Chloride Transport Measurements for a Plain and Internally Cured Concrete Mixture

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Synopsis: Over the last fifteen years there has been growing interest in using internally cured concrete. While the original intention of using internal curing was to reduce autogenous shrinkage, it has been observed that the internally cured concretes have additional benefits. For example, previous research has shown that internally cured concrete has lower water absorption than comparable conventional (plain) concrete mixtures. This paper presents results of chloride transport experiments performed using a conventional (plain) concrete mixture and an internally cured concrete mixture. Chloride transport performance was evaluated using a series of experimental techniques including: 1) resistivity, 2) rapid chloride penetration (RCP), 3) rapid chloride migration (the Nord Test), 4) migration cell testing (STADIUM cells) and 5) chloride ponding and profiling. Tests were performed 28, 56, and 91 days after casting. The results indicate that internally cured concretes have similar or superior performance to plain concrete. Several testing artifacts are noted associated with the pre-wetted lightweight aggregate that overestimate the transport measures for the internally cured concrete. The experimental results suggest that by reducing the chloride transport rate the use of internally cured concrete can result in structures with improved durability (due to the time it takes chloride ions to cause corrosion at the reinforcing steel).

Keywords: chloride transport, internal curing, lightweight aggregate, rapid-chloride penetrability, resistivity, service life, titration

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1.0 INTRODUCTION

Transportation agencies strive to construct durable reinforced concrete structures. The durability of the concrete structures is largely governed by the fluid transport properties of the concrete which include: 1) absorption, 2) permeation and 3) diffusion of ionic species [1]. For example, the ingress of chloride ions is of particular interest in bridge decks due to the application of deicing salt and in marine structures due to the salinity of the water. If the chloride ions reach the reinforcing steel they can reduce the passivity of the reinforcing steel and promote the formation of corrosion products. The time that it takes the reinforcing steel to begin to corrode in a structure is strongly related to the rate of chloride ions penetration [2, 3]. Corrosion is a concern since it can shorten the service life of reinforced concrete structures.

It is generally known that the transport ionic species in concrete (absorption, diffusion and permeability) can be reduced by using mixtures with a lower porosity (i.e., a low water to cement ratio, w/c) and with the use of supplementary cementitious materials [1, 4]. While these low w/c mixtures reduce transport, they have in many cases exacerbated the problem of early-age cracking [5, 6].

The use of prewetted lightweight aggregate as an internal curing agent has been shown to mitigate early age cracking [7, 8, 9]. In addition, it has been shown that internal curing can reduce the fluid transport properties of concrete such as water absorption and chloride transport [10, 14]. The fluid transport properties in an internally cured concrete are reduced for three reasons. First, internal curing supplies additional water that enables increased hydration thereby reducing the porosity of the concrete [8]. Second, internal curing densifies the interfacial transition zone around the LWA. The more dense ITZ zone can depercolate preferential transport paths resulting in higher resistance to ionic and fluid transport [11]. Third, internal curing reduces unwanted early-age cracking thereby reducing paths for fluid to reach the reinforcing steel [7, 12].

2.0 RESEARCH SIGNIFICANCE

While internal curing has been shown to be beneficial in reducing shrinkage and early-age cracking, relatively little research has documented the effects of internal curing on reducing ionic ingress and transport [8]. This paper describes the transport properties of a conventional (plain) and internally cured concrete bridge deck mixture. These concrete mixtures are identical to those used in a comparative field evaluation in Monroe County Indiana in September 2010. Chloride transport performance was evaluated using a series of tests including: 1) resistivity, 2) rapid chloride penetration (RCP), 3) rapid chloride migration (the Nord Test), 4) migration cell testing (Stadium Cells), and 5) chloride ponding and profiling. Tests were performed 28, 56, and 91 days after casting. These results of this study can be useful in determining the chloride transport performance of internally cured concrete which has implications on the time to corrosion and service life of reinforced concrete elements.

3.0 CONSTITUENT MATERIALS AND MIXTURE PROPORTIONS

Two different concrete mixtures are compared in this study. The first mixture is a conventional (plain) mixture that is commonly used by a local ready mixed concrete provider to meet the INDOT Bridge deck specifications. The second mixture is similar; however a portion of the volume of the fine aggregate has been replaced with an equivalent volume of prewetted lightweight aggregate. The second mixture will be referred to as the internally cured concrete mixture. The samples were prepared in laboratory with identical proportions to the mixtures that were eventually used in the Monroe County bridge deck trials [13]. Table 1 shows the mixture proportions.

Table 1 – Mixture proportions for plain and internally cured concretes.

	Cement Content (kg/m^3)	W/C	Fine Aggregate (kg/m^3)	Fine LWA (kg/m^3)	Coarse Aggregate (kg/m^3)	Mixture Water (kg/m^3)	Water in LWA (kg/m^3)	WRA (%)^A	AE (%)^A
Plain Concrete	390	0.39	726	-	1046	152	-	0.22	0.22
Internally Cured Concrete	390	0.39	313	270	1046	152	25	0.08	0.08

^{A} Percentage referred to the cement weight.

These proportions are based on the saturated surface dry condition of the materials with the exception of the LWA which is given in oven dry condition. An additional column is used to represent the water to maintain the 24 hour prewetted surface dry conditions.

The volume of the sum of the fine aggregate and fine lightweight aggregate was the same for both mixtures.

The lightweight aggregate used for the internally cured mixture was a fine lightweight aggregate (Haydite AX, Brooklyn IN). The 24 hours absorption of the LWA, based on the paper towel testing procedure outlined by the NYDOT, was 10.4%. The specific gravity of the lightweight aggregate was 1.56. The absorption of the coarse and fine aggregate was 1.1 % and 1.6 % respectively. The specific gravity of the coarse and fine aggregate was 2.672 and 2.647 respectively.

The cement used for the plain and internally cured mixture is an ordinary portland cement (OPC) conforming to ASTM C150 type I specification. The characteristics of the cement used are given in Table 2.

Table 2 – Characteristics of ordinary portland cement used in this study.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O Equiv.	Blaine (m^2/kg)
OPC Type I	20.4%	4.8%	3.2%	63.2%	2.1%	3.4%	0.67%	398

4.0 MIXING, CURING AND SAMPLE PREPARATION

Prior to mixing, the aggregate (including lightweight aggregate) was dried in an oven at 105 ± 5 °C for 24 hours. The aggregate was then allowed to cool down to room temperature. The lightweight aggregate was soaked in the mixture water for 24 hours being careful that the water remained above the top surface of the lightweight aggregate. In order to avoid loss of water to evaporation the lightweight aggregate was covered with plastic sheets. After 24 hours the excess water was decanted and used in mixing.

The coarse and fine aggregate were placed in the pan mixer. Water was then added to the mixture (along with lightweight aggregate in the case of the internally cured mixture). Cement and admixtures were then added. After all the materials were placed in the mixer they were mixed for 3 minutes, followed by a 3 minutes rest and a 2 minutes final mixing in accordance with ASTM C 192.

Cylindrical sample were prepared. The cylinders had a diameter of 102 mm (4 in.) and length of 203 mm (8 in.). External vibration was used to consolidate the specimens. Immediately after casting the cylinders were covered. These specimens were demolded after one day and sealed in double plastic bags until the test age were reached: 28, 56, 91 days (with the exception of the surface resistivity samples). At the time of testing the samples were prepared using the procedures described in the following section.

5.0 EXPERIMENTAL METHODS

In this study the transport properties of the concrete were evaluated using five experimental techniques. These techniques include: 1) surface resistivity, 2) rapid chloride penetration (RCP),

3) rapid chloride migration (the Nord Test), 4) migration cell testing (Stadium Cells), and 5) chloride ponding and profiling. The experimental procedures are described in the following section.

5.1 Surface resistivity

The electrical resistivity at the surface of water-stored concrete samples was measured using the four-point Wenner probe surface (Figure 1). Measurements of electrical resistivity were conducted as described in AASHTO TP 95-11 using cylindrical samples that were 102 mm (4 in.) in diameter and 203 mm (8 in.) long. The samples were demolded at 24 h after casting and kept under lime water until the time of testing at a temperature of 23 ± 1 ºC. It should be noted that by storing the samples under water it is believed that the samples will absorb water during the test which may increase the degree of hydration of the specimen [14].

In the surface resistivity test a current is applied at the outer probes and the potential difference is measured between the two inner probes. Assuming that the concrete has homogeneous semi-infinite geometry the concrete resistivity is described by equation 1:

$$\rho = (2 \cdot \pi \cdot a) \cdot \frac{V}{I} \qquad \text{eq. 1}$$

where a is the electrode spacing, V is the voltage, and I is the current.

Morris et al. [15] showed that for concrete cylinders the surface resistivity ($\rho_{surface}$) requires a correction to attain the true resistivity (ρ) of the material that depends on probe spacing and sample geometry. A geometry correction (K) of approximately 1.9 can be used for probe spacing (a = 38 mm, 1.5 in) and specimen size used in this study (Equation 2). This has been recently confirmed through experiments by Spragg et al. [21].

$$\rho_{bulk} = \rho_{surface}/K \qquad \text{eq. 2}$$

Relationships have been developed between RCP test and surface resistivity test results [16, 17] (assuming saturation) since both tests are based on measures of the electrical resistance of the concrete. It should however be noted that the RCP test test may contain artifacts related to sample heating caused by the joule effect.

Figure 1 – Surface resistivity measurements using a Wenner probe.

5.2 Rapid Chloride Penetration (RCP)

The rapid chloride penetration (RCP) test was performed in accordance with ASTM C 1202. A cylindrical specimen was prepared that was 102 mm (4 in.) diameter and 51 ± 3 mm (2 in.) long. Prior to testing the sample was vacuum saturated as described in ASTM C 1202. During the test one surface of the sample was exposed to a sodium chloride solution (3% NaCl) and the other surface was exposed to a sodium hydroxide solution (0.3 M NaOH). A 60 V externally applied potential and the current at 15 minute intervals was recorded for a 6 hour period. Figure 2 shows the experimental set up with four samples being tested simultaneously.

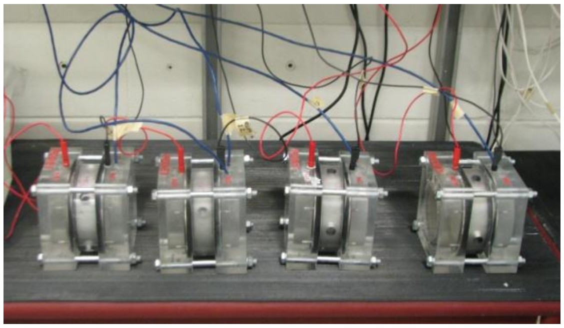

Figure 2 – Rapid Chloride Penetration (RCP) test cells.

5.3 Rapid Chloride Migration (RCM)

The rapid chloride migration test was conducted to determine the non – steady state chloride migration coefficients following the NT Build 492 procedure [18]. The RCM test is a non-steady state migration test to accelerate the chloride transport by means of the application of a potential across a 50 mm thick specimen for a specified period of time.

The test was performed using specimens cut from a concrete cylinder to produce a disk that is 51 ± 3 mm (2 in.) thick and 102 mm (4 in.) diameter. The samples are vacuum saturated after cutting. The sample is then placed in a rubber sleeve. The top portion of the sleeve is used to create a reservoir where 0.3 M NaOH is placed in contact with the upper surface of the sample. The bottom of the sample is placed in a solution of 10% NaCl. The test is illustrated in Figure 3. An initial potential of 30 V is applied to the specimen. This potential is adjusted according to the current response (as outlined in the NT Build standard) and the applied potential is maintained for a 24 hour period.

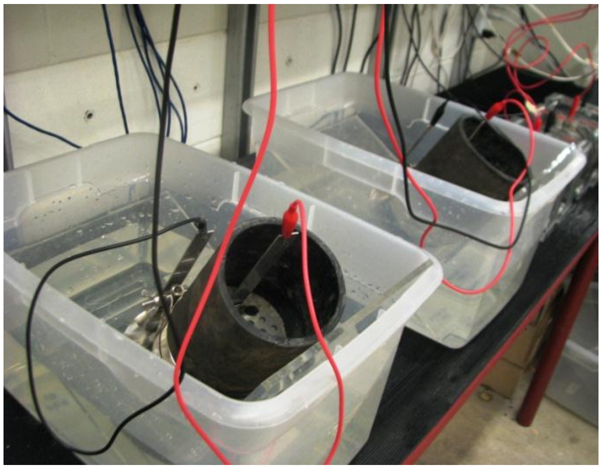

Figure 3 – Rapid Chloride Migration (RCM) experimental set up.

At the end of the 24 hour period where voltage is applied the sample is rinsed with distilled water and the surface is wiped with a cloth. The sample is then split into two pieces as shown in Figure 4. A 0.1 M silver nitrate solution is sprayed on the sample. Where sufficient chloride is present, the silver nitrate causes white silver chloride to precipitate as shown in Figure 4. The chloride penetration depth is measured at 10 locations across the section and used to determine an average depth of penetration.

Figure 4 – A Sample from the Rapid Chloride Migration (RCM) test that was split after and sprayed with Silver Nitrate (AgNO3). The white portion of the sample at the top represents the chloride penetration while the brown area represents the portion of the concrete that has not received substantial chloride penetration. The sample is 101 mm (4 in wide) and 50 mm (2 in tall).

The chloride non steady state migration coefficient (D_{nssm}) is calculated using equation 3, assuming the migration process as dominant and that the chloride binding capacity during the test to be constant [2, 19].

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right) \quad \text{eq. 3}$$

where D_{nssm} is the non steady state migration coefficient (x10^{-12} m^2/s), U is the absolute value of the applied voltage (V), T is the average value of the initial and final temperatures in the solution

(C), L is the thickness of the specimen (mm), x_d is average value of the average chloride penetration depth (mm) and t is the test duration (hour).

5.4 Migration cell

The diffusion coefficients for specific ionic species were measured using a migration cell (Stadium Cell) as shown in Figure 5. The test method consists of monitoring the intensity of electrical current passed through a cylindrical test specimen (50 ± 2 mm (2 in.) thick and 100 ± 2 mm (4 in.) in diameter over 14-days testing period). Before testing the samples are vacuum saturated with 0.3M NaOH for approximately 18 hours. After vacuum saturation the sample was mounted in between the downstream cell filled with 0.3M NaOH solution and the upstream cell filled with 0.5 NaCl + 0.3M NaOH solution. A constant DC potential of 20 V is maintained across the specimen. The data (voltage, current, and temperature) are automatically recorded at 15 minute intervals. These data, along with the porosity (volume of permeable voids) value determined in accordance with ASTM C642, are entered into STADIUM Lab software to evaluate the ion diffusion coefficients [20].

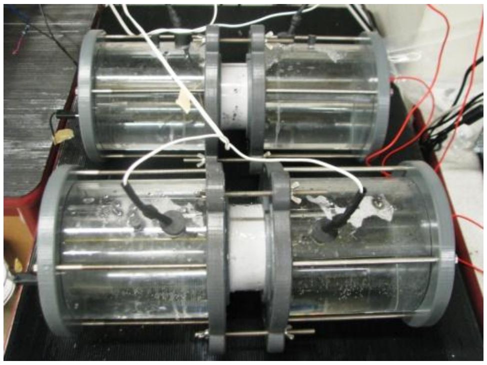

Figure 5 – Migration cell experimental set up.

5.5 Chloride Ponding and Profiling

The penetration of chloride ions into concrete was assessed from a chloride ponding test in which a 3% NaCl solution was ponded on the surface of the specimen following the approach described in ASTM C1543-10. A cylindrical specimen was prepared that was 102 mm (4 in.) diameter and 203 mm (8 in.) long and allowed to cure for 28 days sealed in plastic bags stored at 23 ± 1 °C. After 28 days, the sample was cut obtaining two half cylinders that were 102 mm (4 in.) diameter and 102 mm (4 in.) long. The sides of each concrete specimen were coated with epoxy. After the epoxy hardened and dried, a plastic cylinder was affixed to around the top of each sample, in order to form a dam to contain the salt solutions to be used for ponding. A sketch of the sample is shown in Figure 6.

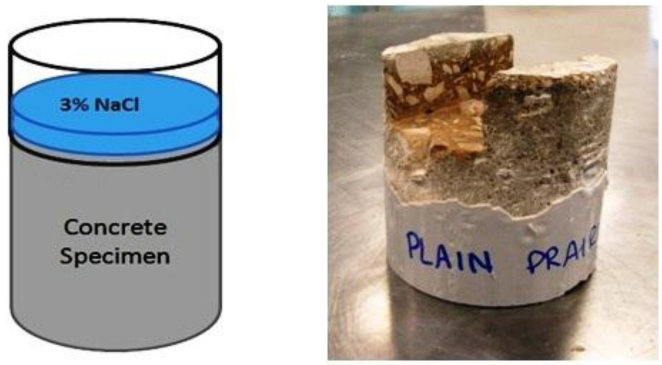

Figure 6 – A sketch of the sample used for chloride ponding and the sample after profile grinding.

After the dam was affixed to the surface water was placed on the specimen to insure that the dam was water-tight. The water was then removed and the sample was filled with a 3% NaCl solution. It should be noted that water could be reabsorbed by the sample, however the samples were not vacuum saturated. The samples were stored in a chamber at 23 ± 1 °C and 50 ± 2% RH. Periodically (approximately every 10 days), the salt solution was replaced with fresh solution. Once the testing ages were reached (28, 56 and 91 days) the plastic dam was removed and the epoxy sealed sides were removed. The concrete was placed on a milling machine and ground with successively 2 mm steps using a 50 mm diamond tipped drill bit. The powder that was collected at different depths was analyzed to determine the chloride content as described in the following section.

An automated system was used to titrate up to 14 samples (a sample here refers to the powder obtained at each grinding depth) simultaneously. The acid-soluble chloride content was determined using a procedure similar to AASHTO T 260; however some modifications to the specification were adopted as highlighted below. First, 3 grams of ground powder from the concrete were placed in contact with 10 ml of hot distilled water. This was mixed for several mixtures. Then, 3 ml of nitric acid was added to the suspension, stirring the solution continuously. Next, the solution was diluted with an additional 40 ml of hot distilled water, yielding approximately 50 ml of sample. Each sample was covered and boiled for 1 minute. It should be noted that some layers may have a very low chloride concentration that was difficult for the titrator to detect and as such a full analysis would be done that was both time consuming and consumed silver nitrate. In order to alleviate this problem, 1 ml of 0.01M sodium chloride solution was added to each sample prior to titration.

The titration probe used in this study did not require the sample to be filtered. The solution was placed in the titration unit shown in (Figure 7). While stirring the solution, the titrator adds 0.01M silver nitrate to the solution in 0.2 ml increments (this addition rate however decreases while approaching the saturation point), while simultaneously monitoring the electric potential of the solution with a silver reference electrode. A plot of the electrical potential versus volume-of-titrant (i.e., volume of silver nitrate) is then prepared. The principle of the test is that as the chloride (Cl- ions) are paired with the silver (Ag+) ions causing the solution to neutralize and change the electric potential. A typical example of this change is shown in Figure 8. The chloride content of the sample is determined using the maxima of the first derivative curve of the potential. Once the inflection point is reached, the dosing unit stops adding silver nitrate to the sample and begins to process the next sample. This entire process takes approximately 5 minutes for each sample, as compared to approximately 1 hour when the test was performed manually. The chloride concentration is computed using equation 4 accounting for the silver nitrate that was added to each sample during sample preparation.

$$\% \, \boldsymbol{Cl} = \frac{\boldsymbol{M_{Cl}} \times [(\boldsymbol{V_{AgNO3}}) - (\boldsymbol{V_{NaCl}})] \times \boldsymbol{C_{AgNO3}}}{\boldsymbol{M_{powder}}} \times \mathbf{100} \qquad \text{eq. 4}$$

where M_{Cl} is the atomic weight of chlorine (35.453 g/mol), V_{AgNO_3} is the total volume of $AgNO_3$ added, V_{NaCl} is the volume of sodium chloride added, C_{AgNO_3} is the concentration of silver nitrate used for the titration (0.0102 mol/l) and M_{powder} is the mass of concrete powder.

The results of the automated method were compared with those obtained by hand as shown in Figure 9. The results shown that the chloride content values obtained from both methods are similar.

Figure 7 – Automated titration unit.

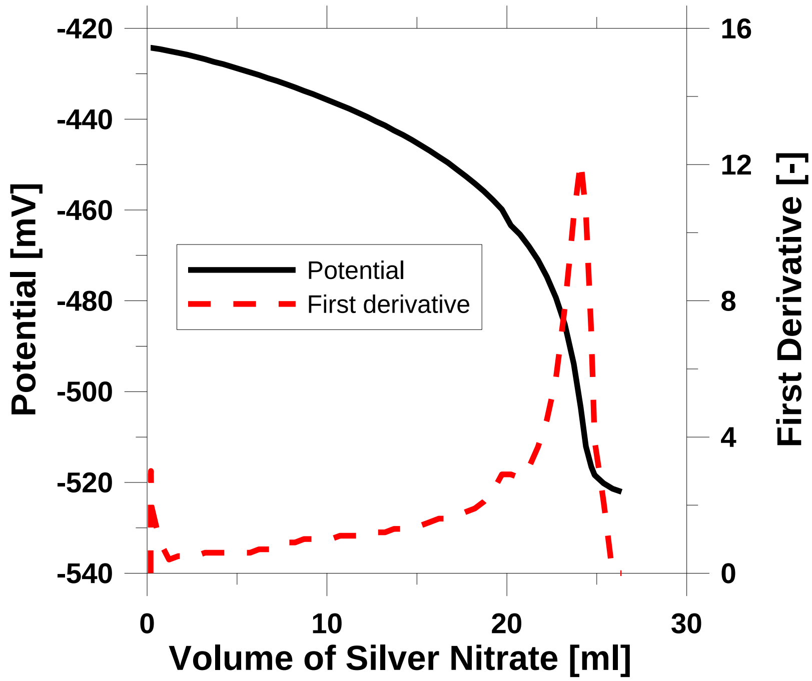

Figure 8 – An example of a titration response illustrating the change in electrical potential and how the inflection point was used to determine the initial chloride content.

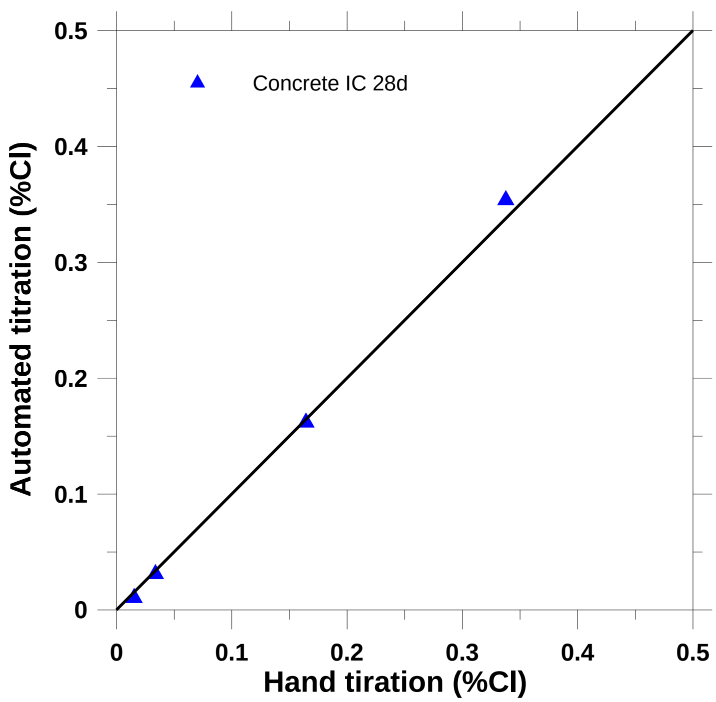

Figure 9 - Comparison of the chloride concentration obtained from a sample of internally cured concrete at 28d using the conventional titration method and using the automated titration system.

6.0 EXPERIMENTAL RESULTS AND DISCUSSION

6.1 Surface resistivity

The electrical resistance of the concrete is known to be related to the pore volume, the ionic concentration of pore solution [16, 17] the degree of saturation in the concrete, and the tortuosity of the pore network. The resistivity of the concrete can be used as a surrogate measurement of the transport properties since the Nernst-Einstein relationship [21] allows the electrical properties to be related to ionic diffusion.

Figure 10 shows the surface resistivity measurements for plain and internally cured samples. Initially the internally cured concrete has a lower resistivity (likely due to the conductive nature of the aggregate [14]); however by 56 days the resistivity of the internally cured concrete has a similar resistivity and at later ages it is more resistive thanks to the enhanced hydration and denser ITZ [8,11] .

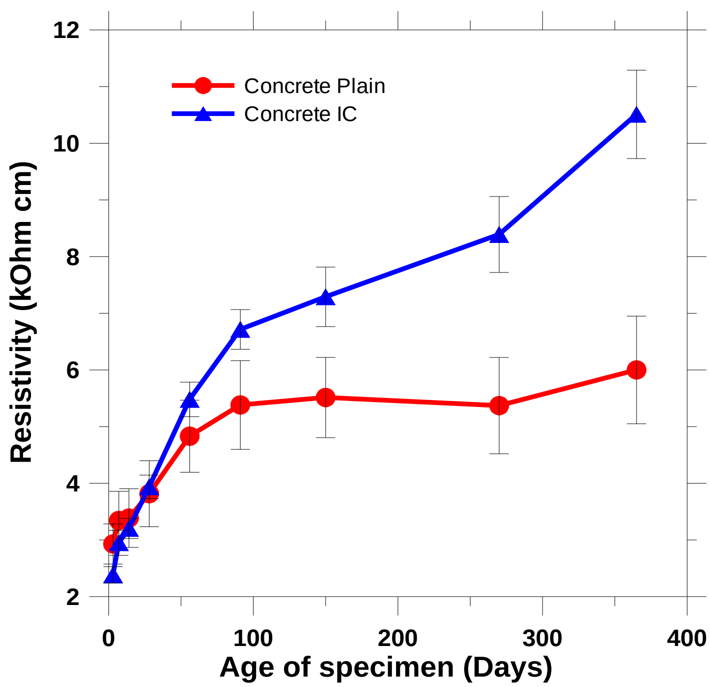

Figure 10 – Electrical resistivity if the plain and an internally cured concrete samples kept in lime water during the testing period.

It should be noted that by storing the samples in lime water they will hydrate more than a sealed sample. While the surface resistivity test is easy to perform, the samples are stored in water through the test which may not represent the way these specimens are cured in the field.

6.2 Rapid Chloride Penetration (RCP)

The most widely used method by transportation agencies to assess a concrete's ability to resist to chlorides ion penetration is ASTM 1202 (or AASHTO T277). Similar to the resistivity test described in section 5.1, the RCP test is influenced by the pore volume, the ionic concentration of pore solution [22, 23] the degree of saturation in the concrete, and the tortuosity of the pore network. However, unlike the resistivity tests, the RCP test samples used in this paper were sealed until the time of testing and then vacuum saturated. The results from the rapid chloride penetrability test are shown in Table 3 for the plain and internally cured concrete. The internally cured mixture shows consistently lower charge passed. For example, at an age of 91 days the internally cured concrete has an RCP value that is approximately 35% lower than the plain concrete.

Table 3 – Rapid Chloride Penetration Test Results for the Plain and Internally Cured Concrete Samples.

	Monroe County Bridge Deck Concrete			
Time [days]	Charge Passed [Coulombs]			
	Plain Concrete	Standard Deviation	Internally Cured Concrete	Standard Deviation
28	4252	116	3822	159
56	2863	560	2458	55
91	3174	450	2065	113

At the age of 56 days the plain concrete shows a lower value than expected. In fact, at 91 days the charge passed increases. This can be addressable to a misleading measurement at the age of 56 days.

The use of the rapid chloride penetration test method can be thought of essentially as a measure of concrete resistivity. However, it should be noted that RCPT was performed with high voltage and the sample heated during testing which increase due to Joule effect. As such there is no need to continue the test for six hours, and changes in the current during this time are most likely due to increases in temperature, not chloride penetration [24, 25]. Therefore alternative ways have been developed to measure concrete resistivity and assess the concrete chloride penetration resistance [23] [22].

6.3 Rapid Chloride Migration (RCM)

Table 4 shows the non steady migration coefficients obtained at 28, 56 and 91 days for the concrete samples with and without internal curing. The internally cured concrete shows benefits of internal curing for each test compared to the plain concrete. For example, at an age of 91 days the internally cured concrete has an RCP value that is approximately 15% lower than the plain concrete.

Table 4 – Chloride diffusion coefficients obtained from the Rapid Chloride Migration Test.

	Monroe County Bridge Deck Concrete			
Time [day]	Diffusion coefficients (m^2/s)			
	Plain Concrete	Standard deviation	IC Concrete	Standard deviation
28	1.42E-11	9.89E-13	1.15E-11	5.65E-13
56	1.26E-11	4.24E-13	8.98E-12	2.83E-13
91	3.99E-12	4.24E-13	3.42E-12	1.91E-13

Although the internally cured concrete shows lower diffusion coefficients than the plain concrete from the test when it is performed following the standard, it should be noticed that the diffusion coefficients may be actually lower for the internally cured concrete. First, the internally cured concrete is cut to perform the test. As such, the cutting of the concrete exposes the porous lightweight aggregate. When these cut aggregates are exposed to the solution the chloride can easily diffuse into the concrete which may not represent what happens in field concrete. As such this may skew the results of test with more resistant matrices [26]. In addition, since the sample is saturated the conductivity of the aggregate may alter the electrical response of the concrete [27]. Despite these testing anomalies the internally cured concrete performed as well, or better than the plain concrete.

6.4 Migration cell

A multi-ionic model considers the electrical coupling between ions, chloride binding, and chemical reactions was used to interpret the results from the migration cell [20]. This analysis was performed using a program called STADIUM lab which used results from the migration cell along with the porosity results obtained from ASTM C 642 (Table 5). It should be noted that at the current time it is believed that this code does not consider the porosity of the aggregate explicitly. The modeled diffusion coefficients in Table 6 have a similar trend when compared with the rapid chloride penetration test; however the diffusion coefficients obtained with this method are not directly comparable with one another.

Table 5 - Tortuosity modeled by Stadium Lab software and porosity determined in accordance with ASTM 642.

	Monroe County Bridge Deck Concrete					
Time [days]	Porosity %				Tortuosity	
	Plain Concrete	STD	IC Concrete	STD	Plain Concrete	IC Concrete
28	12.6	0.49	13.0	0.49	0.0421	0.0284
91	13.3	0.35	14.5	0.83	0.0377	0.0146

Table 6 - Chloride diffusion coefficients obtained using the Migration Cell.

	Monroe County Bridge Deck Concrete	
Time [day]	Diffusion coefficients (m^2/s)	
	Plain Concrete	IC Concrete
28	8.56E-11	5.78E-11
91	7.67E-11	2.97E-11

The differences in the diffusion coefficients between the plain and internally cured concrete obtained by Stadium IDC are greater than that observed from the NT Built test method. For example, at an age of 91 days the internally cured concrete has an RCP value that is approximately half that of the plain concrete.

The porosity and the pore characteristics of the concrete play a fundamental role in the permeability and in general on the durability of the concrete. The effects of porosity and pore characteristics can be captured through a single parameter called tortuosity [28]. Tortuosity, in fact, depends on the connectivity of the pore system and represents an important physical quantity for understanding and modeling the transport phenomena that influences the durability performance [29]. STADIUM Lab also provides a measure of the tortuosity of the pore structure in concrete as shown in table 5. While the porosity for internally cured concrete is higher due to the presence of the lightweight aggregates, the tortuosity of the internally cured concrete is lower than that of the plain concrete presumably due to the increased hydration and densified interfacial transition zone in internally cured concrete.

6.5 Chloride Ponding and Profiling

Figures 11 through 13 show the acid-soluble chloride content of samples ponded with a 3% NaCl for a period test of 28 and 91 days, respectively.

Figure 11 shows the chloride content for the plain concrete and the internally cured concrete ponded for 28 days.

Within the first 8-10 mm the chloride concentration is greater in the internally cured mixture. This could be explained by the fact that the samples are cut, thereby exposing the pores of the lightweight aggregates at the surface of the sample. The chloride solution can be absorbed or diffuse into the LWA pores rapidly.

To confirm the artifact of the test method two samples were prepared, a plain concrete and internally cured concrete at an age of 91 days. The samples were not exposed to water as the other samples were however they were ponded for 15 minutes with a sodium chloride solution. The solution was then removed and the samples were ground. Figure 12 shows that both concretes absorb fluid. The internally cured concrete however absorbs more solution near the surface due to pores of the LWA being connected to the surface. Field concrete however does not have exposed aggregate and it appears that the increased concentration of the chloride at the surface is in part an experimental artifact of the test method. Additional testing is being done to better quantify this effect. Consequently, due to the higher concentration at the surface in the internally cured concrete it could be expected that the chloride concentration would have been for the entire profile higher compared to the plain concrete. However, as it can be seen from Figure 11 at depths greater than 8-10 mm the concentration of chloride is already similar for both mixtures. This confirms the results above where the diffusion coefficient for the internally cured concrete was found to be lower.

Figure 13 shows the experimental data after 91 days of ponding. The results show a similar trend observed for the mixtures ponded for 28 days with the internally cured concrete again showing a higher chloride concentration within the first 8 mm.

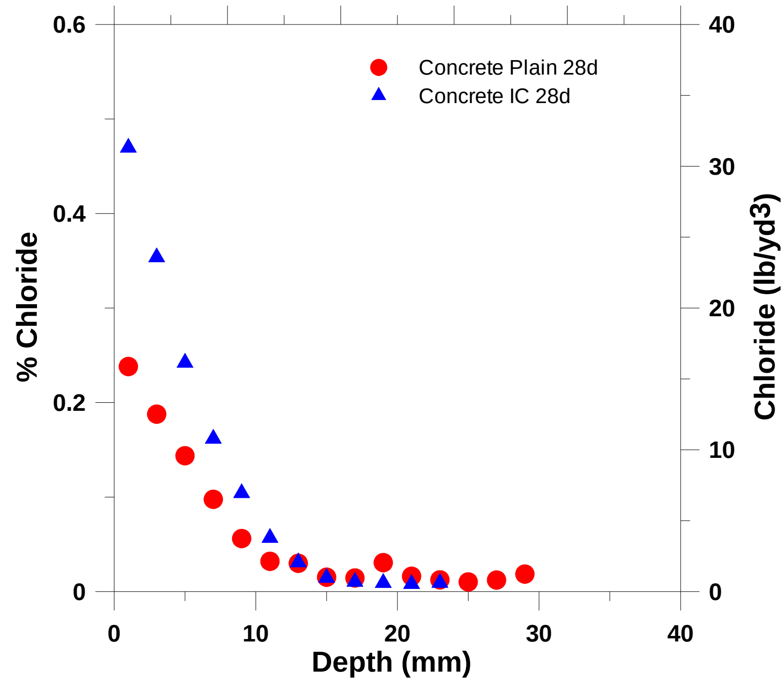

Figure 11 - Chloride content in a plain and internally cured concrete after 28 days of ponding.

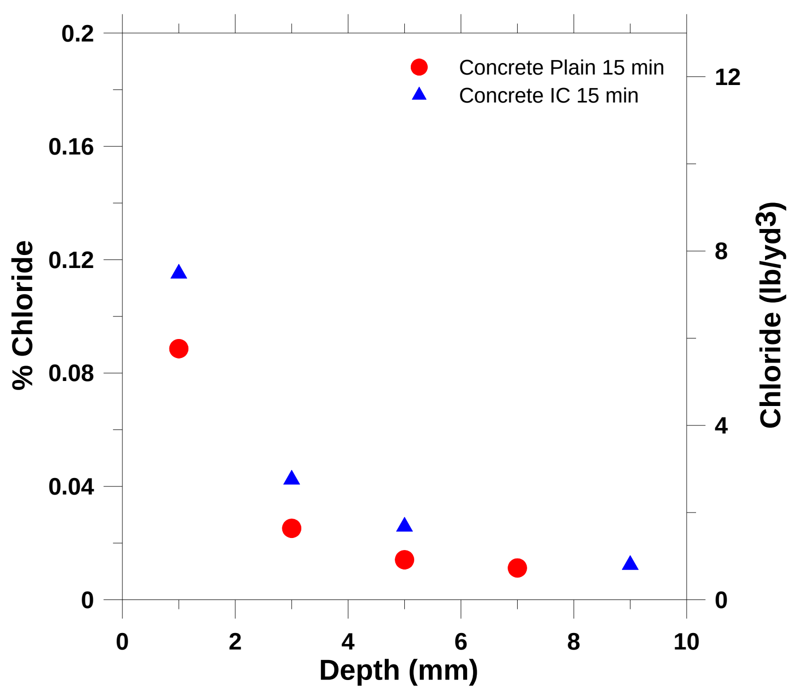

Figure 12 - Chloride content in a plain and internally cured concrete at 91 days after only 15 minutes of ponding.

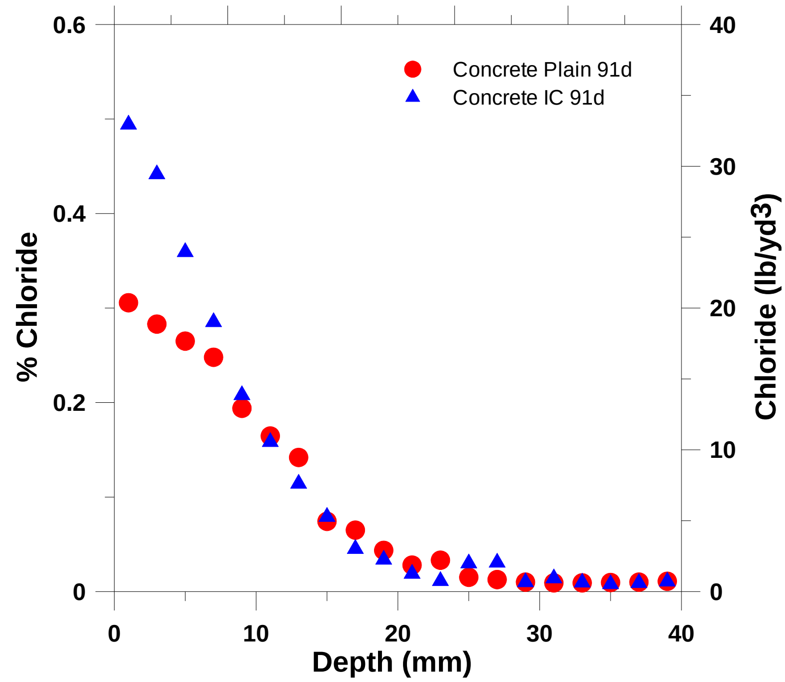

Figure 13 – Chloride content in a plain and internally cured concrete after 91 days of ponding.

7.0 SUMMARY AND CONCLUSIONS

This paper reports results from two concrete mixtures consistent with those used in field trials of concrete placed in bridge decks in Monroe County Indiana. The bridges were in close proximity to one another placed by the same contractor using similar materials and construction methods on consecutive days to obtain a direct comparison of the two mixtures. The first bridge deck was made using conventional concrete (i.e., plain concrete) that satisfied typical INDOT specifications while the second bridge deck was made using a similar mixture however the concrete had a portion of the fine aggregate replaced with an equivalent volume of prewetted lightweight aggregate to make an internally cured concrete. Samples from these mixtures were used to evaluate the chloride transport performance using a series of tests including: 1) resistivity, 2) rapid chloride penetration (RCP), 3) rapid chloride migration (the Nord Test), 4) migration cell testing and 5) chloride ponding and profiling. Tests were performed 28, 56, and 91 days after casting.

The diffusion coefficients measured the rapid chloride migration and the migration cell (STADIUM cell) showed that the internally cured concrete had a lower diffusion coefficient than the plain concrete (15% and 50%, respectively). The rapid chloride penetrability of the internally cured concrete is lower than the plain concrete at all the ages (approximately 35% at 91 days). The electrical surface resistivity of the internally cured concrete is higher than the RCPT measurements. Finally, the internal curing is able to reduce the diffusion coefficients of the conventional concrete. This demonstrates that the internally cured concrete has the ability to reduce transport properties. It is believed that this is due to increased cement hydration [30] and reduced porosity at the interfacial zone based on earlier studies.

While the all the electrical based tests showed benefits of using internal curing, it should be noted that some artifacts are believed to exist in the test that are caused by the presence of the prewetted lightweight aggregates. The use of the cut surface in samples prepared for the rapid chloride penetration (RCP), rapid chloride migration, migration cell testing and chloride ponding and profiling enable chloride to enter the lightweight aggregate at the surface which appears to influence the testing results. For example, the chloride penetration was observed to be higher in the internally cured concrete in the 6 to 8 mm near the surface. In addition, tests that use vacuum saturation enable water to fill the lightweight aggregate which allows them to behave as electrical conductors which reduces the resistivity of the concrete. Procedures are currently being developed to quantify these effects and to develop methodologies to account for these artifacts.

8.0 ACKNOWLEDGMENTS

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