Investigation of Deterioration of Joints in Concrete Pavements:

Field Study of Penetrating Sealers

Technical Report
March 2016

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16. Abstract

The objective of this research was to assess the efficacy of various waterproofing sealers applied to pavement joints with respect to limiting water ingress. The measure of water ingress was the chloride concentration profile as measured by scanning electron microscopy and energy dispersive spectroscopy.

The fieldwork was conducted at the MnROAD facility. Cores were retrieved from pavements to assess the before condition. Various silane- and siloxane-based sealers were applied in 2013, and the pavements were exposed to service for two years. After two years, cores were retrieved.

The chloride profiles for various pavement sites were compared before and after application of the sealer. No appreciable differences were noted. The lack of measured differences is attributed to the short time span allowed for ingress. The older pavements measured had a considerable degree of chloride ingress and, as such, small changes were difficult to detect. The newer pavement analyzed also showed no appreciable change, but it would be worth re-analyzing after more time has elapsed (e.g., two more years).

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INVESTIGATION OF DETERIORATION OF JOINTS IN CONCRETE PAVEMENTS: FIELD STUDY OF PENETRATING SEALERS

Technical Report
March 2016

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This project was done in conjunction with the Federal Highway Administration (FHWA) DTFH61-06-H-00011 (Work Plan 26) Investigation of Deterioration of Joints in Concrete Pavements project. This research was conducted under the FHWA Transportation Pooled Fund TPF-5(224) involving the following state departments of transportation (DOTs):

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EXECUTIVE SUMMARY

Background and Problem Statement

Over the past 10 to 15 years, state, county, and local agencies in wet freeze-thaw environments have seen a significant increase in premature joint distress in portland cement concrete (PCC) pavements. This distress has been attributed to a number of chemical and physical mechanisms, and the evidence is strong that ingress of water and deicers at the joints is integral to the problem. Research indicates that keeping the water and deicers from penetrating the concrete at the joints will reduce or eliminate the observed joint distress.

Objective

The objective of this research was to assess the efficacy of various waterproofing sealers applied to PCC pavement joints with respect to limiting water ingress.

Research Approach/Description

The fieldwork performed for this study was conducted at the Minnesota Department of Transportation (MnDOT) MnROAD facility on I-94 40 miles northwest of Minneapolis/St. Paul, Minnesota. The mainline section used is located on a 3.5 mile section of westbound I-94 and comprises a number of different evaluation cells with various pavement materials and designs that were placed between 1992 and 2011.

The operating premise for this evaluation was that permeation of water can be inferred by measuring the ingress of chloride ions, which are carried by deicing chemicals in the winter months and require water for transport into the concrete. The chloride concentration profile was measured by scanning electron microscopy and energy-dispersive spectroscopy (EDS).

Cores were retrieved from pavements to assess the before condition. Six-inch cores were extracted immediately adjacent to the selected joints. All cores were extracted from the approach side of each joint, with respect to traffic. Cores were positioned so the edge of the expansion joint just intersected the perimeter of the core. Five cores were taken from different joints in each cell, with one joint to serve as the control and the other four to have different sealers applied.

Various silane- and siloxane-based sealers were applied in 2013 to study the protection of joints, and the pavements were exposed to service for two years. After two years, cores were retrieved.

The cores were cut into 1/2 in. thick slabs, and the slabs were cut in a pattern to produce billets for chloride profiling in planes normal to (vertical) and parallel with (horizontal) the wear surface. The chloride profiles for various pavement sites were compared before and after application of the sealers.

A form of Fick's second law of diffusion incorporating a background concentration term was used to fit a curve to the measured profiles. This form of the law was used because EDS measures total chlorine signal and cement paste natively contains a small but detectable concentration of chlorine that must be accounted for.

While obtaining cores in 2015, a visual inspection of all three cells and digital-image documentation of all joints was performed.

Key Chloride Profiling Findings

All of the chloride diffusivities are the same order of magnitude, indicating no measurable difference between 2013 and 2015.

In general, the horizontal profiles from the older pavement in Cells 8 and 9 (23 years old as of the time of coring in 2015) demonstrate a noisy concentration gradient only poorly fit using Fick's second law. The uniformly lower initial concentration of chloride in the horizontal profiles compared to their vertical counterparts suggests a more diluted salt solution is present in the joint than is present on the wearing surface. This may indicate the seal system mitigates the flow of water/salt solution into the joint, even when compromised.

The chlorine concentration gradients in the vertical direction in the 23 year old pavement are generally nicely fit by Fick's second law, with inflection points uniformly occurring at a depth of approximately 50 mm.

Both the horizontal and vertical profiles in the four-year-old unbonded concrete overlay in Cell 505 are nicely fit by Fick's second law. Inflection occurs in both the vertical and horizontal directions at a distance of approximately 20 mm from the exposed surfaces. These profiles are predictably steep and uniformly have higher initial concentrations than those found in the pavement in Cells 8 and 9.

In contrast to the 23 year old pavement, the initial concentration in the horizontal direction of Cell 505 is the same as that found in the vertical direction, suggesting the dilution evident in the older pavements does not take place in Cell 505. The joints in Cell 505 were not sealed with silicone or hot pour asphalt, and the concrete overlay was placed over a separation fabric. The lack of sealing permits free entry of salt solution and debris from the wearing surface into the joint.

The low diffusivities mean that very little change in the concentration profile has taken place even over the two years separating the collection of cores evaluated in this study, regardless of the age of the pavements or whether sealer was applied.

The younger concrete overlay in Cell 505 should be more sensitive to changes in diffusivity given the greater driving force resulting from a higher concentration gradient, but no clear difference is apparent in the profiles. Further exacerbating analysis of the data is the small sample population. The apparent variations are likely stochastic.

Conclusions

- The older pavements measured had a considerable degree of chloride ingress and therefore small changes were difficult to detect.

- The method employed for generating chlorine profiles appears to be effective. The premise that determining chloride diffusivity as a proxy for measuring water permeation is theoretically sound, even though the results from this limited study are inconclusive.

- Because there is no clearly apparent difference in the chlorine concentration profiles between 2013 and 2015, it is not possible to determine with any certainty the performance of the various waterproofing sealers applied for this study. This is as much due to the short timeframe of the study as to any other reason.

- The difference in initial concentration between the vertical and horizontal profiles of the 23 year old pavements may indicate that silicone joint seals mitigate the joints' exposure to water from the wearing surface. This is especially apparent considering that the horizontal and vertical profiles from the four-year-old concrete overlay, which had no joint seals, showed no difference in initial concentration. Therefore, the results suggest that joint seals are effective at limiting water ingress into the concrete.

Implementation Benefits

The use of penetrating sealers on PCC pavements may improve freeze-thaw durability by reducing the amount of water permeating the concrete. This may be particularly beneficial in concrete immediately adjacent to joints, where two perpendicular surfaces permit water to enter simultaneously and where freeze-thaw distress tends to be concentrated.

Implementation Readiness/Future Research

- Given the limited time and scope of this project, the results should not be seen as absolutely conclusive with respect to the performance of penetrating sealers. The newer pavement analyzed showed no appreciable change, but it would be worth re-analyzing after more time has elapsed.

- Given the significant level of chloride ingress observed in Cells 8 and 9, further measurements of chloride ingress would likely not yield any conclusive results. However, extraction of cores from Cell 505 in 2017, after another two seasons' of exposure, may provide data indicating a trend.

- Future research should focus on developing the means to directly measure water ingress by some means other than chloride ingress. Ideally, the moisture content at any time could be determined in situ, using a non-destructive test, allowing for continual monitoring of moisture content. Such measurements could provide a rapid way to monitor sealer or sealant efficacy.

INTRODUCTION

Over the past 10 to 15 years, there has been a significant increase in premature joint distress for portland cement concrete (PCC) pavements in wet freeze-thaw environments. This distress has been attributed to a number of chemical and physical mechanisms, and there is strong evidence that ingress of water and deicers at the joints is integral to the problem. Research indicates that keeping the water and deicers from penetrating the concrete at the joints will reduce or eliminate the observed joint distress.

The use of penetrating sealers on PCC pavements may improve freeze-thaw durability by reducing the amount of water permeating the concrete. This may be particularly beneficial in concrete immediately adjacent to joints, where two perpendicular surfaces permit water to enter simultaneously and where freeze-thaw distress tends to be concentrated.

Objective

The objective of this limited study was to assess the efficacy of various waterproofing sealers applied to joints. The operating premise for this evaluation is that permeation of water can be inferred by measuring the ingress of chloride ions, which originate from water-based deicing chemicals used for winter maintenance. It was known at the beginning of this research that, given the limited time and scope of this project, any results would be partial and not absolutely conclusive with respect to the performance of penetrating sealers.

Approach

The fieldwork performed for this study was conducted at the MnROAD facility on I-94 40 miles northwest of Minneapolis/St. Paul, Minnesota. The mainline section used is located on a 3.5-mile section of westbound I-94 and is comprised of a number of different evaluation cells with various pavement materials and designs that have been placed between 1992 and 2011. To accomplish the objective of this research, the following general approach was used:

1. Select the pavement sections to be studied.
2. Perform a visual assessment of the joints in each selected test cell, photo-document the condition of all joints in each test cell, and select specific joints for further study.
3. Remove core samples from specific joints selected for further study (August 2013).
4. With assistance from the manufacturers, remove existing silicone sealants, apply selected penetrating sealers, and replace silicone sealants.
5. Perform chloride profiling of specimens prepared from the joints selected for further study.
6. After two winter seasons, return to MnROAD to photo-document the condition of all joints in each test cell and select specific joints for secondary study.
7. Remove core samples from the specific joints selected for secondary study (July 2015).
8. Perform chloride profiling of the specimens prepared from the joints selected for secondary study.
9. Compare the measured chloride profile for the selected cores.

The cells selected for study were as follows:

1. Cell 8, placed in September 1992 and a traditional grind profile applied in 2007
2. Cell 9, placed in September 1992 but with an ultimate grind applied in 2007
3. Cell 505, having a 5 in. unbonded concrete overlay applied in 2011 over cracked PCC pavement originally placed in 1993

The specific designs of each cell are summarized in Table 1.

Table 1. Design characteristics of the selected test cells

Characteristic	Cell 8	Cell 9	Cell 505
Thickness	7.5 in.	7.5 in.	5 in. UBOL
Base	4 in. PASB	4 in. PASB	Fabric separator and7.5 in. cracked 1993 PCC*
Subbase	3 in. Class 4	3 in. Class 4	3 in. Class 4over 27 in. of Class 3
Joint Spacing	15 ft	15 ft	6 × 7 ft panels
Surface Grind	Traditional Grind	Ultimate Grind	Transverse Broomed
Dowels	1 in.	1 in.	none

* Joints were artificially broken to mimic older distressed joints
PASB: permeable asphalt stabilized base
PCC: portland cement concrete
UBOL: unbonded overlay

Representative images of each cell are shown in Figure 1 through Figure 3.

Len Palek, MnROAD Mainline Cells, June 2014, www.dot.state.mn.us/mnroad/pdfs/MainlineJune2014Cells.pdf

Figure 1. Representative images of Cell 8, June 2014

Len Palek, MnROAD Mainline Cells, June 2014, www.dot.state.mn.us/mnroad/pdfs/MainlineJune2014Cells.pdf

Figure 2. Representative images of Cell 9, June 2014

Len Palek, MnROAD Mainline Cells, June 2014, www.dot.state.mn.us/mnroad/pdfs/MainlineJune2014Cells.pdf

Figure 3. Representative images of Cell 505, June 2014

Additional image documentation of the joint condition for each cell is provided in Appendix A.

Five transverse joints were cored in each cell. One core served as the control, while the remaining four were to have one of five different waterproofing sealers applied to them. An initial set of cores was collected on August 18, 2013, with a second set collected two years later on July 13, 2015, permitting the comparison of chloride diffusion in those pavements to which a waterproofing sealer was applied with those to which no sealer was applied.

Six-inch cores were extracted immediately adjacent to the selected joints. Cores were positioned such that the edge of the expansion joint just intersected the perimeter of the core. Example cores are shown in Figure 4.

Figure 4. Example cores retrieved in 2013 showing the relationship of the core next to the joint: Joint 105, Cell 9 (left) and Joint 4241, Cell 505 with fabric bond-breaker (right)

All cores were extracted from the approach side of each joint, with respect to traffic. For each cell, selected joints were identified and given a label simply to randomly distribute the selected joints between the various sealer types. The coring pattern for a given cell is shown in Figure 5.

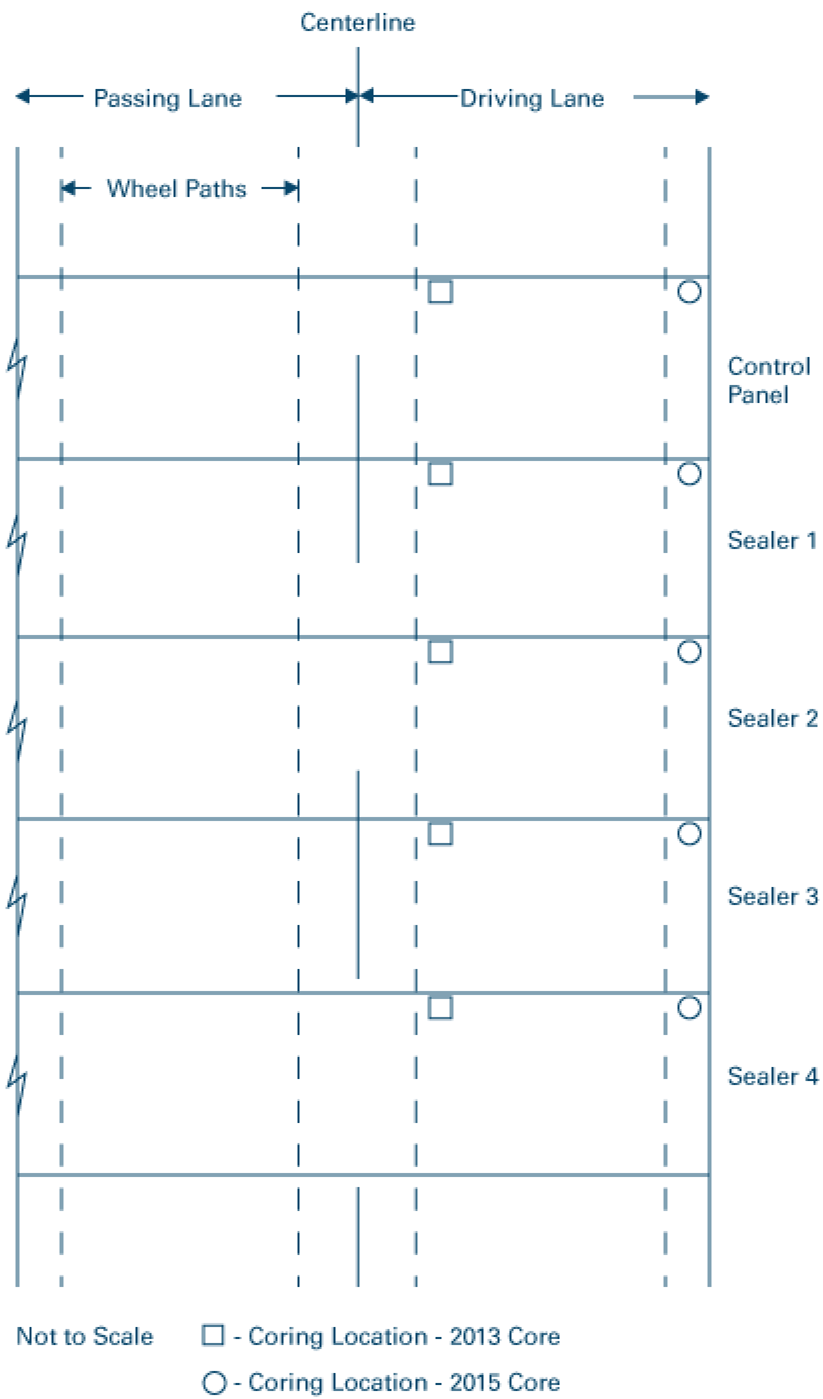


Figure 5. Schematic representation of the coring pattern used for the project

Cores removed in 2013 were obtained from the inside wheel path. Cores obtained in 2015 were obtained from the outside wheel path. The joint labeled Control for each slab was cored as-is both before and after application of the sealer. Joints labeled Sealer 1 through Sealer 4 are joints from each slab assigned to different sealer types.

Note that Figure 5 is a schematic drawing and shows identified joints as being contiguous, which was not the case. In most cases, the joints were not contiguous. Joints that were deemed beyond salvage by application of a sealer were omitted from the study in favor of joints that still appeared to have remaining performance life. Also note that, for Cells 8 and 9, in some cases, the silicone sealants present were compromised while in some cases they were still intact. For Cell 505, the joints were never sealed.

The five waterproofing sealers applied were assigned identification numbers (IDs) S0 through S4. Application methods also varied and are summarized with their identifiers in Table 2.

Table 2. Pretreatment application overlap distances and their identification

Pretreatment Application Overlap Distance	ID
12 inches	A
8 to 12 inches	B
6 inches	C
24 inches	D

Cells and the joints that were treated and/or cored are summarized in Table 3.

Table 3. Joints cored and/or treated with waterproofing sealer during the summer of 2013

Cell	Joint	Pretreatment	Overlap	Cored 2013	Cored 2015	Seal
8	96	Control		X	X	
8	98	S0	A		X	Silicone 888
8	99	S4	B	X	X	Silicone 888
8	105	S2	C	X	X	Silicone 888
8	109	S3	B	X	X	Silicone 888
8	117	S2	C	X		Silicone 888
8	125	S3	B		X	Silicone 888
9	141	Control		X	X	Existing
9	142	S2	C	X		None
9	144	S0	D		X	Silicone 888
9	150	Not used		X		Silicone 888
9	151	Not used		X		Silicone 888
9	155	S1	B		X	Silicone 888
9	158	S4	B		X	Silicone 888
9	160	S3	B	X	X	Silicone 888
505	4236	S2	C	X	X	None
505	4238	S4	B	X	X	None
505	4240	S1	C	X	X	None
505	4241	Control		X	X	None
505	4242	S3	B	X	X	None

The waterproofing sealers were applied by the manufacturer after the existing silicone sealant had been manually removed and the joint face (near the surface) was prepared by either grinding, diamond sawing, or shot blasting. Some images of the installation process are shown in Figure 6.

Figure 6. Sealer installation including sawing (upper left) and sealer application

All joints labeled Control were left unaltered. For the joints that were tested, in most cases, sealants were replaced using Dow Corning 888 Silicone. In some case, joints were left unsealed, and the seal is shown in Table 3 as None.

LABORATORY ANALYSIS – CHLORIDE PROFILING

An approximately 1/2 in. thick slab was cut from each core with a kerosene-cooled precision cutoff saw. Slabs were cut perpendicular to the joint at approximately the axial center of the cylinders so that they had a portion of the joint along one side. Slabs were dried in a forced convection oven at 50°C, dusted with compressed air, and labeled.

Slabs were marked for cutting in a pattern to produce billets for chloride profiling in planes normal (vertical) to and parallel (horizontal) with the wear surface. A slab marked for cutting is shown in Figure 7.

Figure 7. Slab marked for cutting into billets, showing billet orientations

The location of the billets was selected such that the horizontal profile was nearly centered on the base of the joint saw cut. The vertical profile was taken just more than 10 cm from the joint. The billets were cut from the slabs with a kerosene-cooled thin section cutoff saw and dried in a 38°C natural convection oven or a 50°C forced convection oven. The billets were labeled, and working glass was affixed to the backside of the billets. Billet faces were then plane ground with a mineral oil-cooled thin section cup grinder. The billets were rinsed with kerosene, blown off with compressed air, and placed in a 38°C natural convection oven or a 50°C forced convection oven to dry.

Following drying, the billets were dusted with compressed air and a small piece of copper foil tape was affixed to the face of a coarse aggregate particle. All five billets from a single slab were simultaneously placed in a FEI XL40 environmental scanning electron microscope (ESEM). The ESEM was operated in low-vacuum water mode at a pressure of 0.3 torr with an accelerating voltage of 15kV and a spot size producing an x-ray count rate suitable for energy-dispersive spectroscopy (EDS) x-ray analysis at a working distance of 10 mm. X-ray spectra were collected with an Oxford PentaFETx3 Inca EDS detector and anaylzed using Oxford Inca software.

Using backscatter electron (BSE) images, sample sites were selected where the field of view at a magnification of 800x was filled entirely with cement paste. The BSE signal produces an image having compositional contrast. That is, the greyscale intensity varies with the composition of the material the electron beam impinges upon. Paste is easily discriminated from aggregate because each produces BSE images with very different and unique textures. Sample points were selected along as near to a vertical or horizontal line as possible (depending on the orientation of the profile of interest), deviating around voids and aggregate as necessary. Spectra were collected for the entire field of view at 800x magnification so as to area-average the resulting spectrum.

Initially, spectra were collected at 2 mm intervals in the billet nearest the exposed surface, with the intervals increasing to 4 mm for the subsequent two billets. This produced between 30 and 48 sample points for each of the vertical and horizontal chloride profiles. Evaluation of the data collected indicated that the spacing between sample intervals could be doubled without sacrificing precision. Subsequent analyses were performed, with a total sample size of between 20 and 24 points and sample intervals of 4 mm and 8 mm. Because the billet nearest the wear surface tended to extend only about 25 mm into the pavement (due to the location of the base of the joint saw cut), the second billet in the vertical series was also sampled at the smaller of the two sample intervals to improve the probability of detecting the chlorine concentration profile's inflection point.

ESEM specimen stage locations were used to establish distances based upon a datum defined to be the intersection of the exposed surface with the ground face of the billet. That is, the datum for a vertical profile was established as the intersection of the wear surface with the ground face of the billet containing the wear surface. Because neither the wear surface nor the cracked expansion joint have a planar intersection with the ground surface, an "average" location was established as datum. The kerf produced by the thin section saw used to cut the billets was approximately 3 mm and was accounted for during generation of the profile.

An internal calibration method was used to determine chlorine concentration, wherein the k-ratio for chlorine divided by the k-ratio for calcium, from a given spectrum, served as the basis for calculating chlorine concentration. The k-ratio is the x-ray intensity of a given element divided by the x-ray intensity produced by that element's pure element standard. A calibration curve was produced using mortars prepared with known amounts of chlorine and a fixed water-cement (w/c) ratio of 0.45.

As a quality control step, the beam current was monitored by collecting spectra from the copper foil on a regular basis. All measured intensities are normalized to the pure copper x-ray intensity. By this means, variations in the electron beam current from sample to sample are eliminated.

Fick's second law of diffusion was used to fit a curve to the measured profile ((1).

$$C_{z,t} = C_s - (C_s - C_0) \times \operatorname{erf}\left(\frac{z}{\sqrt{2Dt}}\right) \tag{1}$$

Where:

$C_{z,t}$ = Concentration at time t and depth z, wt.%
C_s = Initial concentration, wt.%
C_0 = Background concentration in the cement paste, wt.%
z = depth, m
D = Diffusivity, m^2/s
t = time, s
erf = the error function

This form of Fick's second law incorporating the background concentration term was used because EDS measures total chlorine signal. Other chloride profiling methods typically measure only water-soluble chloride. Because cement paste natively contains a small but detectable concentration of chlorine, it must be accounted for.

Initial chloride concentration was estimated by extrapolating the curve towards the exposure surface. Background concentration was determined by averaging a portion of the horizontal portion of the concentration profile.

The value of diffusivity (*D*) was arrived at numerically by minimizing the sum of the squares of errors for all sample points in a given profile (a least squares fit). The resulting diffusivity was then used to produce a predicted chlorine concentration profile for a given specimen. Spurious data points were eliminated from the profile; typically, only two or three points were eliminated per profile.

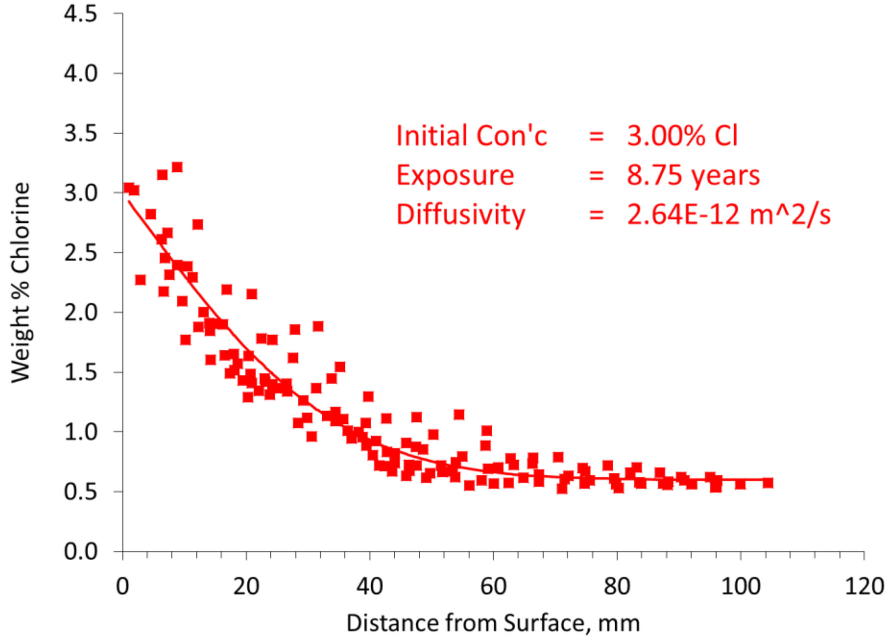
Because chloride exposure is seasonal, occurring only during the winter, the exposure time was estimated to be five months out of every calendar year. The total chloride exposure time is therefore 5/12 the overall age of the pavement.

The hypothesis being tested was that application of waterproofing sealers will decrease permeation of water into the cement paste, effectively decreasing the diffusivity of chloride ions in that same cement paste. In order to test the hypothesis, the diffusivity of chloride was compared pre- and post-application of waterproofing sealers. The 2013 average chloride diffusivities and chlorine concentration profiles for both the vertical and horizontal directions for each cell were established as the baseline pre-application values to which the 2015 individual profiles in that same cell were compared. For example, all of the vertical chloride diffusivities from the five cores collected from Cell 8 were averaged and used to produce an average pre-application chlorine concentration profile. That average profile was then compared to the individual chlorine concentration profiles in cores collected from Cell 8 in 2015.

RESULTS AND DISCUSSION

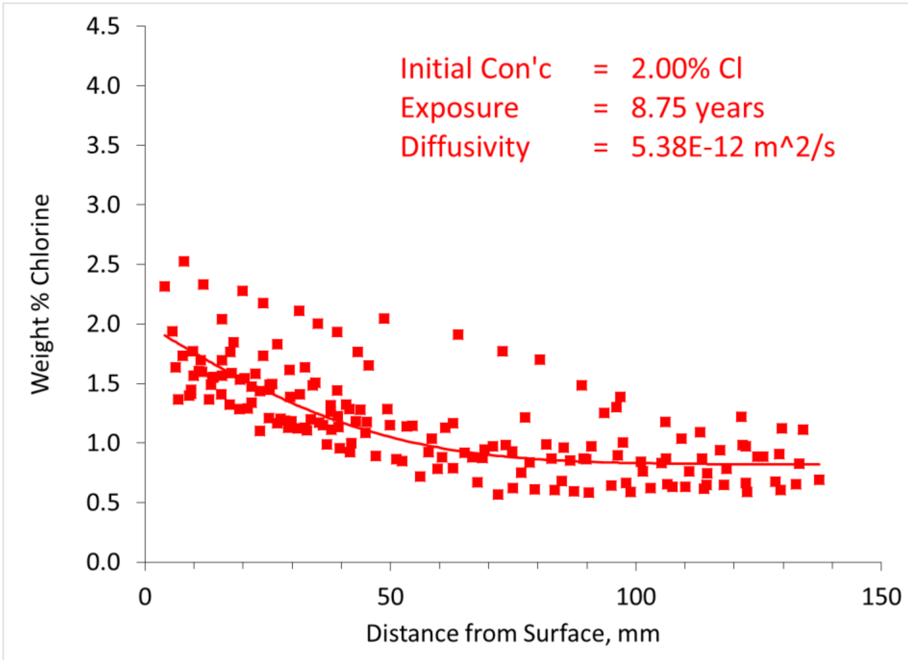
Chloride Profiling

The compiled 2013 chlorine concentration profiles and chloride diffusivities for each of the three cells tested (Cells 8, 9, and 505) are presented in Figures 8 through 13.



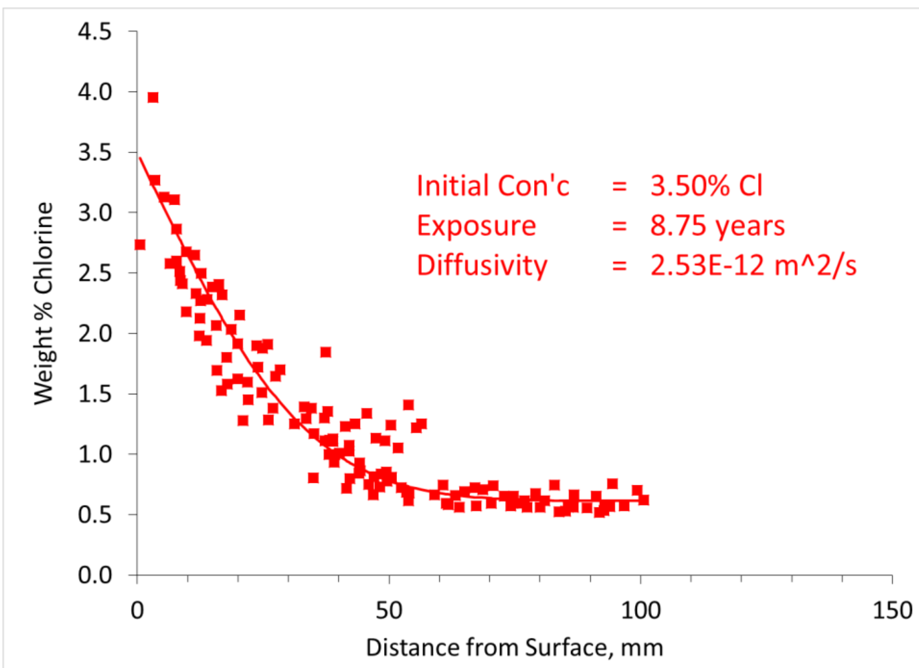
Five cores were analyzed to produce this profile

Figure 8. Cumulative chlorine profile in the vertical direction, Cell 8, 2013



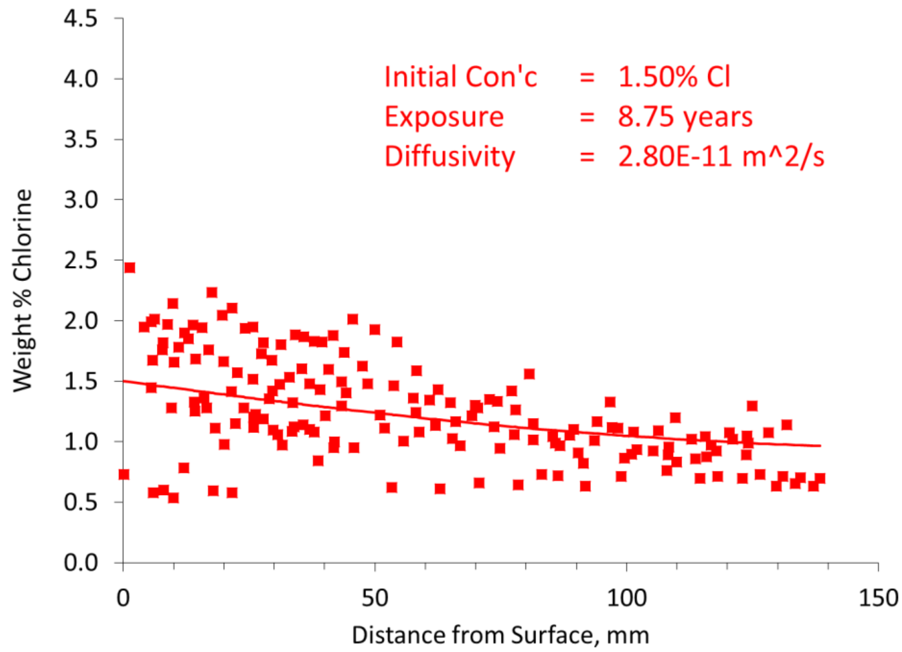
Five cores were analyzed to produce this profile

Figure 9. Cumulative chlorine profile in the horizontal direction, Cell 8, 2013



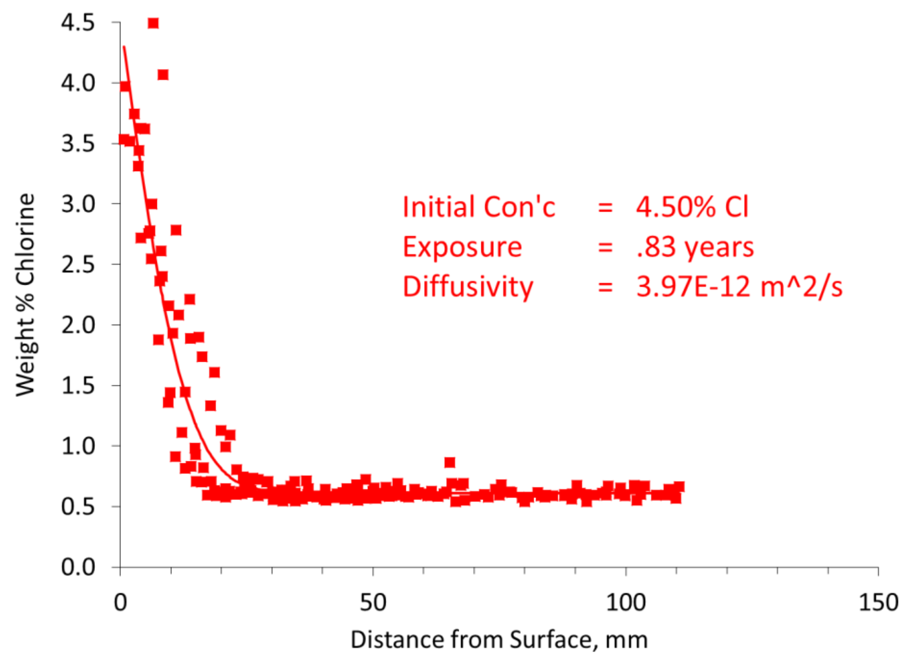
Five cores were analyzed to produce this profile

Figure 10. Cumulative chlorine profile in the vertical direction, Cell 9, 2013



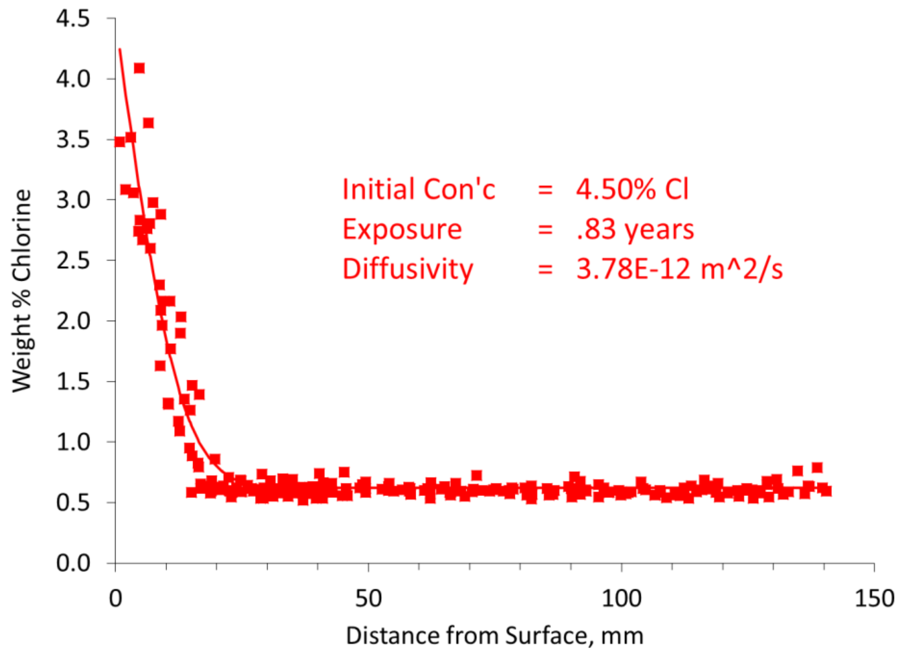
Five cores were analyzed to produce this profile

Figure 11. Cumulative chlorine profile in the horizontal direction, Cell 9, 2013



Five cores were analyzed to produce this profile

Figure 12. Cumulative chlorine profile in the vertical direction, Cell 505, 2013



Five cores were analyzed to produce this profile

Figure 13. Cumulative chlorine profile in the horizontal direction, Cell 505, 2013

These results established the pre-application baselines that individual profiles from their respective cells were compared.

Chlorine concentration profiles for each of the cores collected in 2015 and their respective baseline profiles, collected in 2013, are presented in Figures 14 through 45.

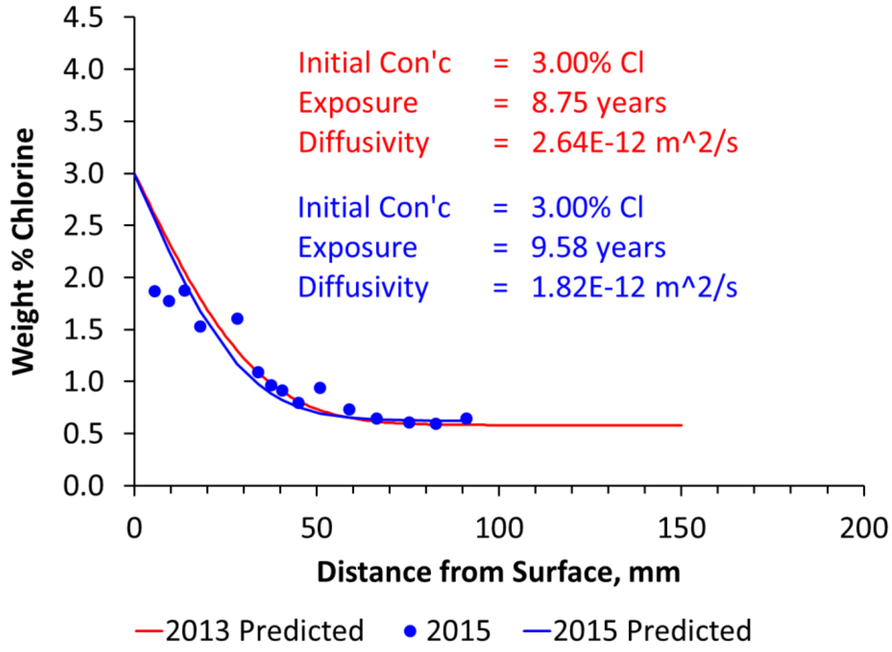


Figure 14. Chlorine profile in the vertical direction from Joint 96 (control) Cell 8 with no sealer applied

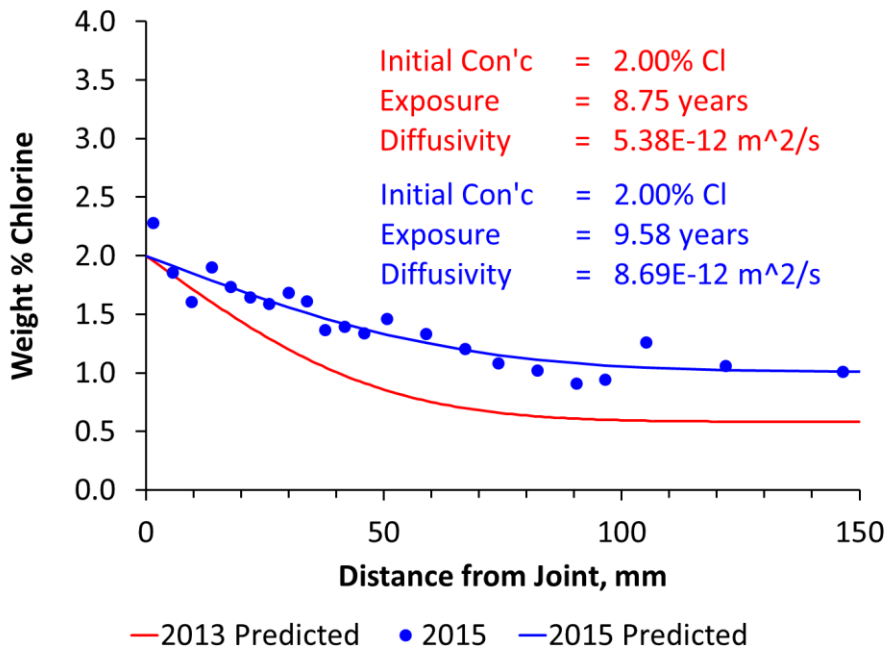


Figure 15. Chlorine profile in the horizontal direction from Joint 96 (control) Cell 8 with no sealer applied

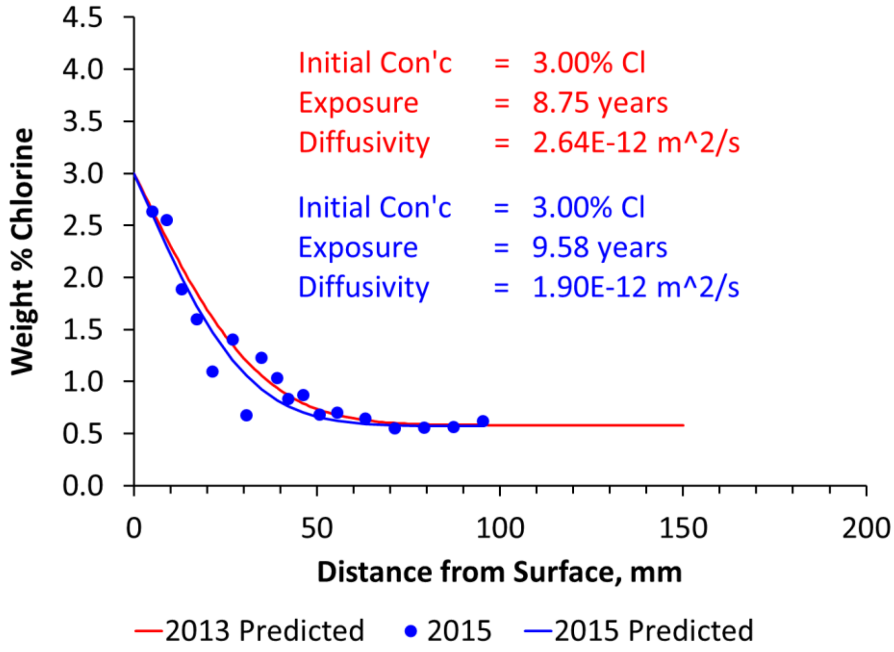


Figure 16. Chlorine profile in the vertical direction from Joint 98 Cell 8 treated with sealer S0, August 19, 2013

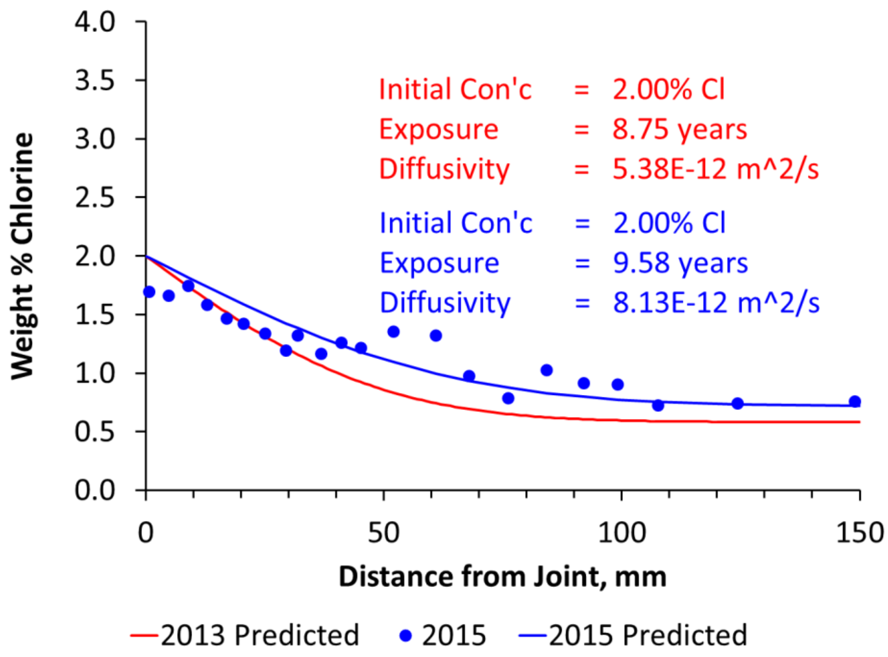


Figure 17. Chlorine profile in the horizontal direction from Joint 98 Cell 8 treated with sealer S0, August 19, 2013

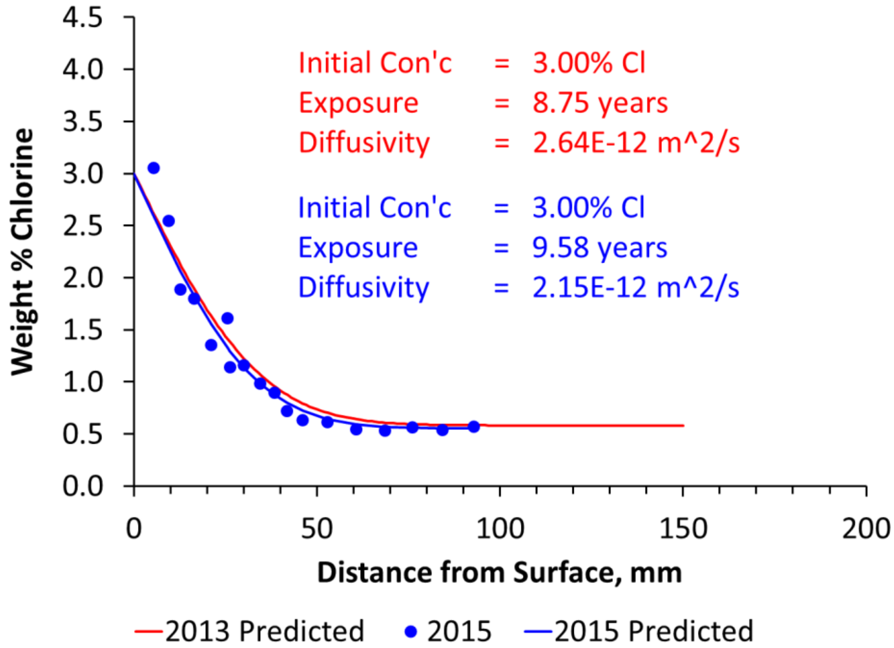


Figure 18. Chlorine profile in the vertical direction from Joint 99 Cell 8 treated with sealer S4, August 19, 2013

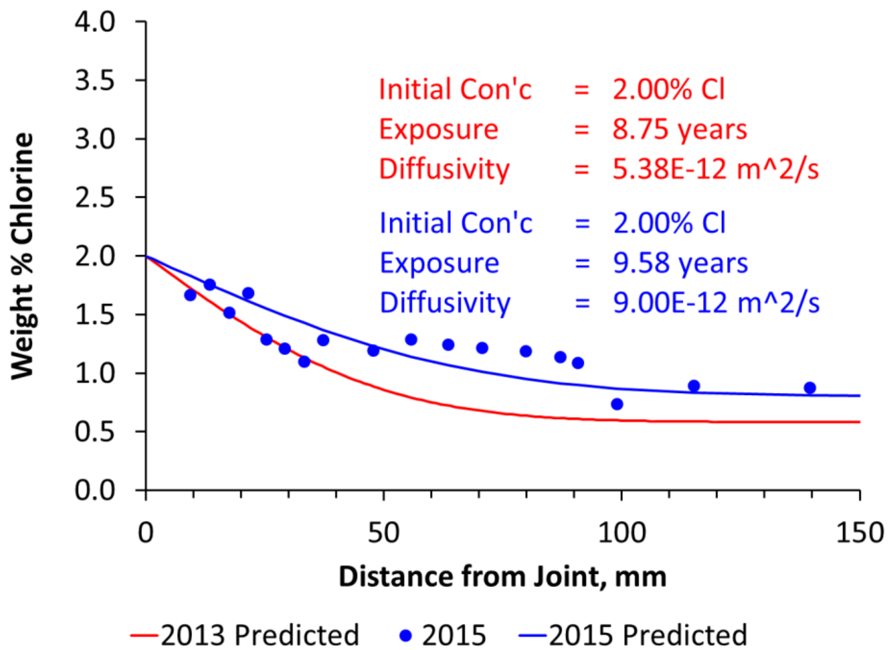


Figure 19. Chlorine profile in the horizontal direction from Joint 99 Cell 8 treated with sealer S4, August 19, 2013

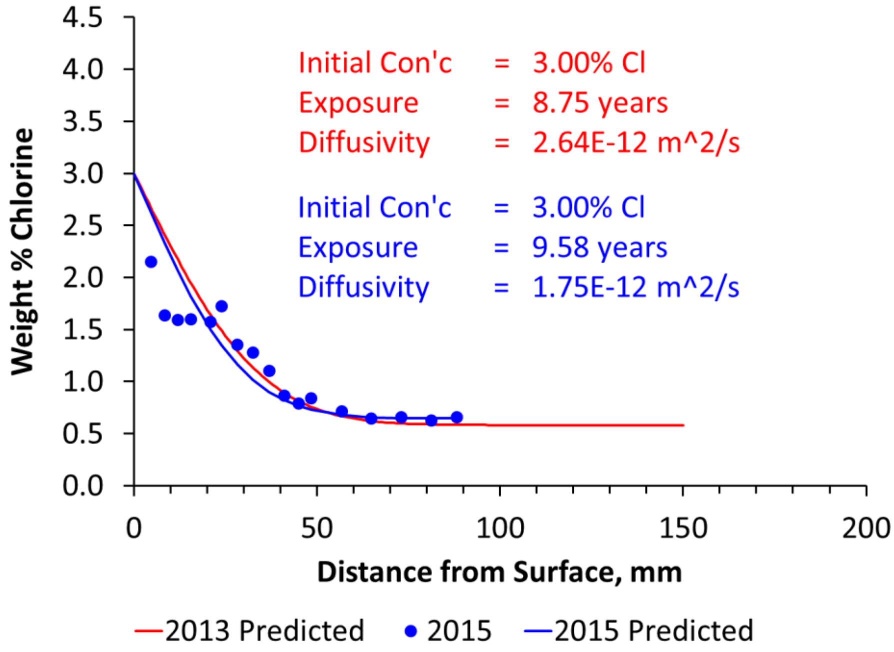


Figure 20. Chlorine profile in the vertical direction from Joint 105 Cell 8 treated with sealer S2, August 19, 2013

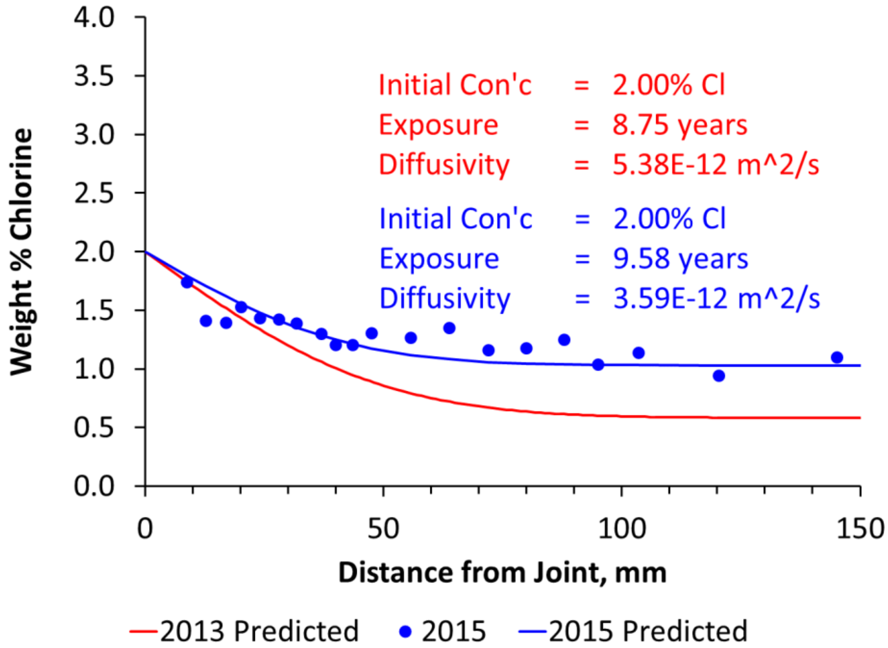


Figure 21. Chlorine profile in the horizontal direction from Joint 105 Cell 8treated with sealer S2, August 19, 2013

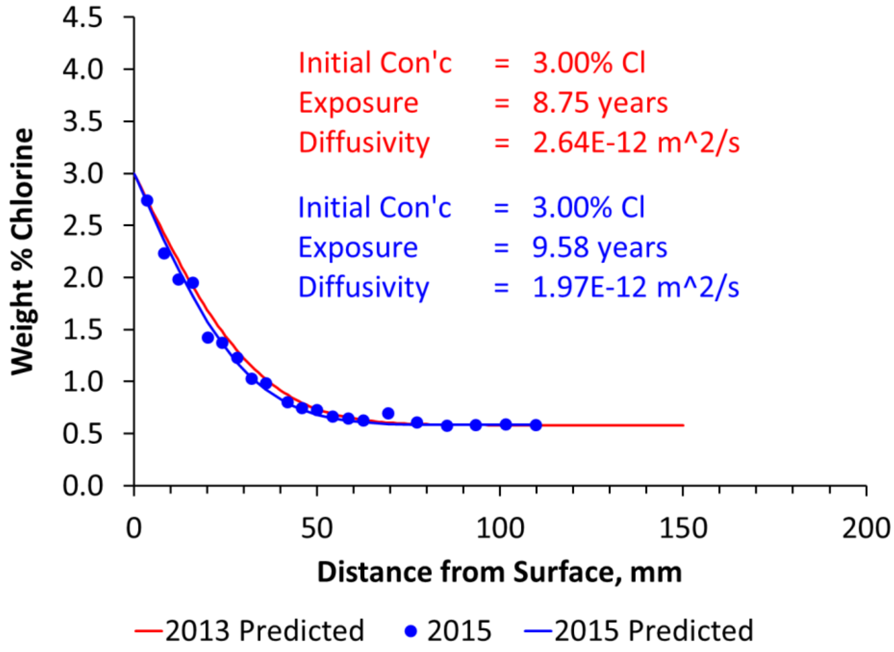


Figure 22. Chlorine profile in the vertical direction from Joint 109 Cell 8 treated with sealer S3, August 19, 2013

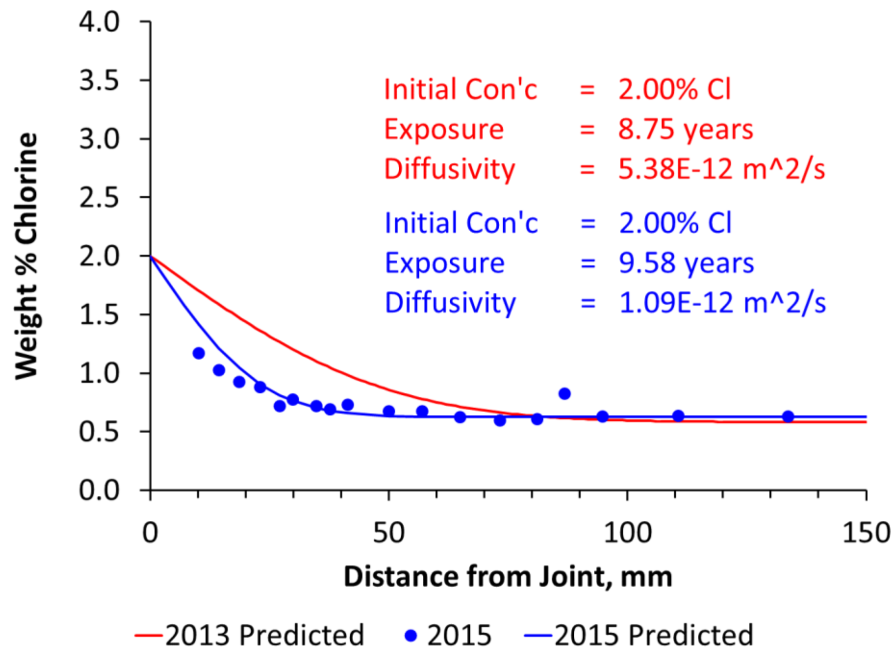


Figure 23. Chlorine profile in the horizontal direction from Joint 109 Cell 8 treated with sealer S3, August 19, 2013

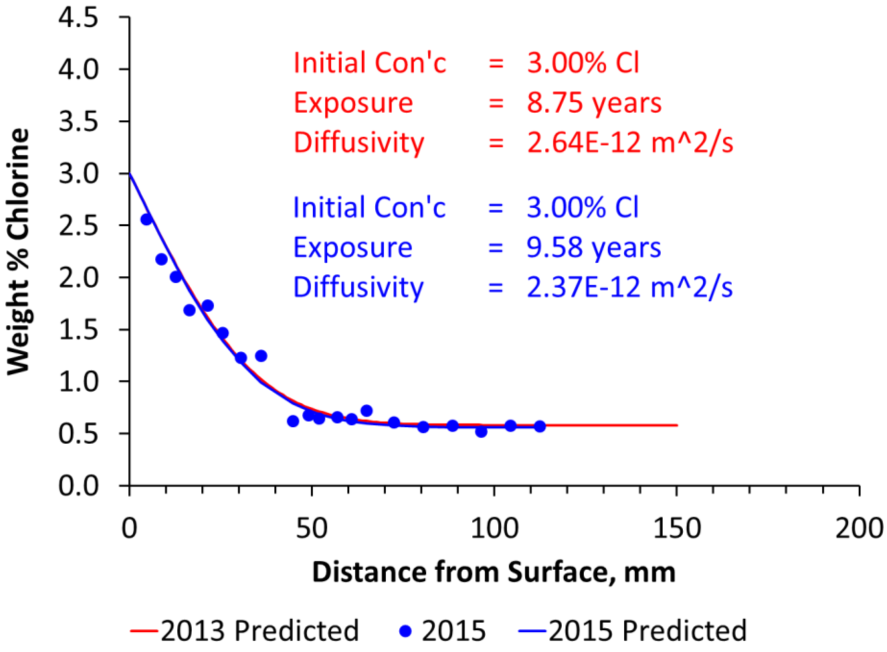


Figure 24. Chlorine profile in the vertical direction from Joint 125 Cell 8 treated with sealer S3, August 19, 2013

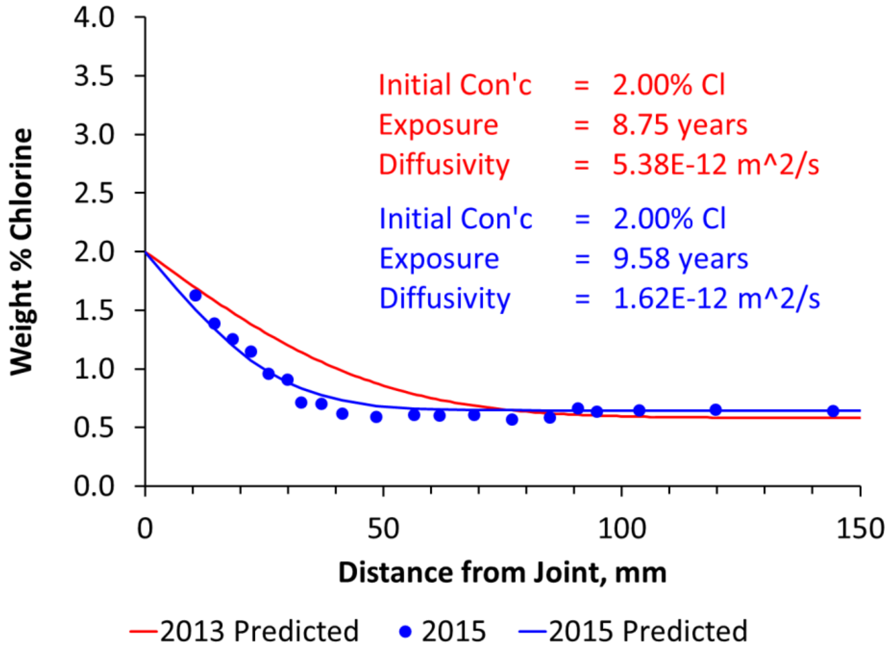


Figure 25. Chlorine profile in the horizontal direction from Joint 125 Cell 8 treated with sealer S3, August 19, 2013

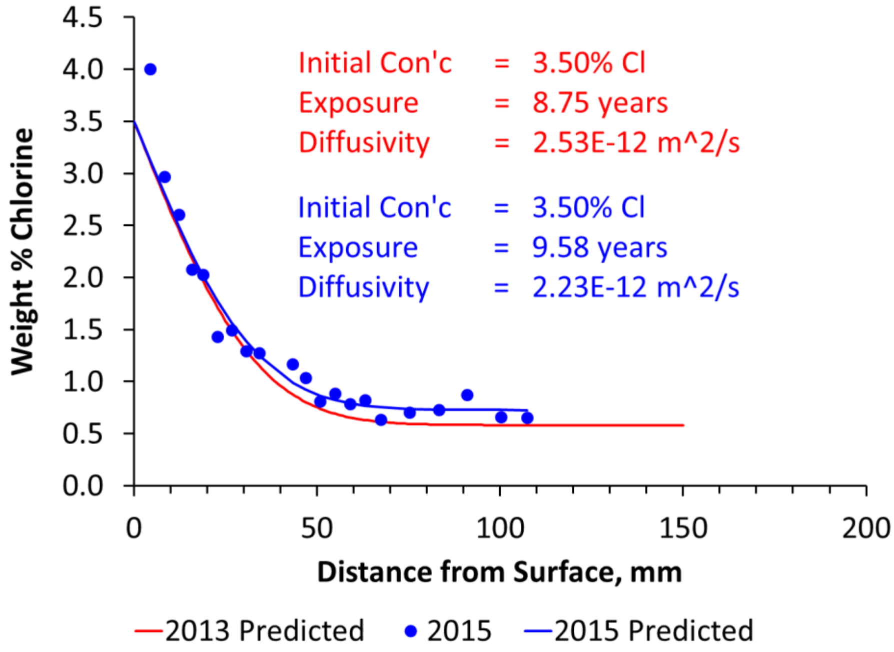


Figure 26. Chlorine profile in the vertical direction from Joint 141 (control) Cell 9 with no sealer applied

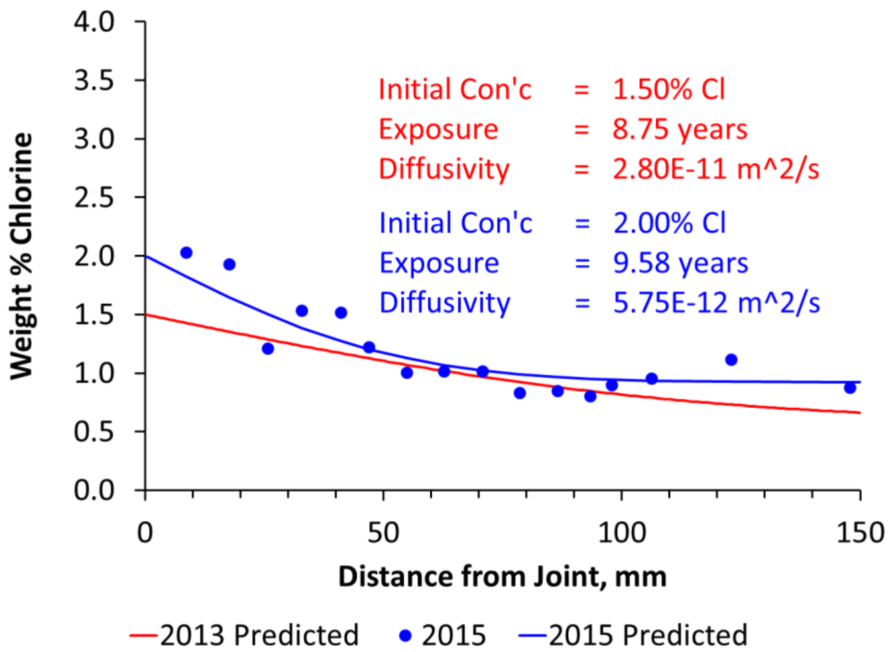


Figure 27. Chlorine profile in the horizontal direction from Joint 141 (control) Cell 9 with no sealer applied

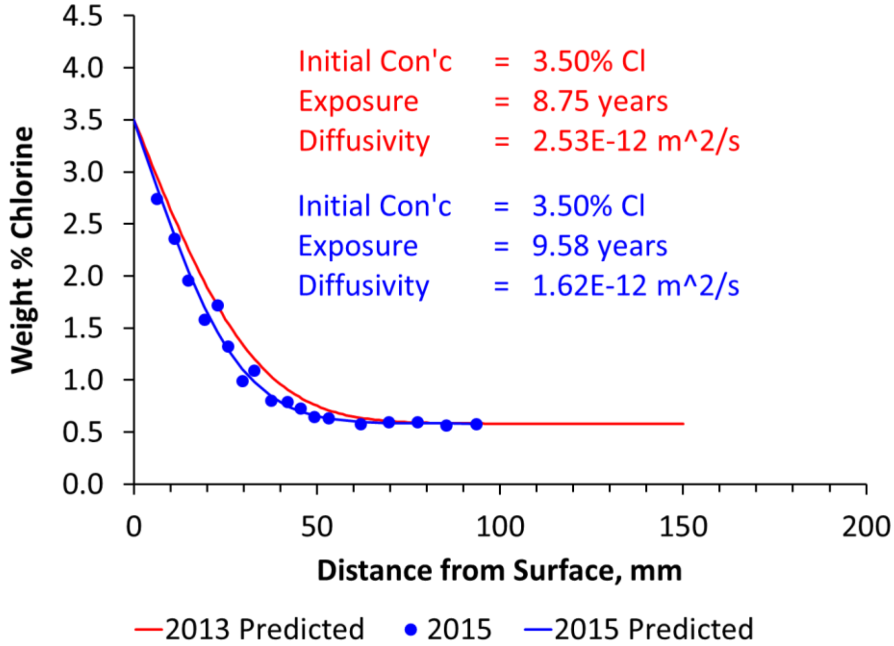


Figure 28. Chlorine profile in the vertical direction from Joint 144 Cell 9 treated with sealer S0, August 19, 2013

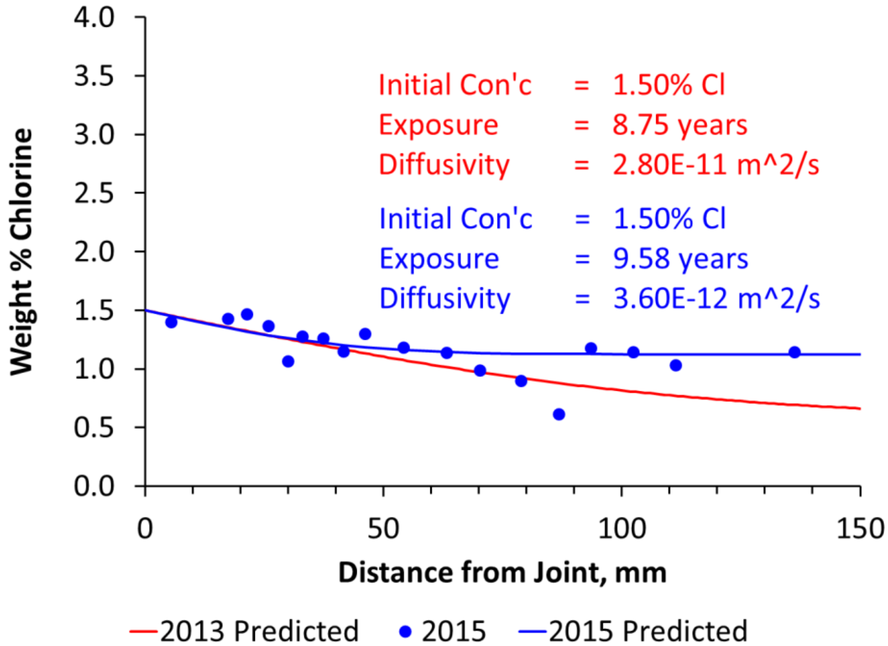


Figure 29. Chlorine profile in the horizontal direction from Joint 144 Cell 9 treated with sealer S0, August 19, 2013

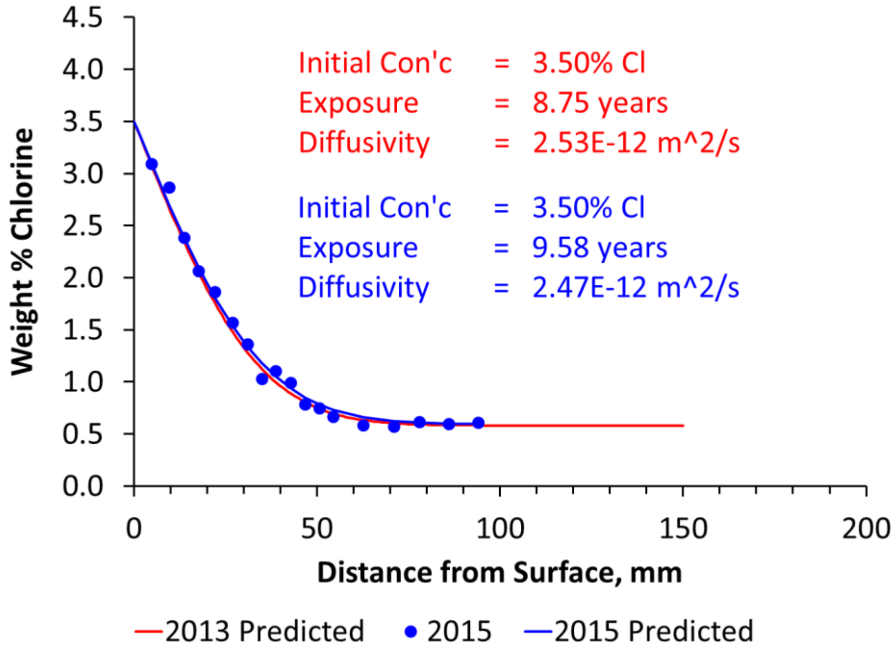


Figure 30. Chlorine profile in the vertical direction from Joint 155 Cell 9 treated with sealer S1, August 19, 2013

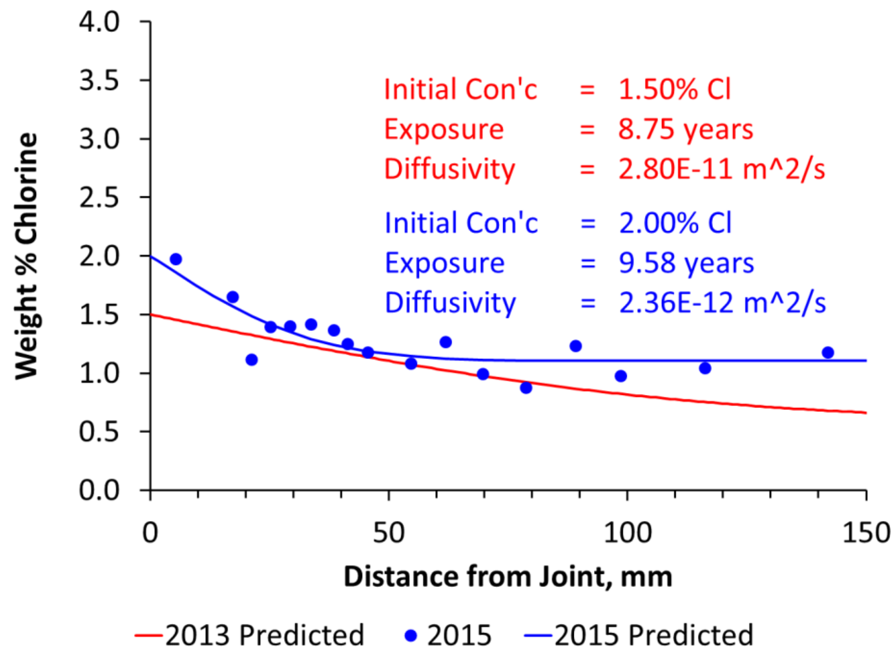


Figure 31. Chlorine profile in the horizontal direction from Joint 155 Cell 9 treated with sealer S1, August 19, 2013

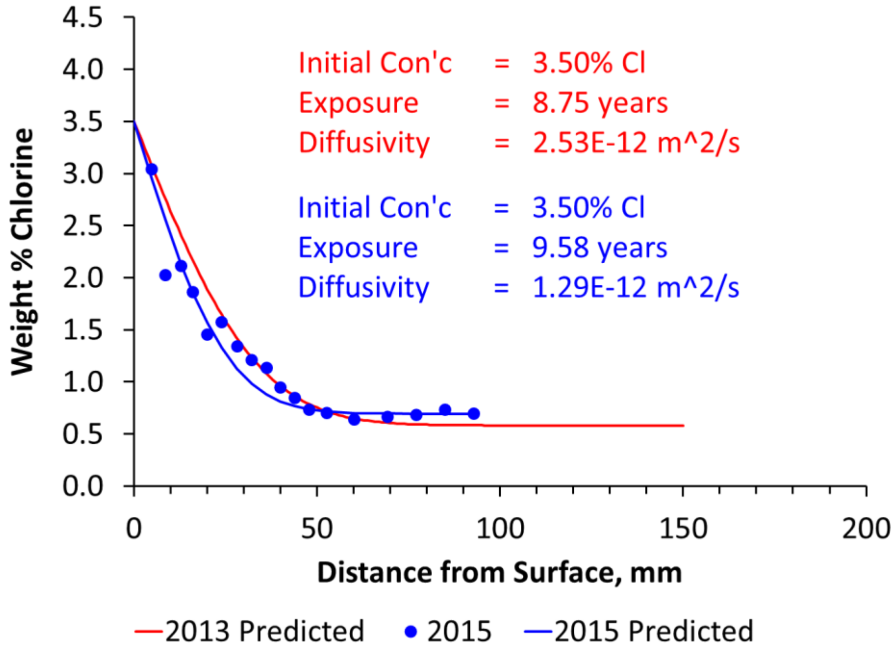


Figure 32. Chlorine profile in the vertical direction from Joint 158 Cell 9 treated with sealer S4, August 19, 2013

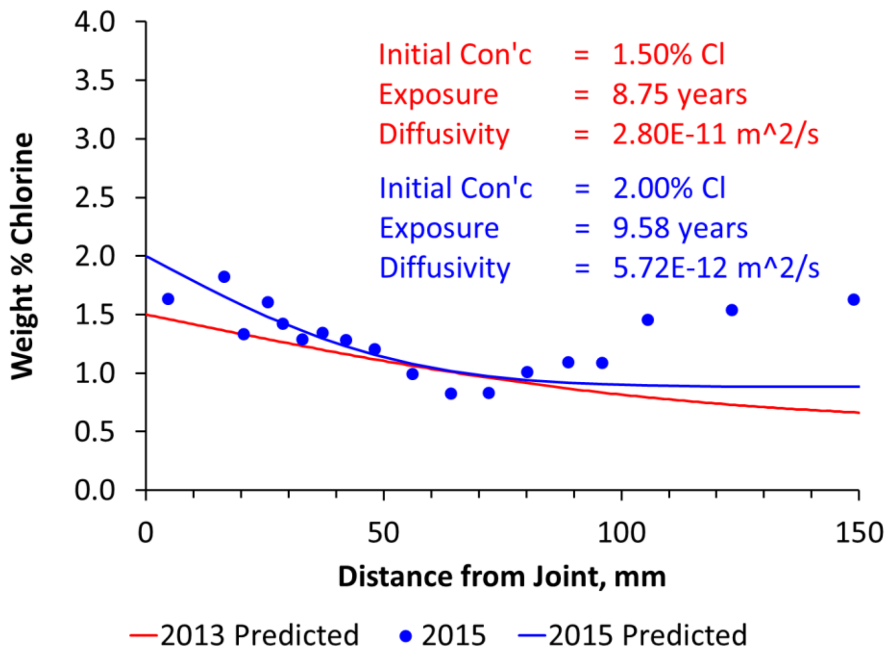


Figure 33. Chlorine profile in the horizontal direction from Joint 158 Cell 9 treated with sealer S4, August 19, 2013

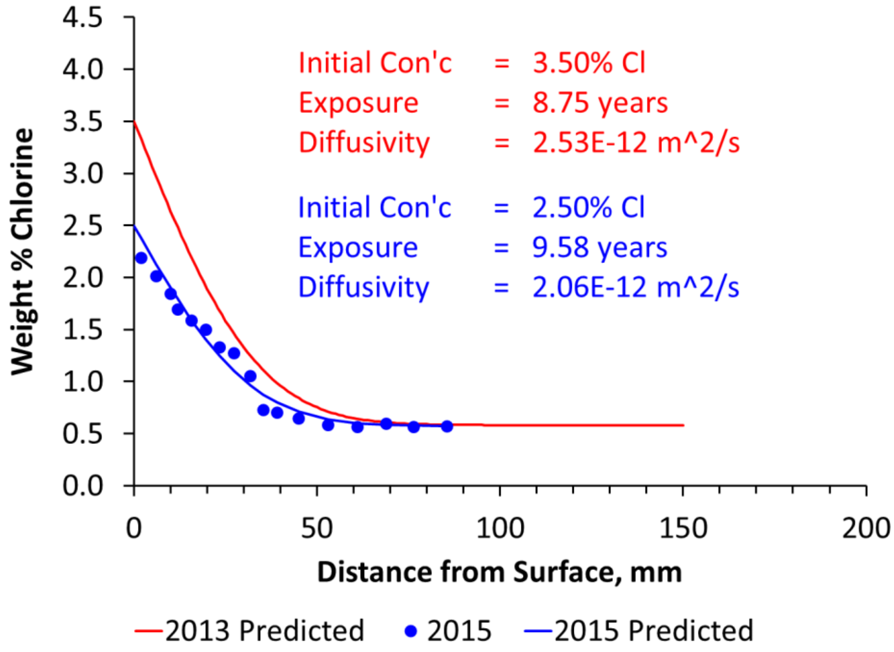


Figure 34. Chlorine profile in the vertical direction from Joint 160 Cell 9 treated with sealer S3, August 19, 2013

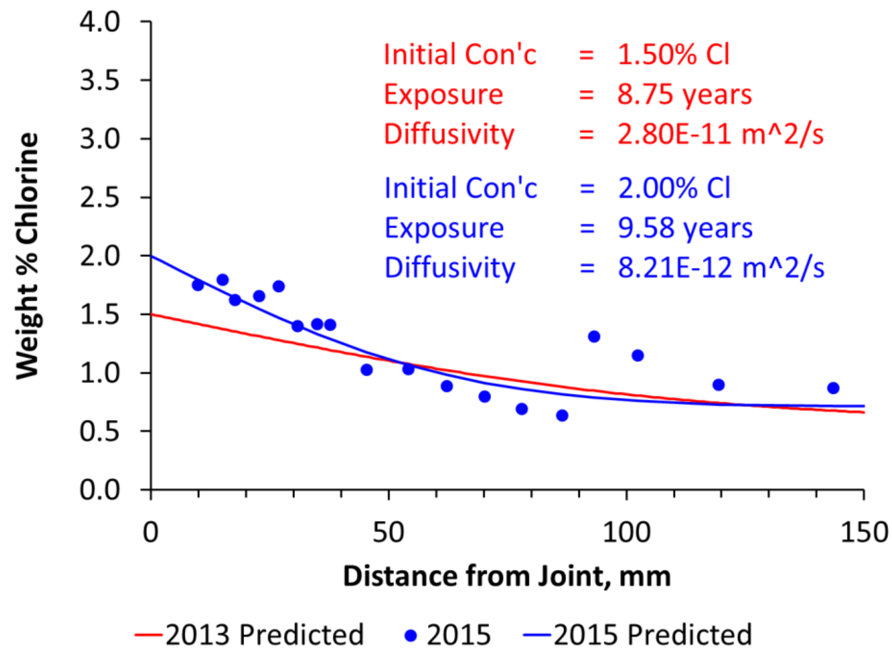


Figure 35. Chlorine profile in the horizontal direction from Joint 160 Cell 9 treated with sealer S3, August 19, 2013

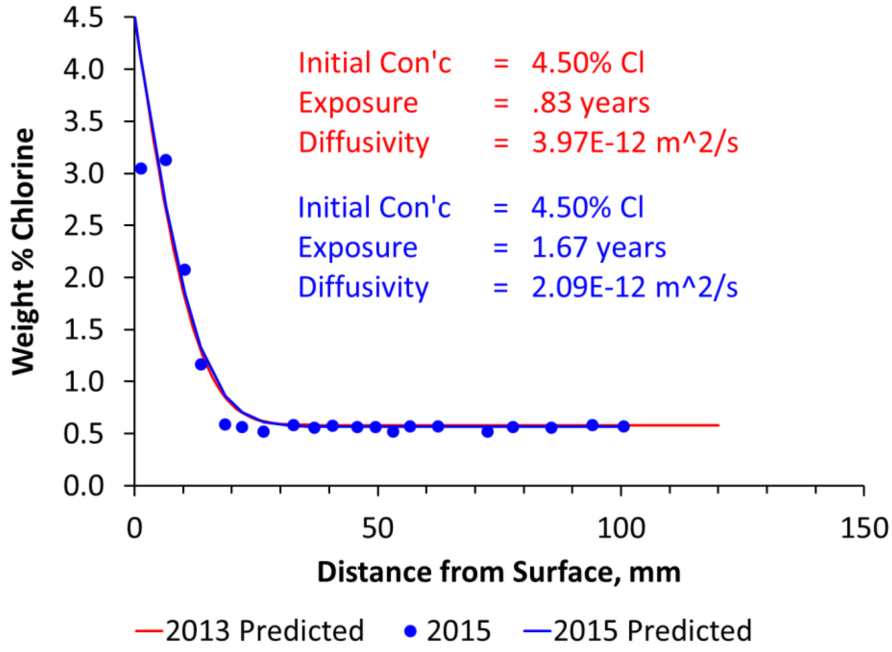


Figure 36. Chlorine profile in the vertical direction from Joint 4236 Cell 505 treated with sealer S2, August 19, 2013

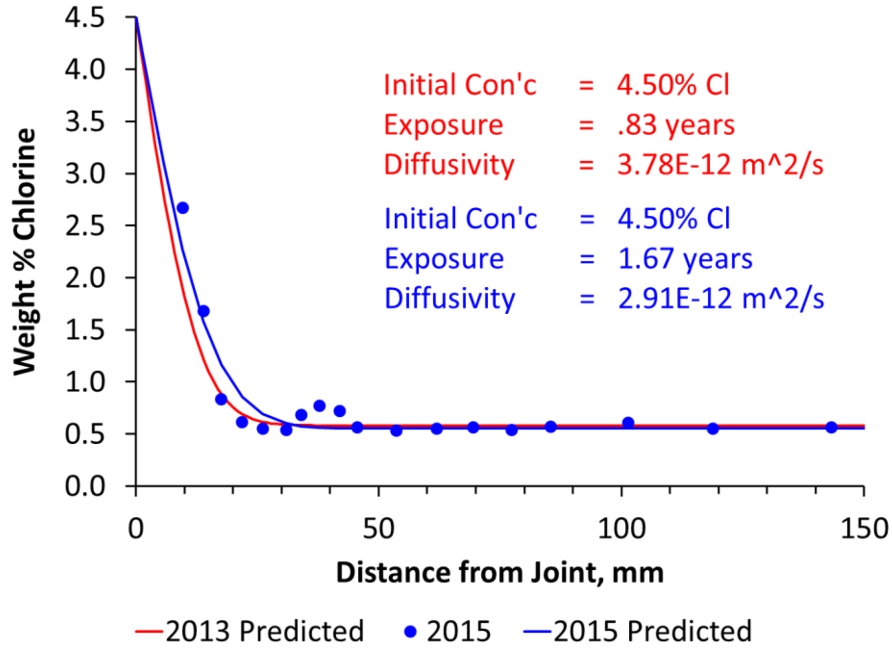


Figure 37. Chlorine profile in the horizontal direction from Joint 4236 Cell 505 treated with sealer S2, August 19, 2013

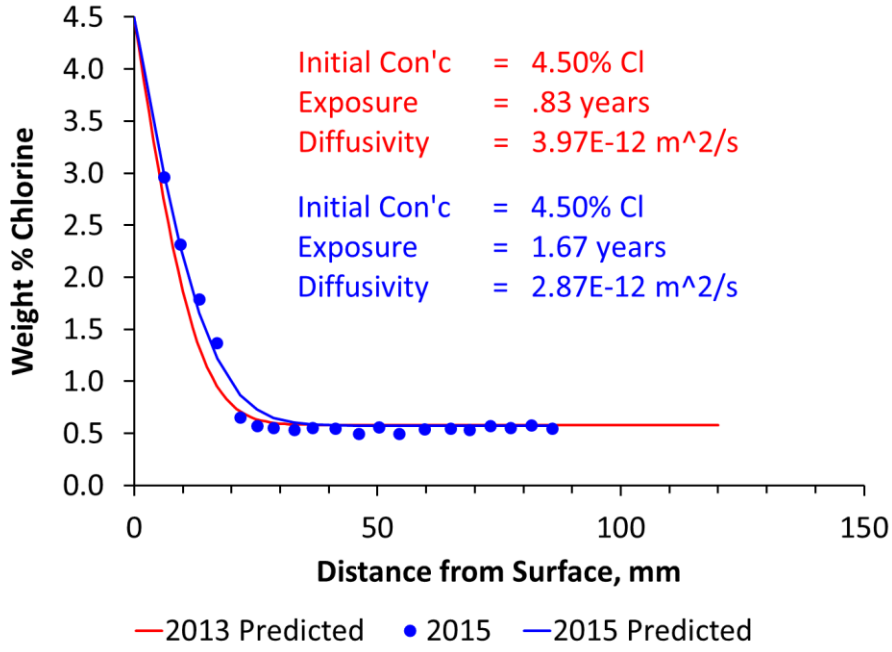


Figure 38. Chlorine profile in the vertical direction from Joint 4238 Cell 505 treated with sealer S4, August 19, 2013

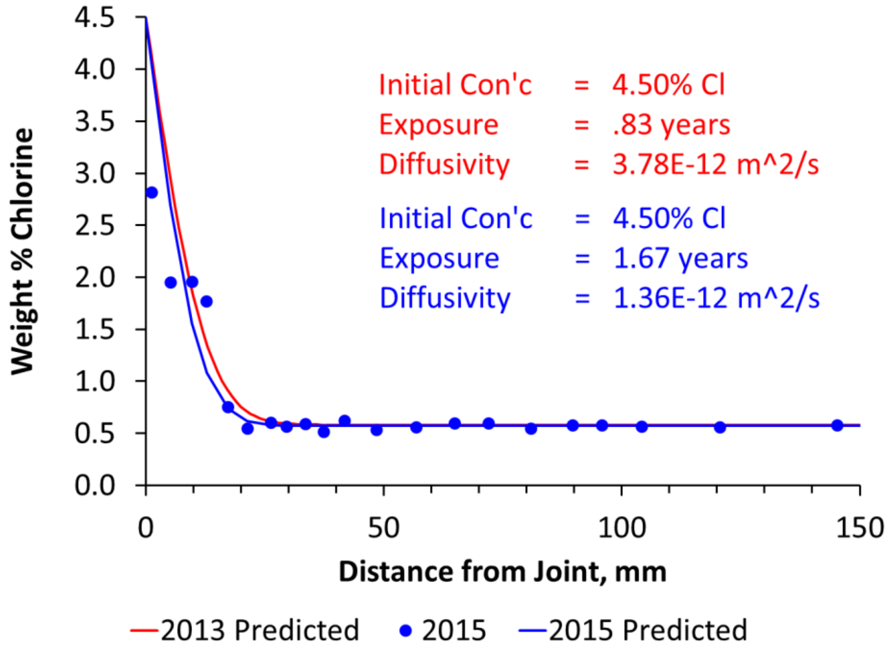


Figure 39. Chlorine profile in the horizontal direction from Joint 4238 Cell 505 treated with sealer S4, August 19, 2013

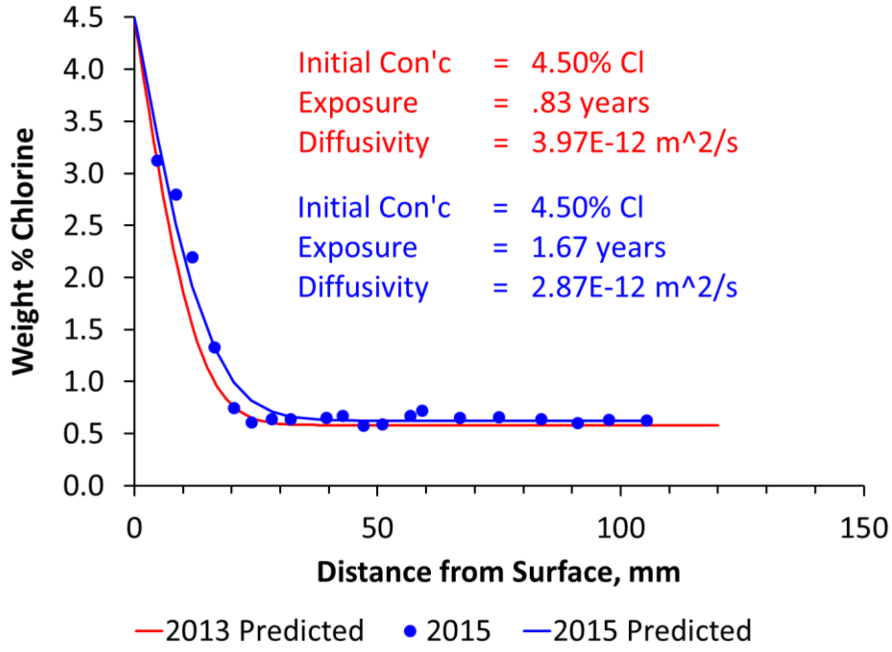


Figure 40. Chlorine profile in the vertical direction from Joint 4240 Cell 505 treated with sealer S1, August 19, 2013

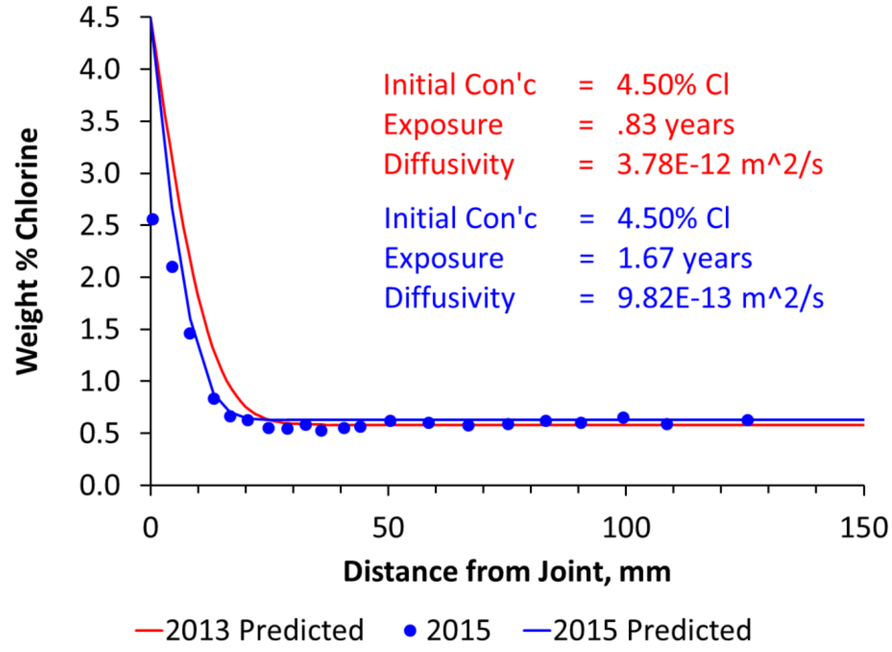


Figure 41. Chlorine profile in the horizontal direction from Joint 4240 Cell 505 treated with sealer S1, August 19, 2013

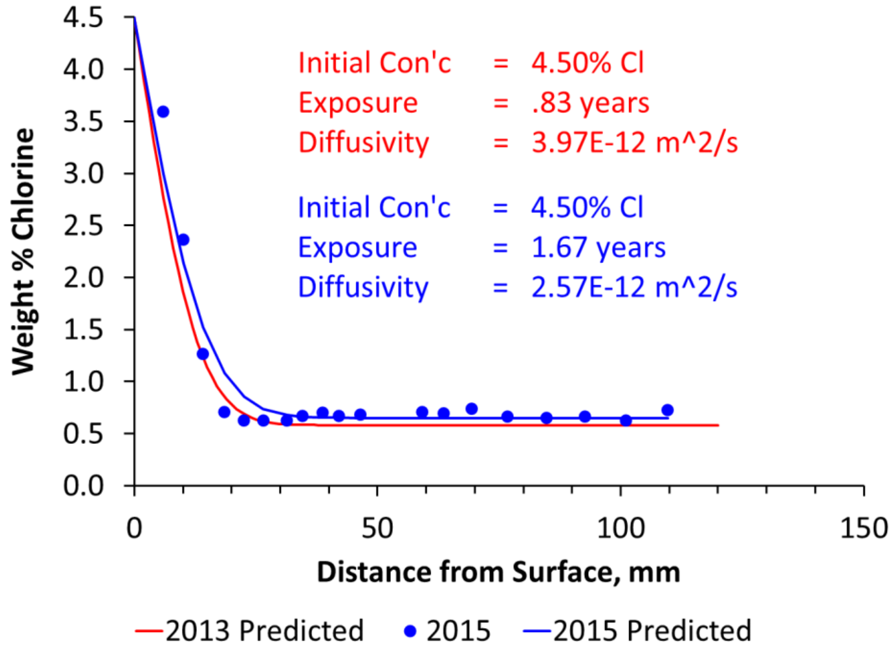


Figure 42. Chlorine profile in the vertical direction from Joint 4241 (control) Cell 505 with no sealer applied

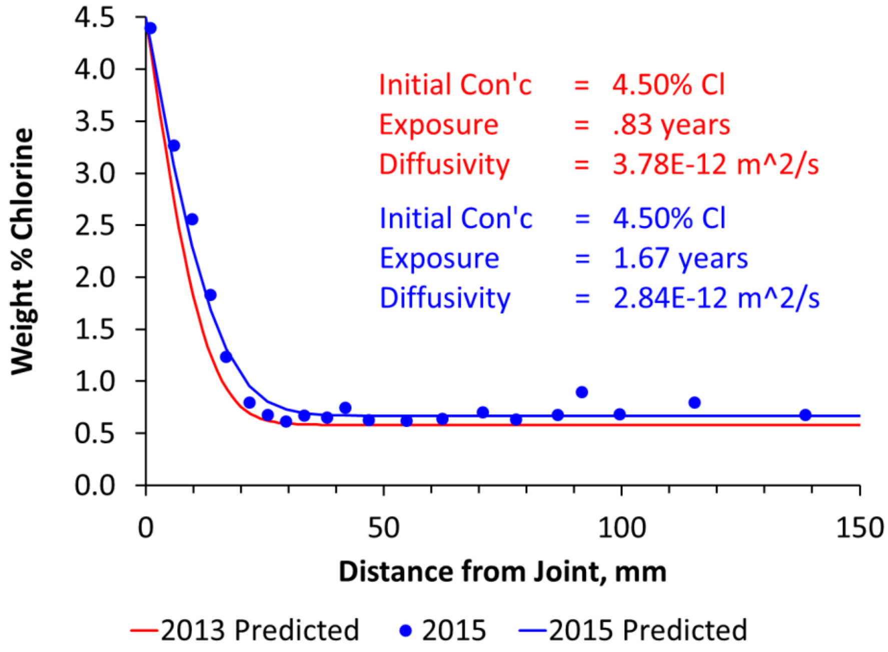


Figure 43. Chlorine profile in the horizontal direction from Joint 4241 (control) Cell 505 with no sealer applied

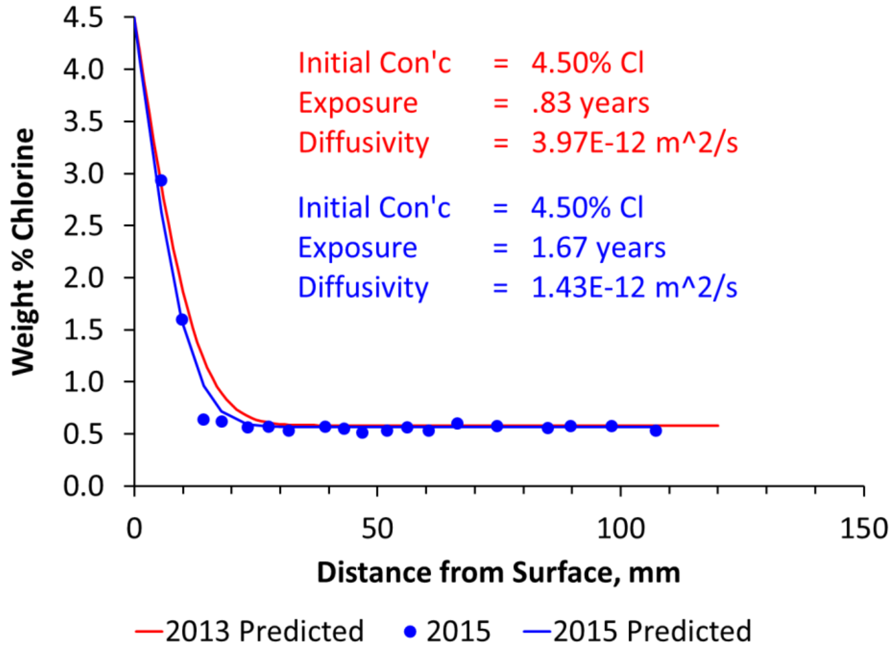


Figure 44. Chlorine profile in the vertical direction from Joint 4242 Cell 505 treated with sealer S3, August 19, 2013

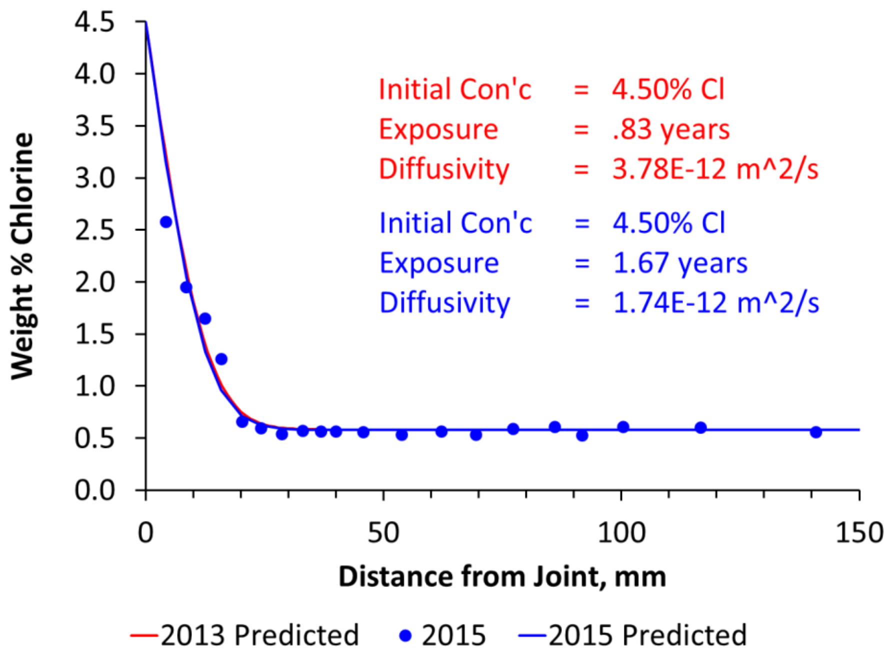


Figure 45. Chlorine profile in the horizontal direction from Joint 4242 Cell 505 treated with sealer S3, August 19, 2013

In all cases, the curve and associated text in the charts represent the baseline pre-application profile and exposure and diffusivity values, respectively. The points represent point concentrations, and the line associated with those points represents the predicted profile using the exposure and diffusivity conditions indicated by the text.

All of the chloride diffusivities are the same order of magnitude, indicating no measurable difference between 2013 and 2015.

In general, the horizontal profiles from the older pavement in Cells 8 and 9 (23 years old as of the time of coring in 2015) demonstrate a noisy concentration gradient only poorly fit using Fick's second law. The uniformly lower initial concentration of chloride in the horizontal profiles compared to their vertical counterparts suggests a more diluted salt solution is present in the joint than is present on the wearing surface. This may indicate the seal system mitigates flow of water/salt solution into the joint, even when compromised.

The chlorine concentration gradients in the vertical direction in the 23-year-old pavement are generally nicely fit by Fick's second law, with inflection points uniformly occurring at a depth of approximately 50 mm.

Both the horizontal and vertical profiles in the four-year-old unbonded concrete overlay in Cell 505 are nicely fit by Fick's second law. Inflection occurs in both the vertical and horizontal directions at a distance of approximately 20 mm from the exposed surfaces. These profiles are predictably steep and uniformly have higher initial concentrations than those found in the pavement in Cells 8 and 9. In contrast to the 23-year-old pavement, the initial concentration in the horizontal direction is the same as that found in the vertical direction, suggesting the dilution evident in the older pavements does not take place in Cell 505. The joints in Cell 505 were not sealed with silicone or hot pour asphalt, and the concrete overlay was placed over a separation fabric. The lack of sealing permits free entry of salt solution and debris from the wearing surface into the joint.

The low diffusivities mean that very little change in the concentration profile has taken place even over the two years separating the collection of cores evaluated in this study. There is no clear difference in the profiles from 2013 and 2015, regardless the age of the pavements. In the case of the joints with a sealer, this would suggest the sealer was slowing ingress and thus maintaining the status quo. However, the same effect was also seen on the control joints where no sealer was applied. The younger concrete overlay in Cell 505 should be more sensitive to changes in diffusivity given the greater driving force resulting from a higher concentration gradient, but no clear difference is apparent in the profiles. Further exacerbating analysis of the data is the small sample population. The variations that are apparent are likely stochastic.

Other Observations

While obtaining cores in 2015, a visual inspection of all three cells was performed. For Cells 8 and 9, digital-image documentation of all joints was performed. The digital-image documentation is provided in Appendix A. Overall, very little difference was seen between the joints as documented in 2013 and 2015.

Staining caused by application of waterproofing sealers was evident on some of the joints inspected in 2015. An example is shown in Figure 46.

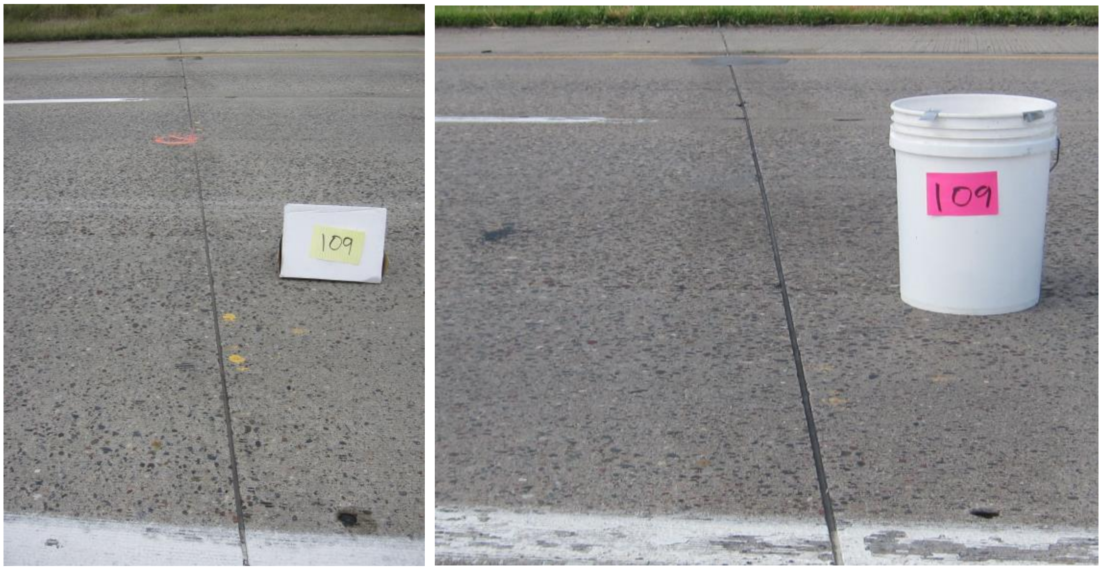


Figure 46. Visible persistence of sealer after two years: Joint 109 in 2013 prior to treatment with sealer S4 (left) and Joint 109 in 2015 after treatment with sealer S3 in 2013 (right)

The visible shadowing in the image on the right in Figure 46 is residual sealer. This suggests that components of the sealers persisted even after two years of service.

For Cell 505 a number of differences between 2013 and 2015 were noted. First, cracking in the wheel path emanating from the joint was observed.

Figure 47 provides examples of this observed cracking. The same cracking was not detected in 2013.

Figure 47. Cracking in the wheel path observed in Cell 505, an unbonded concrete overlay

In many cases, the cracking was pronounced. Staining in the cracks was observed in some cases, but not in every case; no exudate was noted. The cracking had the appearance of a materials-related distress crack rather than a structural crack. There is reason to suspect there was an increased moisture content in the concrete overlay that led to freeze-thaw deterioration.

The other observation regarded edge breaks on the traverse joints slightly out of the wheel path. As seen in Figure 48, the edge breaks were in a line and occurred on nearly every joint.

Figure 48. Edge breaks observed just outside the wheel path in Cell 505, an unbonded concrete overlay

The edge breaks were observed in both lanes, typically in the left wheel path. No evidence of abrasion or other damage that might be attributed to winter maintenance operations was observed.

CONCLUSIONS AND RECOMMENDATIONS

Because there is no clearly apparent difference in the chlorine concentration profiles between 2013 and 2015, it is not possible to determine with any certainty the performance of the various waterproofing sealers applied as part of this study. This is as much due to the short time frame of the study as to any other reason (i.e., the diffusivities are very small, requiring a considerable amount of exposure time to effect a change in the concentration profile). Extraction of cores from Cell 505 in 2017, after another two seasons of exposure, may provide data indicating a trend.

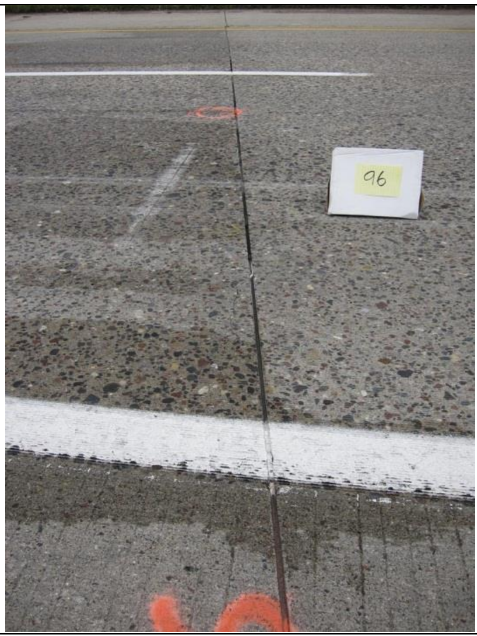
The difference in initial concentration between the vertical and horizontal profiles of the 23 year old pavements with sealed joints may indicate that joint seals mitigate the joints' exposure to water from the wearing surface. This is especially apparent upon considering that no difference in initial concentration exists when comparing the horizontal and vertical profiles from the four-year-old concrete overlay, which had no joint seals. Therefore, the results suggest that joint seals are effective at limiting water ingress into the concrete.

Regarding future work, it would be of interest to revisit the various sites in the future, retrieve more core samples, and further investigate any progression of fluid ingress. This would be particularly valuable for Cell 505, which has no seals and is relatively new. The effect of the sealer, if any, should become apparent. Cells 8 and 9 are worth observing, but given the significant level of chloride ingress in the concrete in these cells, further measurements of chloride ingress would likely not yield any conclusive results.

The method employed for generating chlorine profiles is effective. The premise that determining chloride diffusivity as a proxy for measuring water permeation is theoretically sound, even though the results from this limited study are inconclusive. Chloride ingress is a year-round process. Although chlorides are deposited in the winter only, year-round moisture transports the chloride deeper into the concrete. An effective sealer should slow the water ingress and, in turn, slow the chloride migration. However, future research should focus on developing the means to directly measure water ingress by some means other than chloride ingress. Ideally, the moisture content at any time could be determined in situ, using a non-destructive test, allowing for continual monitoring of moisture content. Such measurements could provide a rapid way to monitor sealer or sealant efficacy.

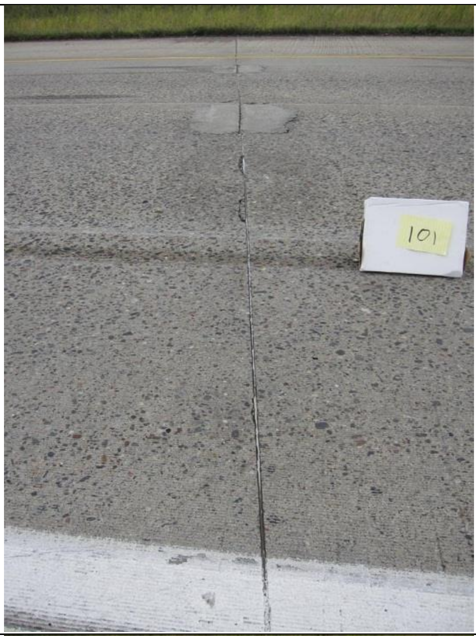
APPENDIX A. IMAGE DOCUMENTATION OF JOINTS IN MNROAD CELLS 8, 9, AND 505

Cell 8

Joint	2013	2015
95	N/A	
96		

Joint	2013	2015
97		
98		

Joint	2013	2015
99		
100		

Joint	2013	2015
101		
102		

<table>
<tr><th>Joint</th><th>2013</th><th>2015</th></tr>
<tr><td>103</td><td>
</td><td>
</td></tr>
<tr><td>104</td><td>
</td><td>
</td></tr>
</table>

Joint	2013	2015
105		
106		

Joint	2013	2015
107		
108		

Joint	2013	2015
109		
110		

Joint	2013	2015
111		
112		

Joint	2013	2015
113		
114		

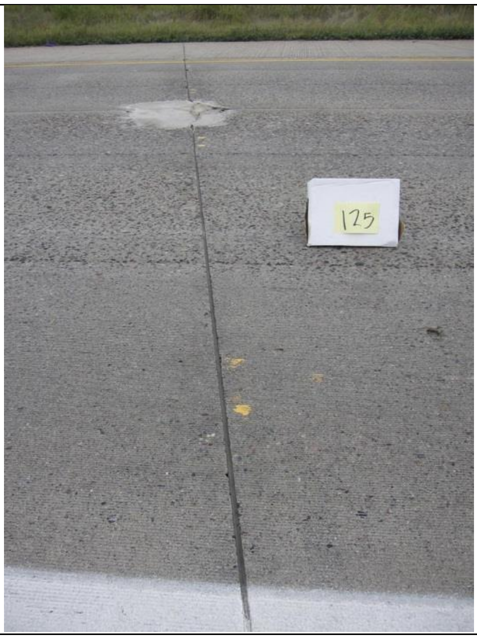
Joint	2013	2015
115		
116		

Joint	2013	2015
117		
118		

Joint	2013	2015
119	N/A	
120	N/A	

Joint	2013	2015
121	N/A	
122	N/A	

Joint	2013	2015
123	N/A	
124	N/A	

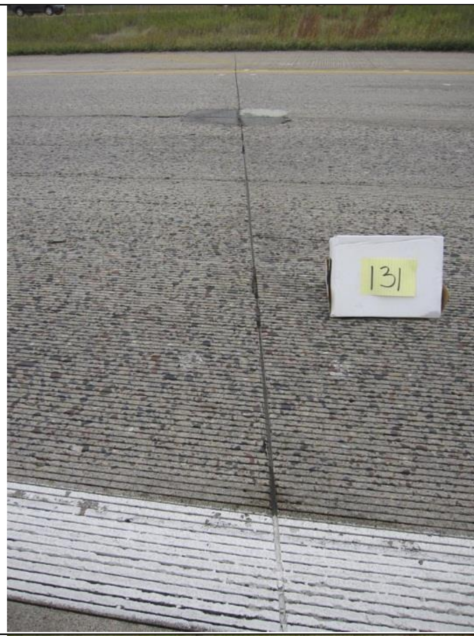
Joint	2013	2015
125		
126	N/A	

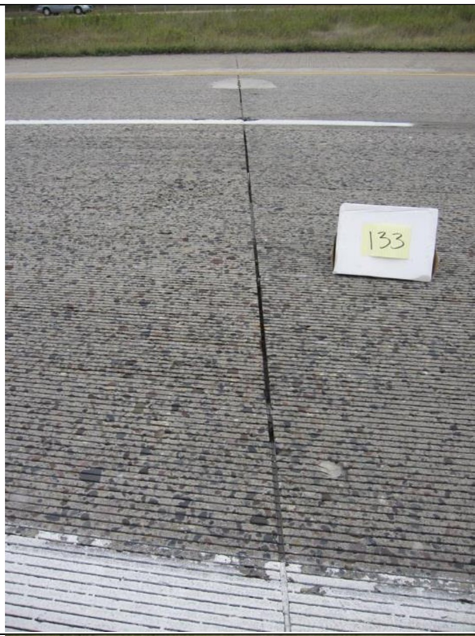
Joint	2013	2015
127	N/A	

Cell 9

Joint	2013	2015
128	N/A	

Joint	2013	2015
129	N/A	
130	N/A	

Joint	2013	2015
131		
132		

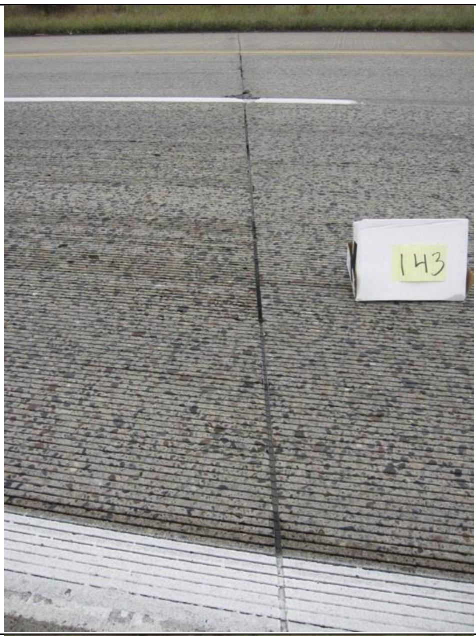
Joint	2013	2015
133		
134		

Joint	2013	2015
135		
136		

Joint	2013	2015
137		
138		

Joint	2013	2015
139		
140		

Joint	2013	2015
141		
142		

<table>
<tr><th>Joint</th><th>2013</th><th>2015</th></tr>
<tr><td>143</td><td>
</td><td>
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<tr><td>144</td><td>
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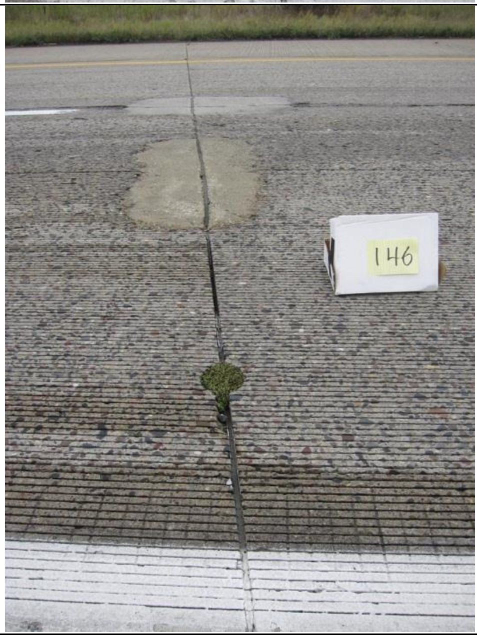
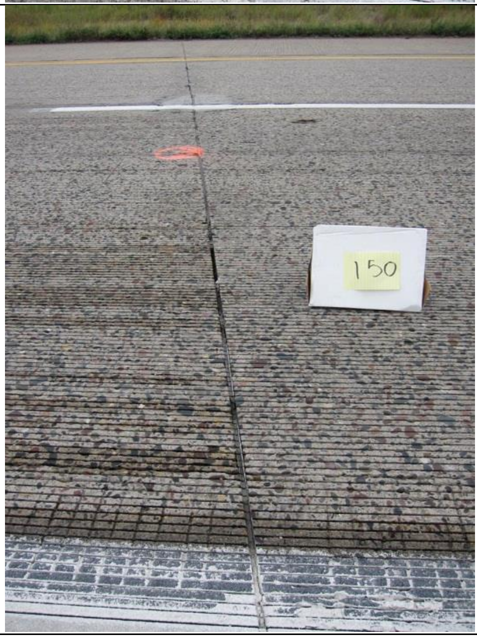
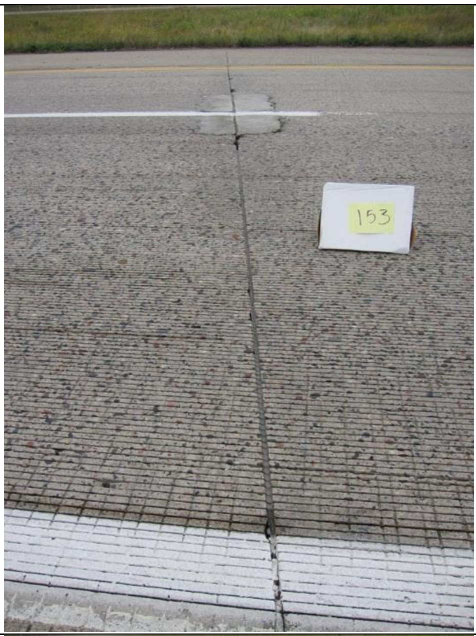
Joint	2013	2015
145		
146		

Joint	2013	2015
147		
148		

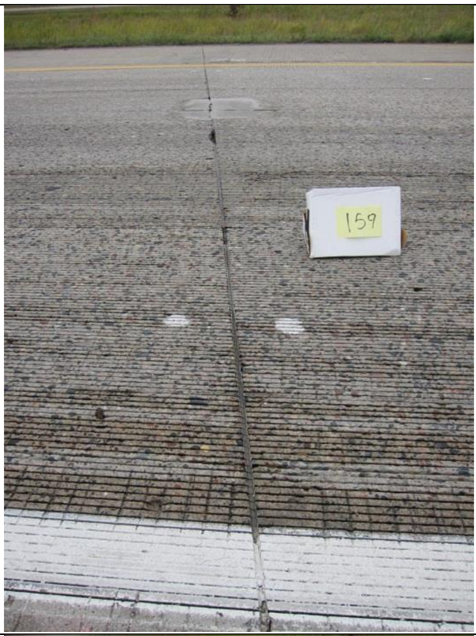
Joint	2013	2015
149		
150		

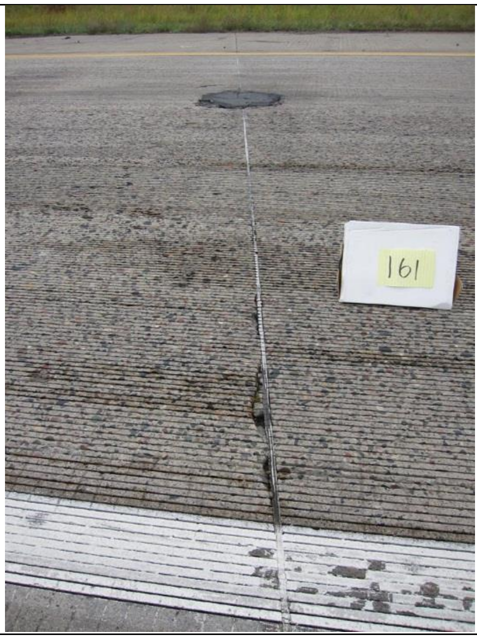
Joint	2013	2015
151		
152		

Joint	2013	2015
553		
154		

Joint	2013	2015
155		
156		

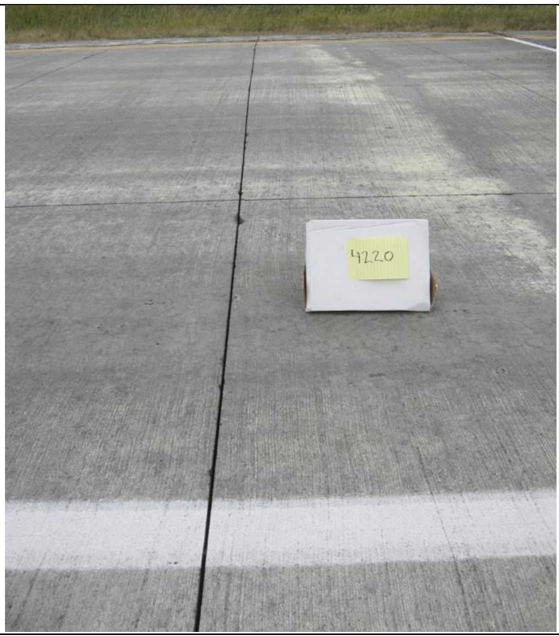
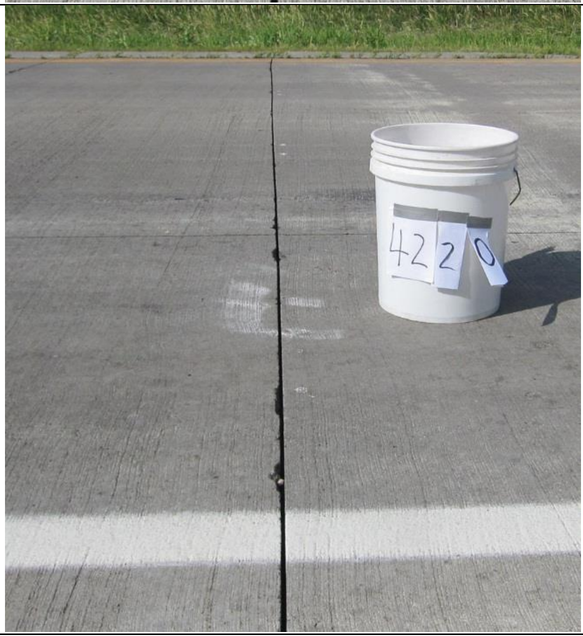
Joint	2013	2015
157		
158		

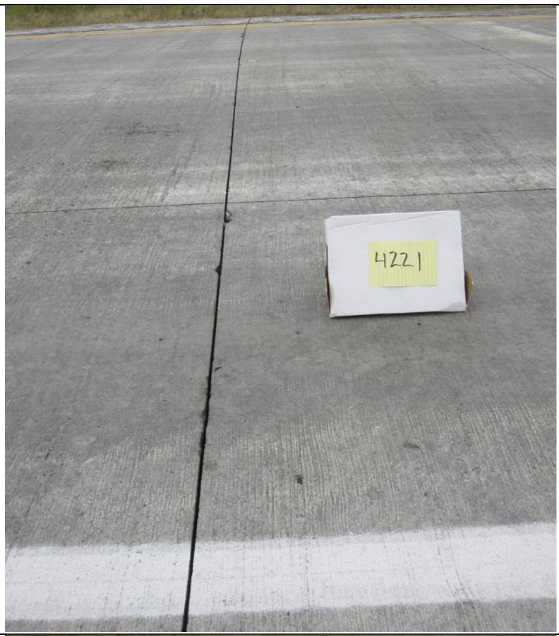
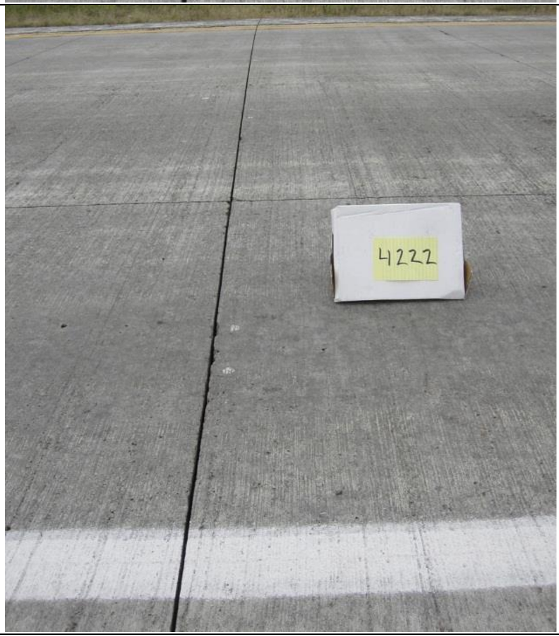
Joint	2013	2015
159		
160		

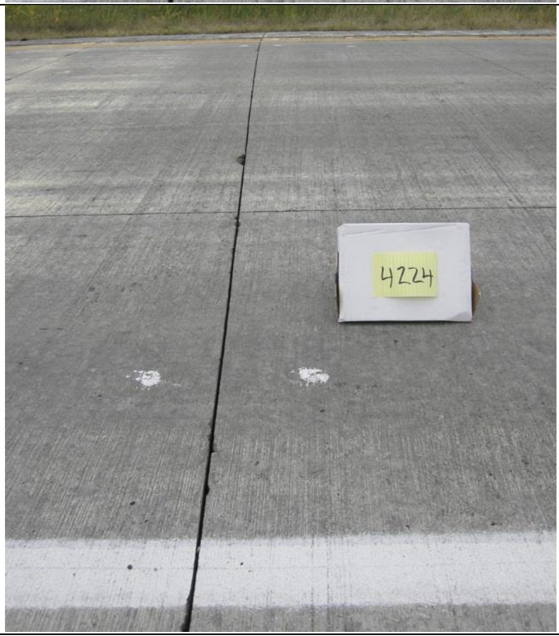
Joint	2013	2015
161		
162	N/A	

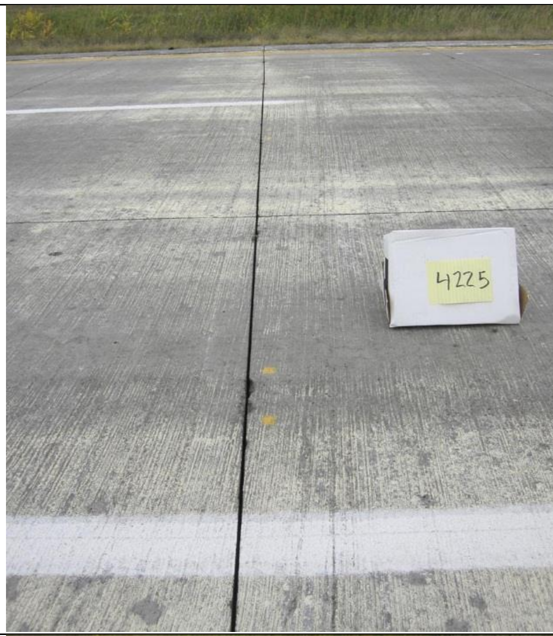
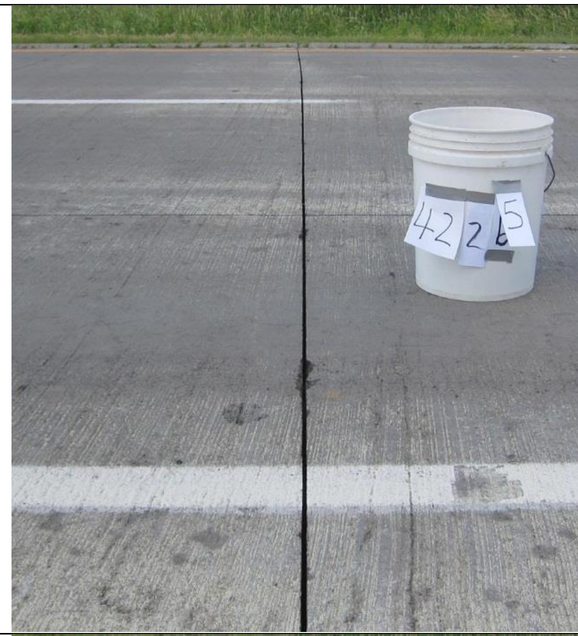
Joint	2013	2015
163	N/A	
164	N/A	

Cell 505

Joint	2013	2015
4219	N/A	
4220		

Joint	2013	2015
4221		
4222		

Joint	2013	2015
4223		
4224		

Joint	2013	2015
4225		
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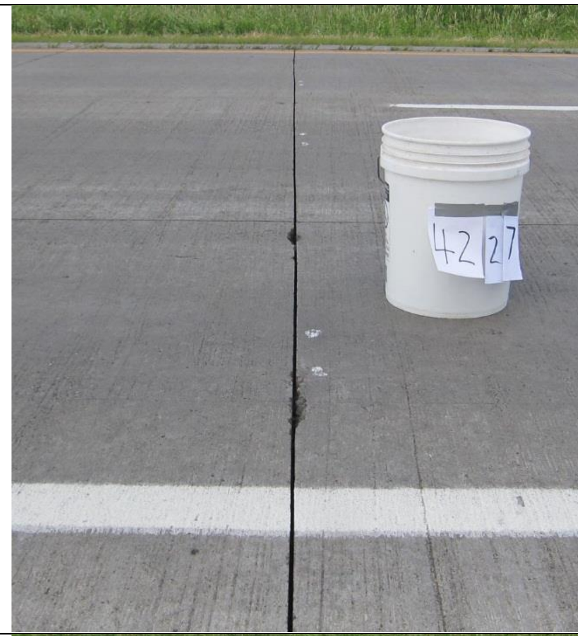
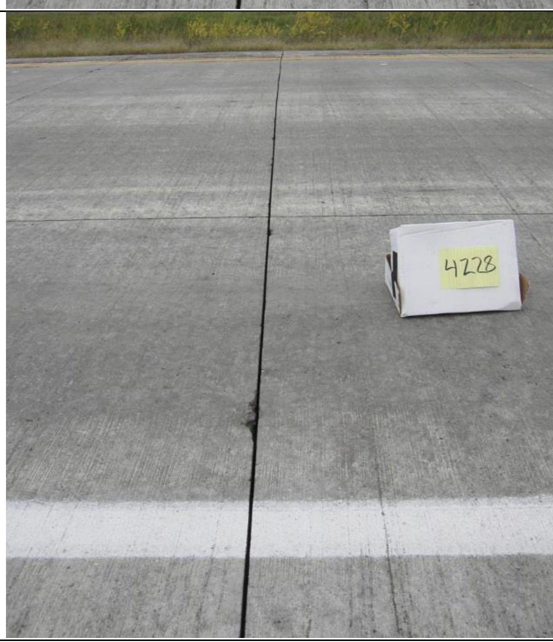
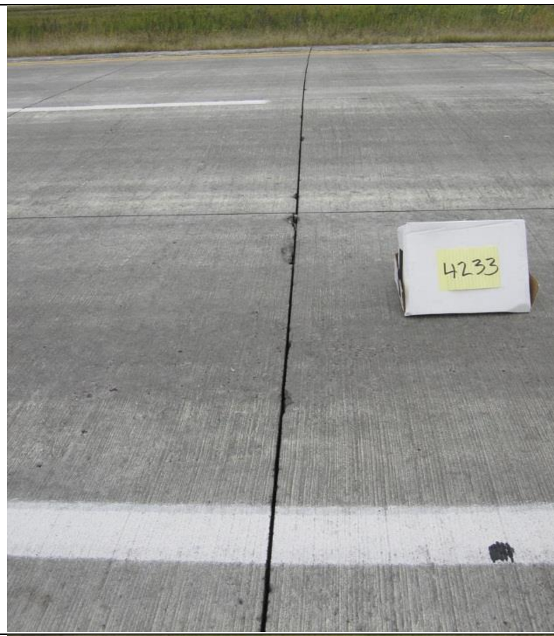
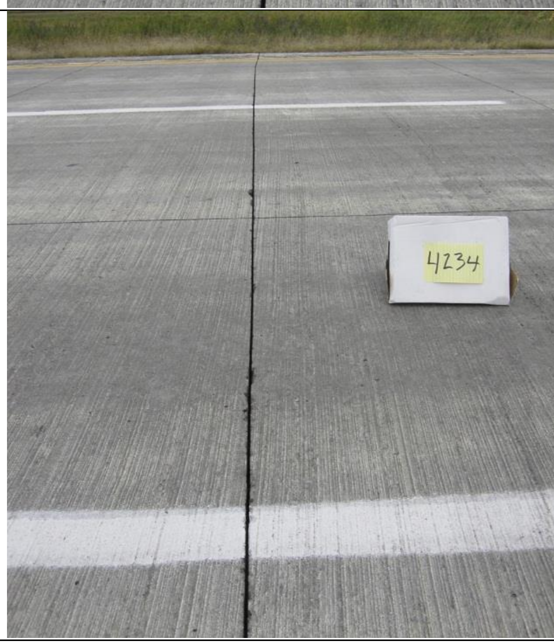
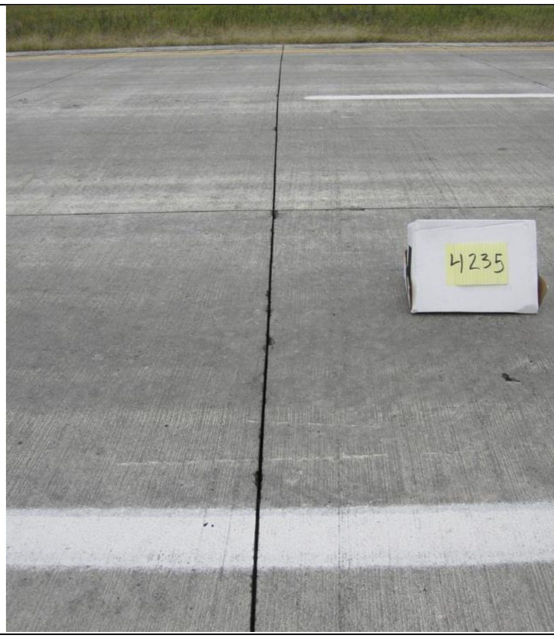
Joint	2013	2015
4227		
4228		

Joint	2013	2015
4229		
4230		

Joint	2013	2015
4231		
4232		

Joint	2013	2015
4233		
4234		

Joint	2013	2015
4235		
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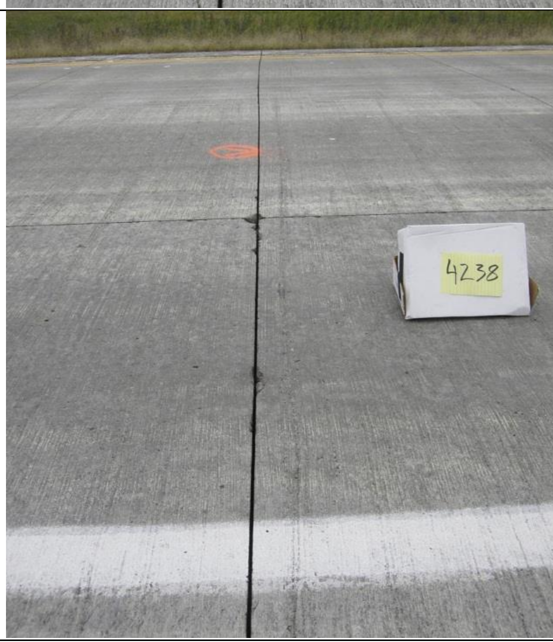
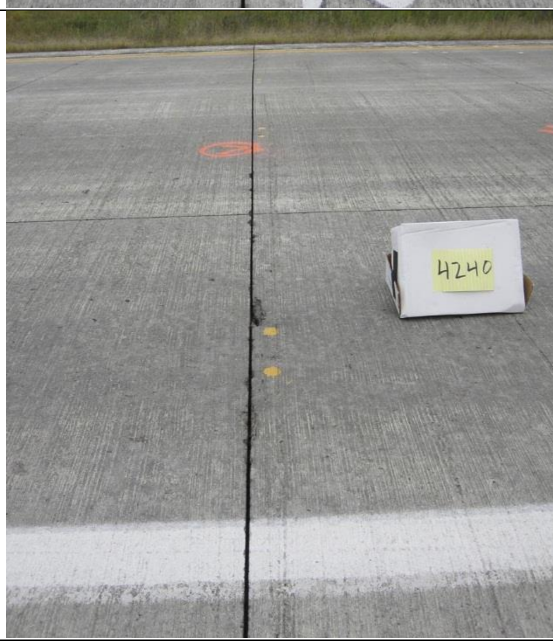
Joint	2013	2015
4237		
4238		

Joint	2013	2015
4239		
4240		

Joint	2013	2015
4241		
4242		

Joint	2013	2015
4243	N/A	
4244	N/A