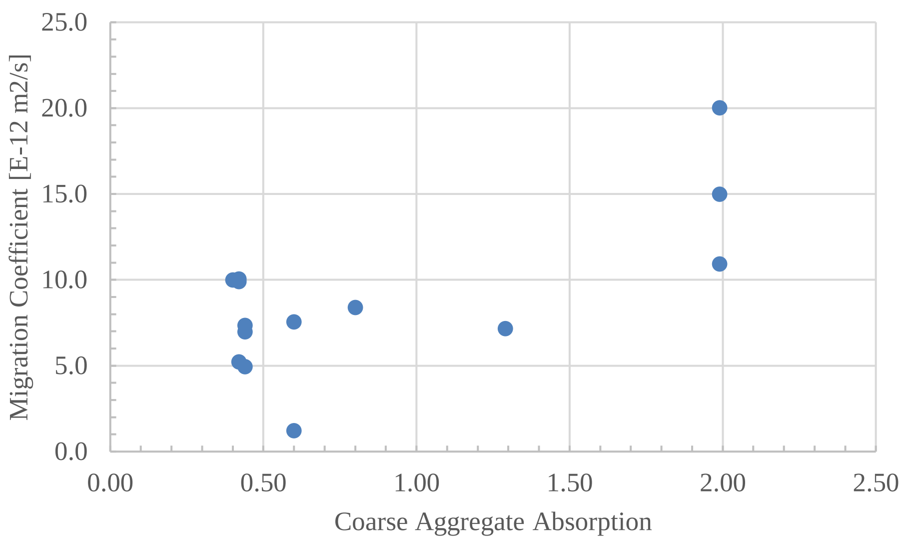


Figure 17: Migration coefficient with coarse aggregate absorption

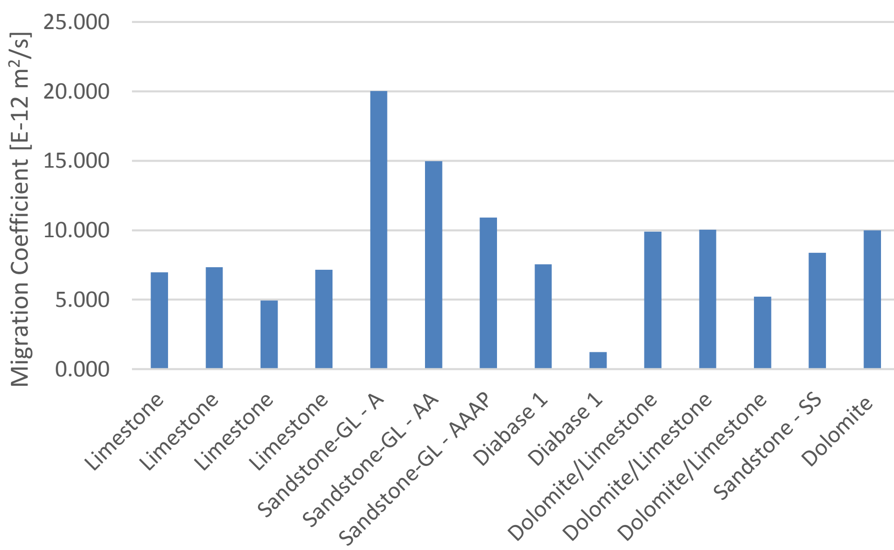


Figure 18: Migration coefficient with coarse aggregate type

PROBABILISTIC ASSESSMENT OF PENNDOT CERTIFIED MIXES

A parallel task of this research effort was to develop tool to perform the full-probabilistic design approach detailed in fib Bulletin 34 - Model Code for Service life Design [2006], for the chloride-induced corrosion in uncracked concrete. Service life design of the concrete is based on the solution to a mathematical model for initiation of corrosion in the reinforcing steel in a concrete section exposed to chlorides. . The model uses Fick's 2nd law to compare the chloride content in the concrete at the depth of the reinforcement at a desired time, to the critical chloride content for the reinforcing steel. A Monte Carlo simulation is used to solve the problem repeatedly, by changing the value of each of the random variables in the equation based on their predefined probability distribution.

The tool was developed is titled Probabilistic Chloride Ingress Model (ProCIM). It is executable in Microsoft Excel [2013] and is detailed in [Shojaeian, Bocchini, Naito, Ma, Karamlou, and Fox 2016]. The data generated on the chloride migration coefficient for each mix in this report is used to determine the performance of a structure when fabricated from the various concrete mixes. Default parameters are used for the majority of inputs for the model with the following exceptions. An average temperature of 55.85°F with a standard deviation of 15.7°F is assumed for Pennsylvania. The clear cover is assumed to be 2.5 in. based on deck reinforcement requirements for PennDOT Bridge Design Standards BD-600 [2014]. A construction tolerance for the vertical location of the reinforcement is assumed to be 0.25 in. in accordance with PennDOT Specifications [2016]. Three cement types are defined by *fib* 34, Portland Cement Concrete (I), Portland Fly Ash Cement Concrete (F) and Blast Furnace Slag Cement Concrete (S). Since data on the exact formulations used by the PA concrete producers do not match the mixes used in the *fib* 34 the closest match was used. Concretes containing slag are identified as cement type S, those containing fly ash are designated as cement type F and those with neither are designated as cement type I. The concretes were tested at an age of approximately 28, 56 and 112 days. The aging coefficient in the tool is based on the use of 28 day strengths however since the migration coefficient did not change considerably over 112 days the performance of all concretes are compared using the same aging coefficient. This is done regardless of whether the chloride migration coefficient was computed at 28, 56 or 112 days. Consequently the performance of the older concretes using the tool will be unconservative.

The ability of the concrete to achieve a 100 year design life is examined. Two environmental conditions are studied. The first considers a splash road environment. This correlates to a concrete element that is within 1.5 m from a chloride source. The second environment consists of a spray road environment where the concrete element is more than 1.5 m from a chloride source. Note that these calculations are conducted for uncoated reinforcing bars. By PennDOT requirements reinforcement would likely be epoxy coated for these environments and would thus perform better. Additional study is required to modify the formulations to assess the performance of epoxy coated bars. The performance of all concretes tested with three or more samples are summarized in Table 8.

In assessment of performance the following terminology is used. Failure occurs when the chloride concentration is greater than the critical chloride concentration at the location of the reinforcement at the service life of interest. The probability of failure is the probability of this event occurring. The reliability index is the defined as minus the inverse of the standard Gaussian cumulative distribution function computed at the probability of failure. According to *fib* 34 an acceptable probability of failure is 10% which corresponds to a reliability index of 1.3. A calculated reliability index greater than 1.3 at the reinforcement at the service life of interest is deemed satisfactory performance. A calculated reliability index less than 1.3 at the reinforcement at the service life of interest is deemed unsatisfactory performance.

Table 8: Service life performance of concretes								
Type	Chloride migration coefficient [E-12 m^2/s]		Age (days)	Cement Type	Splash Road Environment		Spray Road Environment	
	Average	COV			Calculated Reliability Index	Satisfactory / Unsatisfactory	Calculated Reliability Index	Satisfactory / Unsatisfactory
B-A	6.970	10.50%	54	S	0.23	U[1]	0.42	U
D-A	20.019	13.50%	56	FA	0.36	U	0.58	U
D-A	17.601	4.00%	111	FA	0.44	U	0.68	U
F-A	9.960	11.30%	28	S	0.03	U	0.21	U
F-A	9.889	10.50%	56	S	0.04	U	0.21	U
H-A	7.288	13.00%	28	S	0.21	U	0.39	U
H-A	5.828	19.90%	58	S	0.34	U	0.53	U
I-A	8.569	9.70%	112	S	0.11	U	0.30	U
A-2A	7.043	9.30%	52	S	0.22	U	0.41	U
B-2A	7.340	16.60%	55	S	0.21	U	0.39	U
B-2A	7.075	20.50%	112	S	0.23	U	0.42	U
B-3A	4.939	5.50%	55	S	0.42	U	0.62	U
B-3A	4.798	1.50%	112	S	0.45	U	0.64	U
C-2A	7.157	6.50%	65	S	0.21	U	0.40	U
D-2A	13.682	8.80%	113	F	0.62	U	0.86	U
F-2A	10.375	11.70%	27	S	0.01	U	0.19	U
F-2A	10.040	9.30%	55	S	0.03	U	0.21	U
I-2A	9.995	5.60%	69	S	0.02	U	0.20	U
I-2A	8.344	4.70%	70	S	0.13	U	0.31	U
I-2A	7.567	2.40%	113	S	0.18	U	0.36	U
D-3A	10.914	5.90%	55	FA	0.81	U	1.03	U
D-3A	6.649	9.70%	112	FA	1.14	U	**1.39**	**Sa**
F-3A	5.219	5.90%	56	S	0.41	U	0.60	U
F-3A	5.240	7.00%	112	S	0.39	U	0.58	U
G-3A	8.380	28.70%	54	I	-0.64	U	-0.41	U
H-3A	4.849	13.00%	29	S	0.44	U	0.63	U
H-3A	3.985	6.20%	59	S	0.55	U	0.75	U
E-HES	4.524	16.90%	161	S	0.48	U	0.68	U
E-SCC	1.219	35.90%	57	S	**1.32**	**Sa**	**1.57**	**Sa**
E-SCC	0.858	27.30%	112	S	**1.57**	**Sa**	**1.84**	**Sa**

The results of the analysis indicate that the majority of concretes will not provide adequate protection for uncoated reinforcement when used in a splash or spray condition. The performances of three concrete types are examined in

[1] Sa = Satisfactory reliability, U = Unsatisfactory reliability

more detail below. The concrete with the highest, lowest and median chloride migration coefficient are examined (Table 9). The probabilities of failure of the three mixes are presented as a function of time and are illustrated in Figure 19 and Figure 20.

Table 9: Concrete for further examination					
Type		Chloride migration coefficient [E-12 m^2/s]		Age (days)	Cement Type
		Average	COV		
High	D-A	20.019	13.50%	56	FA
Median	I-2A	7.567	2.40%	113	S
Low	E-SCC	0.858	27.30%	112	S

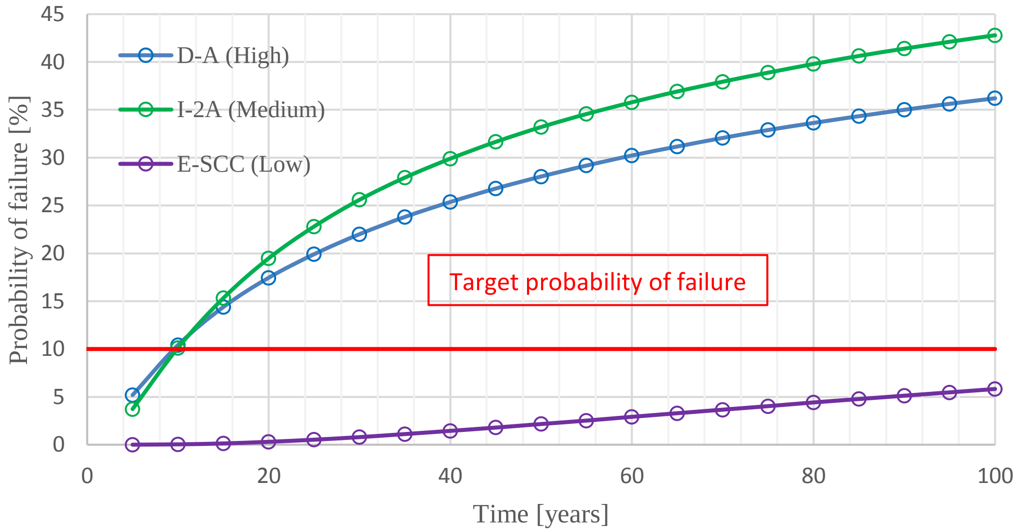


Figure 19: Probability of failure for splash condition

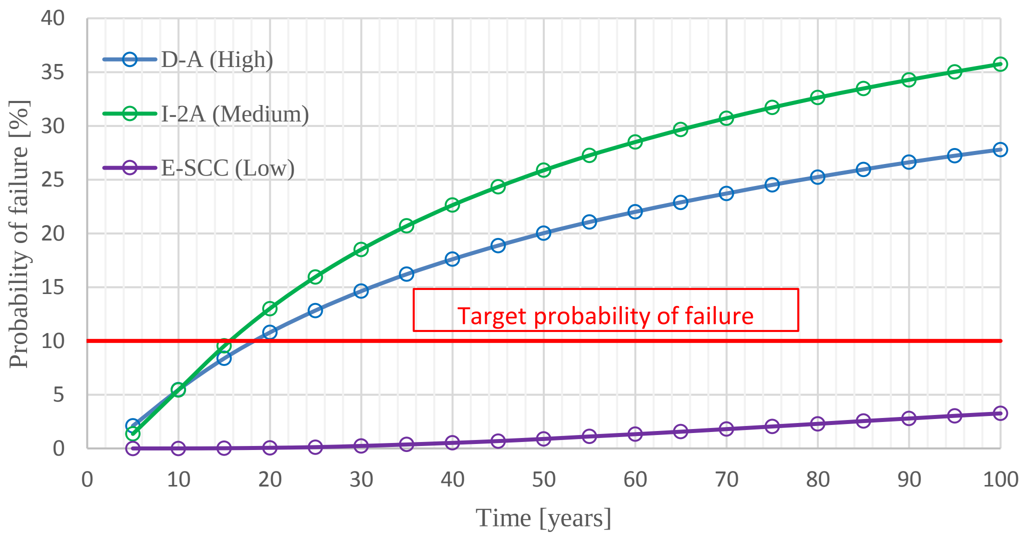


Figure 20: Probability of failure for spray condition

Based on the detailed probabilistic analysis presented in Figure 19 and Figure 20 the high and median migration coefficients do not provide adequate protection for the reinforcement. Based on the study the critical chloride concentrations would be reached at the reinforcement at approximately 15-20 years for the two concretes. The concrete with the low migration coefficient is needed to achieve satisfactory performance at the 100 year design life. As an aside it is interesting to note that the median migration coefficient resulted in a shorter time to failure than the concrete with the high migration coefficient. This can be attributed to the fact that the concrete with the highest migration coefficient contained fly ash while the median contained slag. According to fib 34 these two materials result in different rates of migration over time and are illustrated in Figure 19.

CONCLUSIONS AND FUTURE WORK

A research study sponsored by Pennsylvania Department of Transportation was conducted to examine the non-steady state chloride migration coefficient of concrete commercially produced in Pennsylvania. Concrete produced by ready mix suppliers and precast and prestressed concrete producers were examined. PennDOT certified concrete class A, AA, and AAAp, and precast SCC and HES mixes were procured from suppliers in the form of 4x8 in. cylinders and evaluated in accordance with Nordtest Method NT Build 492. Experiments were conducted on concrete cured to approximately 28, 56 and 112 days. The concrete results for the test program are summarized in Figure 21.

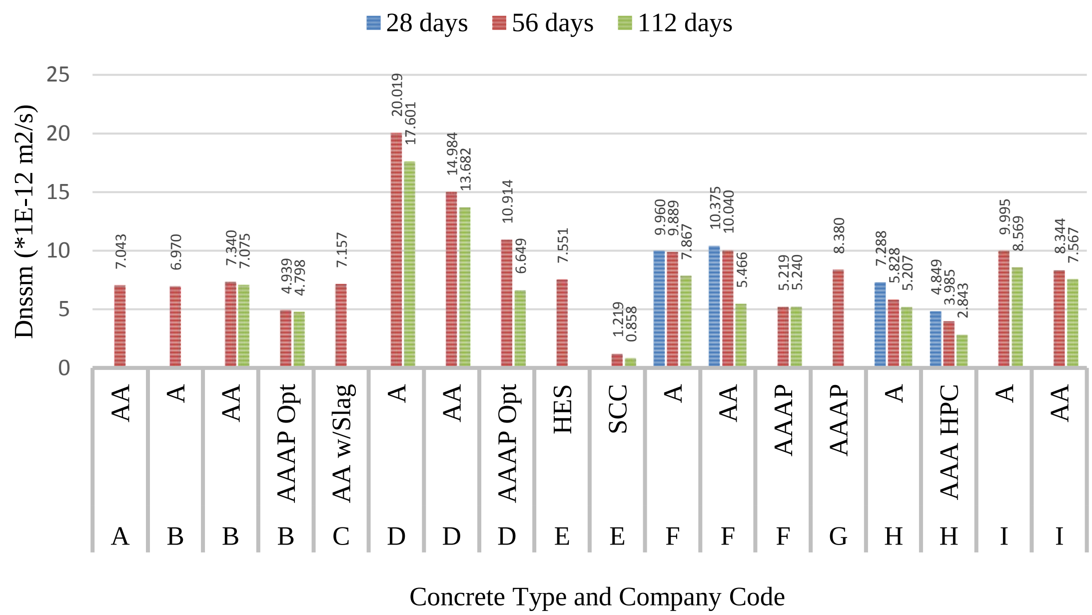


Figure 21: Summary of the experimental results

The following conclusions can be made:

- The NT Build 492 test procedure is easy to follow but may produce a high coefficients of variation. COV varied from 1.5% to 35.9%
- Migration coefficient tends to decrease for higher class concretes. In general SCC performed the best followed by AAAP, HES, AA, and A.
- Across all ages the study resulted in an average non-steady-state migration coefficient of 9.9E-12 m^2/s for class A, 8.3E-12 m^2/s for class AA, 6.1E-12 m^2/s for class AAAP, 7.6E-12 m^2/s for HES and 1.0E-12 m^2/s for SCC.
- Migration coefficient tended to decrease with increased design mix compressive strength and increased concrete age.
- There was minimal correlation between migration coefficient and concrete water/cement ratio, design slump, admixtures, and unit weight.
- High migration values were observed for three concretes types produced by one manufacturer. Each type (A, AA, and AAAP) contained coarse aggregate with a GL classification and an absorption of 1.99. The outlying results produced by these concretes may be related to either the class of aggregate used or the high absorption of the aggregate and should be further examined through microscopy and chemical analysis.

- The measured migration coefficients were used to assess the service life of uncoated reinforcement through a probabilistic analysis. It was found that the majority of concretes tested when used in a bridge structure would not result in an acceptable level of performance at 100 years of service.

References

Andrade, C., Castellote, M., Alonso, C., and González, C. (2000). Non-steady-state chloride diffusion coefficients obtained from migration and natural diffusion tests. Part I: Comparison between several methods of calculation. Materials and Structures, 33(1), 21-28.

Castellote, M., Andrade, C., & Alonso, C. (2001). Measurement of the steady and non-steady-state chloride diffusion coefficients in a migration test by means of monitoring the conductivity in the anolyte chamber. Comparison with natural diffusion tests. Cement and Concrete Research, 31(10), 1411-1420.

ASTM C31/C31M-15 Standard Practice for Making and Curing Concrete Test Specimens in the Field, ASTM International, West Conshohocken, PA, 2015, http://dx.doi.org/10.1520/C0031_C0031M-15AE01

FIB 34 Task Group 5.6. "Model Code for Service Life Design." Tech. no. Bulletin 34. Lausanne: International Federation for Structural Concrete, 2006.

NT Build 492, (1999), "Nordtest Method Concrete, Mortar and Cement-Based Repair Materials: Chloride Migration Coefficient from Non-Steady-State Migration Experiments," Nordic Council of Ministers, Espoo, Finland.

Li, P. P., Dong, G. H., and Xiong, J. B. (2014). The correlation of chloride diffusion coefficient and concrete maturity value and its application in marine engineering. In Advanced Materials Research (Vol. 1004, pp. 1551-1555). Trans Tech Publications.

Luping, T. and Nilsson, L. (1992a). Chloride Diffusivity in High Strength Concrete at Different Ages. Nordic Concrete Research, Nordic Concrete Federation, Vol.11, 162-171.

Luping, T. and Nilsson, L. (1992b). Rapid Determination of the Chloride Diffusivity in Concrete by Applying an Electrical Field. ACI Materials Journal, 89(1), 49-53.

Pennsylvania Department of Transportation. (2016). Publication 408/2016 Specifications, 2016 Edition Effective April 1, 2016.

Pennsylvania Department of Transportation. (2014). PennDOT Index of Standards for Bridge Designs BD-600. http://www.dot.state.pa.us/public/Bureaus/BOPD/Bridge/2014/BD/BD600M.pdf (Accessed June 2016).

Presuel-Moreno, F., Liu, Y., Wu, Y. Y., & Arias, W. (2013). Analysis and Estimation of Service Life of Corrosion Prevention Materials Using Diffusion, Resistivity and Accelerated Curing for New Bridge Structures-Volume 2: Accelerated Curing of Concrete With High Volume Pozzolans (Resistivity, Diffusivity and Compressive Strength).

APPENDIX

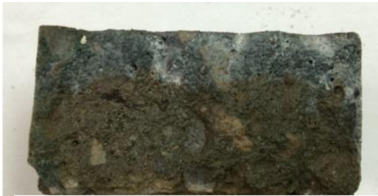
The unprocessed data is provided in this appendix for completeness. The measured data as well as the samples after the completion of testing are included.

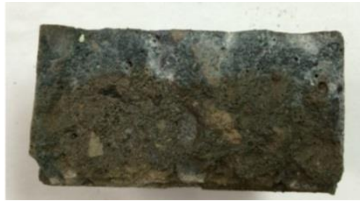
Sample Code	Migration Coefficient (E-12 m^2/s)	Average	COV	Age	Measurement of the chloride penetration depth (mm)							Time duration (hr)	Thickness of the specimen (cm)	Voltage used (V)	initial temperature (°C)	final temperature (°C)
					x2	x3	x4	x5	x6	x7	x8					
Trial	6.716	-	-	-	15.90	12.80	16.00	13.40	17.70	12.90	15.40	24	5	30.00	24.7	21.2
A-2A-1-2	5.372	6.005	-	44	16.22	16.08	16.04	19.36	11.86	9.64	8.34	24	5	35.01	23.8	21.1
A-2A-1-3	6.638				13.14	16.33	17.25	12.68	13.07	15.65	14.80	24	5	30.00	25.1	21.2
F-A-1-1	10.695	9.960	11.3%	28	23.22	24.66	23.92	21.72	22.44	21.52	23.55	24	5	30.00	22.5	21.6
F-A-1-2	10.521				15.53	-	22.43	22.82	23.23	15.46	15.20	24	5	25.00	22.1	21.8
F-A-2-3	8.665				19.21	22.60	20.27	20.77	15.62	17.60	16.41	24	5	30.04	21.7	21.9
A-2A-2-1	6.565	7.043	9.3%	52	22.06	14.67	14.40	11.88	14.68	13.12	11.32	24	5	30.00	23.4	21.2
A-2A-3-2	7.793				16.07	16.02	15.90	17.18	18.38	17.37	18.82	24	5	30.00	23.2	21.2
A-2A-4-3	6.771				20.09	16.35	14.75	18.66	16.49	16.13	18.60	24	5	35.00	23.2	21.2
A-2A-5-2	*3.575*			53	*7.34*	*8.86*	*8.86*	*9.38*	*12.35*	*11.57*	*8.86*	*24*	*5*	*35.00*	*21.2*	*21.8*
A-2A-6-3	*9.710*				*21.66*	*25.07*	*17.73*	*16.83*	*23.64*	*27.40*	*15.12*	*24*	*5*	*30.00*	*20.8*	*21.6*
B-A-1-1	*4.740*			53	*8.35*	*15.42*	*9.54*	*9.42*	*11.14*	*11.76*	*10.39*	*24*	*5*	*30.00*	*21.0*	*21.3*
B-A-2-1	7.793	6.970	10.5%	54	15.28	15.14	18.21	21.49	12.16	19.25	18.48	24	5	30.00	21.7	21.1
B-A-3-2	6.719				15.25	12.80	13.35	16.15	13.53	16.50	17.03	24	5	30.01	22.0	21.0
B-A-4-3	6.397				12.75	12.37	13.94	13.38	18.30	14.82	14.33	24	5	30.01	22.7	20.9
G-3A-1-1	5.126	8.380	28.7%	54	12.31	7.58	5.88	18.45	15.64	9.98	12.01	24	5	30.00	20.0	20.5
G-3A-2-2	8.954				22.00	22.33	21.38	18.13	19.71	18.21	15.06	24	5	30.00	20.0	21.7
G-3A-3-3	10.905				18.95	20.53	26.74	25.89	27.79	25.33	19.60	24	5	30.00	20.0	20.7
G-3A-4-3	8.535			55	13.76	-	20.10	18.23	17.98	19.13	22.81	24	5	30.00	21.8	20.7
E-1-1	7.230	7.551	6.0%	53	16.38	13.72	15.00	17.63	16.25	16.43	16.55	24	5	30.00	21.8	20.9
E-2-2	7.872				16.37	15.88	18.68	17.70	17.57	16.85	18.03	24	5	30.00	22.0	21.2
F-2A-1-1	9.585	10.375	11.7%	27	25.28	17.58	-	18.36	23.13	20.62	19.98	24	5	30.00	21.0	20.9
F-2A-2-2	9.767				21.88	16.32	18.05	15.88	20.17	13.58	20.71	24	5	25.27	20.6	20.8
F-2A-1-3	11.772				21.40	23.57	25.13	-	26.00	29.48	25.22	24	5	29.83	20.9	20.8
H-A-2-B-1	6.292	7.288	13.0%	28	-	18.48	15.01	14.05	18.75	15.32	15.62	24	5	35.00	21.6	20.4
H-A-2-C-2	7.400				18.68	14.01	11.76	19.14	16.78	15.33	18.84	24	5	30.00	21.1	20.8
H-A-1-C-3	8.172				25.15	29.66	24.90	21.69	15.20	12.78	15.60	24	5	35.00	21.2	20.7
H-3A-2-B	4.153	4.849	13.0%	29	11.31	10.75	8.08	8.32	-	15.32	12.49	24	5	35.00	21.1	19.9
H-3A-1-C	5.012				-	11.76	16.67	15.56	10.54	12.37	11.96	24	5	35.00	20.8	19.8
H-3A-2-C	5.384				12.94	16.83	-	11.06	10.73	12.33	20.36	24	5	35.00	20.5	20.3
B-3A-1-C-1	5.174	4.939	5.5%	55	14.59	18.45	10.76	-	12.50	12.17	12.79	24	5	35.00	20.7	19.6
B-3A-2-B-2	5.002				13.38	12.72	12.09	13.04	13.69	13.80	-	24	5	35.00	20.7	19.9
B-3A-2-C-3	4.642				12.13	-	-	11.53	11.16	14.77	11.63	24	5	35.00	20.7	19.9
B-2A-1-B-1	6.993	7.340	16.6%	55	14.00	-	23.41	10.58	14.58	15.88	14.72	24	5	30.00	21.8	20.0
B-2A-2-B-2	6.334				17.99	15.09	13.48	-	11.24	12.19	15.06	24	5	30.00	21.5	20.1
B-2A-2-C-3	8.692				16.83	14.20	15.13	29.82	15.71	-	22.38	24	5	30.00	21.5	20.2
D-3A-1-B-1	10.268	10.914	5.9%	55	29.64	17.97	17.89	22.28	23.17	20.95	23.61	24	5	30.00	21.5	20.3
D-3A-2-B-2	11.552				24.44	26.34	22.32	26.60	19.43	23.04	31.70	24	5	30.00	20.7	20.6
D-3A-2-C-3	10.923				20.67	20.92	23.57	24.62	22.46	25.12	27.61	24	5	30.00	20.3	20.9
C-2A-1-B-1	-	-	-	57	-	-	-	-	-	-	-	-	-	-	-	-
C-2A-1-C-2	-				-	-	-	-	-	-	-	-	-	-	-	-
C-2A-1-C-3	5.894				15.46	15.80	12.92	12.67	12.22	12.34	11.64	24	5	30.00	20.3	19.9
D-2A-1-C-1	16.596	14.984	13.1%	57	22.22	23.76	-	21.83	25.77	22.28	26.83	24	5	20.00	20.1	20.1
D-2A-2-C-2	15.566				21.70	17.53	25.59	-	25.86	22.95	20.86	24	5	20.00	20.1	20.1
C-2A-2-B-3	12.790	-	-	58	28.21	21.02	18.11	12.69	10.62	17.56	22.59	24	5	20.00	21.1	20.1
F-3A-1-B-1	5.427	5.219	5.9%	56	10.46	10.23	-	11.98	10.44	12.83	17.86	24	5	30.00	21.0	20.6
F-3A-1-C-2	5.366				10.64	11.67	8.94	9.96	14.69	15.70	13.60	24	5	30.00	21.1	20.6
F-3A-2-B-3	4.862				13.94	14.00	10.53	13.17	10.50	12.80	14.23	24	5	35.00	22.0	20.9
D-A-1-B-1	17.497	20.019	13.5%	56	16.06	12.27	27.47	30.20	28.81	30.68	29.08	24	5	20.00	20.9	20.3
D-A-2-B-2	22.873				19.93	25.79	25.62	24.58	23.95	26.08	24.28	24	5	15.00	20.3	19.8
D-A-2-C-3	19.687				20.82	24.31	19.86	20.18	22.44	20.06	20.83	24	5	15.00	20.3	20.0
E-SCC-1-C-1	1.480	1.219	35.9%	57	7.21	4.52	5.77	6.58	-	6.42	10.75	24	5	60.00	20.1	19.9
E-SCC-2-C-2	0.714				4.06	3.14	-	2.48	5.15	3.23	3.29	24	5	60.00	19.1	19.6

Sample Code	Migration Coefficient (E-12 m^2/s)	Average	COV	Age	Measurement of the chloride penetration depth (mm)							Time duration (hr)	Thickness of the specimen (cm)	Voltage used (V)	initial temperature (°C)	final temperature (°C)
					x2	x3	x4	x5	x6	x7	x8					
E-SCC-3-B-3	1.464				9.66	3.73	6.53	4.97	10.21	5.70	6.90	24	5	60.00	19.1	20.1
C-2A-1-B-1	6.912				15.40	15.20	16.10	18.76	15.75	13.34	13.07	24	5	30.00	20.9	20.4
C-2A-2-B-2	7.693	7.157	6.5%	65	13.62	21.60	15.98	15.08	20.05	15.98	16.59	24	5	30.00	20.5	20.5
C-2A-2-C-3	6.867				13.43	13.83	26.36	9.20	14.48	16.33	13.44	24	5	30.00	20.2	20.4
F-A-1-C-1	10.714				23.81	25.82	24.62	-	21.72	23.19	19.28	24	5	30.00	21.5	21.7
F-A-2-B-2	10.227	9.889	10.5%	56	24.58	24.43	26.81	24.16	20.77	23.31	10.96	24	5	30.00	20.4	21.0
F-A-2-C-3	8.727				22.61	20.35	15.27	14.52	17.76	27.15	16.08	24	5	30.00	20.2	20.7
F-2A-2-B-1	11.113				21.56	29.72	22.10	16.47	30.22	-	23.56	24	5	30.00	21.2	20.4
F-2A-1-B-2	9.624	10.040	9.3%	55	20.13	15.95	15.94	16.15	-	25.99	31.23	24	5	29.99	21.8	20.1
F-2A-1-C-3	9.384				14.82	19.74	21.84	18.08	18.25	25.08	25.35	24	5	30.00	21.7	19.0
I-A-1-B-1	9.623				21.27	21.62	24.95	20.87	16.58	19.94	21.20	24	5	30.00	20.9	20.5
I-A-1-C-2	9.723	9.995	5.6%	69	20.67	18.27	22.28	20.56	21.47	21.06	23.58	24	5	30.00	20.7	20.5
I-A-2-B-3	10.639				-	-	20.24	25.42	20.51	23.76	25.09	24	5	30.00	20.5	20.3
I-2A-1-B-1	8.185				-	16.58	-	17.88	17.12	19.78	18.65	24	5	30.00	20.3	20.4
I-2A-1-C-2	8.057	8.344	4.7%	70	16.53	14.28	16.47	18.34	20.01	19.00	19.57	24	5	30.00	20.1	20.5
I-2A-2-B-3	8.789				21.18	15.96	19.39	-	18.21	17.97	22.90	24	5	30.00	19.3	20.3
H-A-1-B-1	6.637				12.83	14.72	17.51	15.20	11.74	14.68	17.10	24	5	30.00	20.2	20.2
H-A-3-B-2	4.500	5.828	19.9%	58	11.19	7.33	9.56	9.67	11.93	11.28	11.72	24	5	30.00	20.3	20.3
H-A-3-C-3	6.348				12.48	12.86	14.21	16.51	14.66	14.64	14.29	24	5	30.00	20.1	20.0
H-3A-1-B-1	3.938				9.85	14.35	11.25	9.52	-	10.60	7.46	24	5	35.00	21.6	20.5
H-3A-1-C-2	4.253	3.985	6.2%	59	12.52	8.70	7.69	10.16	10.90	14.17	14.82	24	5	35.00	21.2	20.5
H-3A-2-B-3	3.763				11.19	14.16	8.78	8.34	7.32	-	10.72	24	5	35.00	21.2	20.2
B-3A-3-B-1	4.770				12.56	13.16	11.45	14.87	13.86	10.54	11.31	24	5	35.00	21.5	20.3
B-3A-3-C-2	4.743	4.798	1.5%	112	10.45	8.50	15.36	14.48	13.40	12.62	-	24	5	35.00	21.8	20.1
B-3A-4-B-3	4.880				17.66	14.20	14.30	14.12	11.36	16.19	13.34	24	5	40.00	21.6	20.1
B-2A-3-B-1	6.440				22.87	14.27	15.02	11.76	14.38	10.64	11.86	24	5	30.00	20.9	20.4
B-2A-3-C-2	6.052	7.075	20.5%	112	7.30	15.20	14.77	13.30	13.54	15.96	15.07	24	5	30.00	21.6	20.1
B-2A-4-B-3	8.733				28.87	21.57	21.77	22.47	16.36	21.43	21.92	24	5	35.00	21.6	20.1
D-3A-3-B-1	6.152				18.75	-	13.17	10.66	10.62	14.31	15.43	24	5	30.00	20.2	20.2
D-3A-3-C-2	6.421	6.649	9.7%	112	15.69	16.53	14.86	8.99	13.14	13.43	17.96	24	5	30.00	20.7	20.1
D-3A-4-B-3	7.373				-	24.17	13.34	10.29	19.76	17.45	12.98	24	5	30.00	21.0	19.9
D-2A-3-B-1	13.429				22.60	18.50	-	18.72	19.00	18.92	19.55	24	5	20.00	21.0	19.9
D-2A-3-C-2	14.993	13.682	8.8%	113	18.69	22.22	25.54	17.96	22.35	21.21	23.49	24	5	20.00	20.9	19.8
D-2A-4-B-3	12.622				17.47	18.12	20.21	17.47	17.61	16.62	21.90	24	5	20.00	20.5	19.8
F-3A-3-B-1	5.661				13.40	-	12.58	13.98	15.01	16.59	16.71	24	5	35.00	21.0	19.8
F-3A-3-C-2	4.979	5.240	7.0%	112	17.26	13.91	10.44	10.79	13.56	12.63	12.80	24	5	35.00	21.1	20.0
F-3A-4-B-3	5.081				18.01	13.88	12.84	7.74	16.10	13.08	11.48	24	5	35.00	21.0	20.0
D-A-3-B-1	16.792				22.82	31.94	23.97	24.66	24.42	22.90	17.38	24	5	20.00	21.0	20.0
D-A-4-B-2	17.951	17.601	4.0%	111	20.57	34.60	24.29	22.15	26.39	-	25.34	24	5	20.00	20.5	20.2
D-A-4-C-3	18.058				31.26	25.31	22.04	21.29	24.82	28.24	26.98	24	5	20.00	20.3	20.2
E-SCC-3-B-1	1.117				-	15.89	8.28	9.06	10.26	6.81	10.01	48	5	60.00	21.6	20.7
E-SCC-3-C-2	0.663	0.858	27.3%	112	9.52	5.41	5.36	3.70	8.27	5.43	5.64	48	5	60.00	21.6	20.9
E-SCC-4-C-3	0.793				5.45	5.48	13.07	6.37	6.15	-	-	48	5	60.00	21.5	20.7
I-A-3-B-1	9.102				19.48	17,97	19.41	20.22	21.94	18.92	18.75	24	5	30.00	23.1	20.7
I-A-3-C-2	8.990	8.569	9.7%	112	20.29	16.96	18.31	21.06	23.29	17.59	-	24	5	30.00	22.0	20.9
I-A-4-B-3	7.616				15.29	26.07	13.22	15.34	13.74	17.02	-	24	5	30.00	22.5	20.4
I-2A-3-B-1	7.402				17.04	17.64	17.26	16.14	16.91	14.90	14.76	24	5	30.00	20.3	21.1
I-2A-3-C-2	7.760	7.567	2.4%	113	20.05	16.68	14.86	13.64	17.77	16.40	20.53	24	5	30.00	19.2	21.4
I-2A-4-B-3	7.540				18.25	16.61	17.22	17.27	16.98	14.86	15.58	24	5	30.00	19.5	21.1
F-A-3-B-1	7.867	7.867	-	112	18.42	17.60	16.40	18.79	17.46	16.82	15.50	24	5	30.00	22.1	21.2
F-2A-3-B-1	5.466	5.466	-	111	14.26	16.01	12.16	8.46	13.52	11.80	10.44	24	5	30.00	20.2	21.5
H-A-4-B-2	5.209	5.207	-	112	16.29	17.76	14.05	-	12.14	9.94	11.42	24	5	35.00	20.1	21.6
H-A-4-C-3	5.206				12.50	13.93	15.31	9.86	-	14.09	15.92	24	5	35.00	19.7	21.6
H-3A-4-B-2	3.086	2.843	-	113	12.92	17.37	-	10.33	7.89	9.69	11.08	24	5	50.00	20.5	20.8
H-3A-4-B-3	2.600				8.42	10.98	6.90	10.16	12.04	10.06	10.41	24	5	50.00	20.1	20.5
E-HES-3-B-1	3.724				8.74	8.85	9.50	9.45	9.23	-	6.74	24	5	30	20.7	19.9
E-HES-3-C-2	5.245	4.524	17%	161	12.16	15.60	12.77	12.86	9.76	10.35	10.12	24	5	30	19.9	20.3
E-HES-4-B-3	4.602				9.15	9.70	8.86	11.06	12.79	12.04	-	24	5	30	20	20.4

Post-Test Images

The tested samples are shown below. The identifications include the Specimen ID – Concrete Type – Cylinder Number – Segment of Cylinder (B above the center and C is below) – Test Setup Number


C-2A-1-B-1


C-2A-2-B-2


C-2A-2-C-3

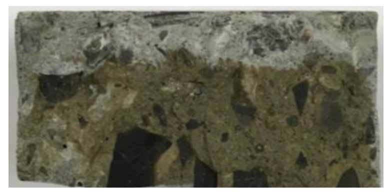

C-2A-2-C-3


B-2A-1-B-1


B-2A-2-B-2


B-2A-2-C-3


B-2A-3-B-1


B-2A-3-C-2


B-2A-4-B-3


B-3A-1-C-1


B-3A-2-B-2


B-3A-2-C-3


B-3A-3-B-1


B-3A-3-C-2


B-3A-4-B-3


B-A-1-1


B-A-2-1

B-A-3-2

B-A-4-3

A-2A-1-1

A-2A-1-2

A-2A-1-3

A-2A-2-1

A-2A-3-2

A-2A-4-3

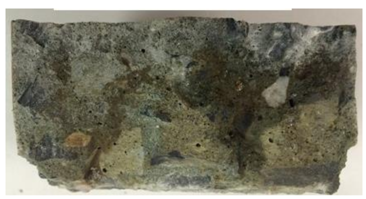
A-2A-5-2

A-2A-6-3

A-3A-3-B-1

G-3A-4-3

A-3A-3-C-2



A-3A-4-B-3

F-2A-1-B-2

F-2A-1-C-3

F-2A-2-B-1

F-3A-1-B-1

F-3A-1-C-2

F-3A-2-B-3

F-3A-3-B-1

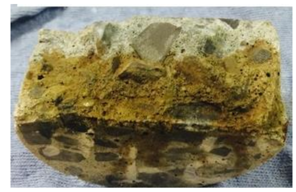
F-3A-3-C-2

F-3A-4-B-3

F-AA-1-1

F-A-1-2

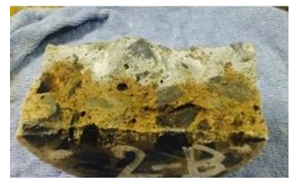
F-AA-1-3



F-A-1-C-1

F-AA-2-2

F-A-2-3



F-A-2-B-2

F-A-2-C-3

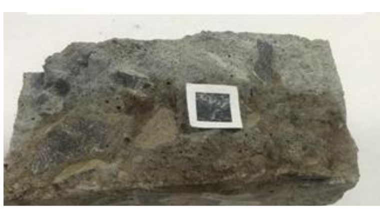
F-A-3-B-1

F-A-3-B-1

I-2A-1-B-1

I-2A-1-C-2

I-2A-B-3



I-2A-3-B-1

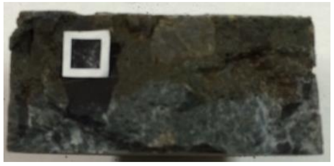
I-2A-3-C-2

I-2A-4-B-3

I-A-1-B-1

I-A-1-C-2

I-A-2-B-3

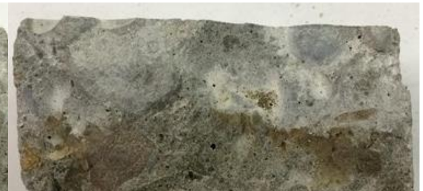


I-A-3-B-1

I-A-4-B-3

D-A-3-B

D-A-4-B



D-A-4-C

D-2A-1-C-1

D-2A-2-B-3

D-2A-2-C-2

D-2A-2-C-2

D-2A-3-B-1

D-2A-3-C-2

D-2A-4-B-3

D-3A-1-B-1

D-3A-2-B-2

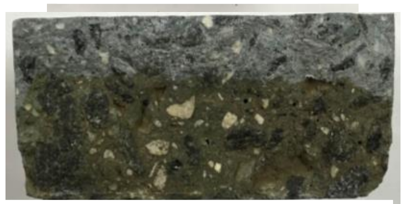
D-3A-2-C-3

D-A-1-B-1

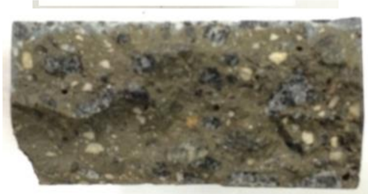
D-A-2-B-2

D-A-2-C-3

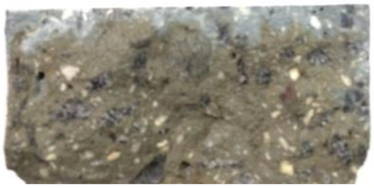
E-HES-1-1



E-HES-2-2

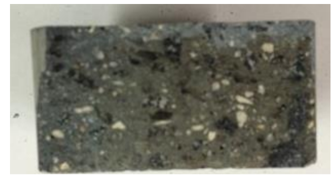


E-SCC-1-C-1

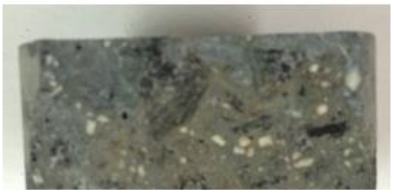


E-SCC-2-C-2

E-SCC-3-B-3

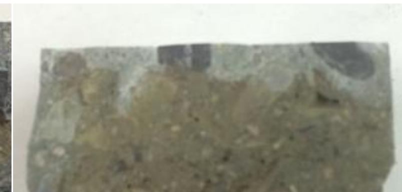


E-SCC-3-C-2



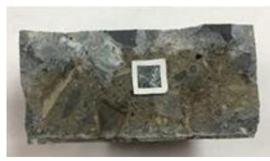
E-SCC-4-C-3

H-2A-3-B-2



H-3A-1-B-1

H-3A-1-C-2



H-3A-3-B-2

H-3A-4-B-3

H-A-1-B-1

H-A-1-C-3

H-A-2-B-1

H-A-2-C-2

H-A-3-B-2

H-A-3-C-3

H-A-4-B-2

H-A-4-C-3

G-3A-1-1

G-3A-2-2

G-3A-3-3