Conclusions from the Investigation of Deterioration of Joints in Concrete Pavements

Final Report
February 2016

Sponsored through
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National Concrete Pavement Technology Center

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The mission of the National Concrete Pavement Technology (CP Tech) Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

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16. Abstract

Premature deterioration of concrete at the joints in concrete pavements and parking lots has been reported across the northern states. The distress may first appear as shadowing when microcracking near the joints traps water, or as cracks parallel to and about 1 inch from the saw cut. The distress later exhibits as a significant loss of material. Not all roadways are distressed, but the problem is common enough to warrant attention.

The aim of the work being conducted under this and parallel contracts was to improve understanding of the mechanisms behind premature joint deterioration and, based on this understanding, develop training materials and guidance documents to help practitioners reduce the risk of further distress and provide guidelines for repair techniques.

While work is still needed to understand all of the details of the mechanisms behind premature deterioration and the prevention of further distress, the work in this report has contributed to advancing the state of the knowledge.

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Conclusions from the Investigation of Deterioration of Joints in Concrete Pavements

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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):

- Colorado
- Indiana
- Iowa (lead state)
- Michigan
- Minnesota
- New York
- South Dakota
- Wisconsin

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- American Concrete Pavement Association (ACPA)
- Iowa Concrete Paving Association (ICPA)
- Portland Cement Association (PCA)

In addition, the work references parallel activities conducted by Purdue University and Michigan Technological University, and we acknowledge their significant contributions to addressing the problem addressed by this project.

EXECUTIVE SUMMARY

Premature deterioration of concrete at the joints in concrete pavements and parking lots has been reported across the northern states. The distress may first appear as shadowing when microcracking near the joints traps water or as cracks parallel to and about 1 inch off the saw cut. The distress later exhibits as significant loss of material. Not all roadways are distressed, but the problem is common enough to warrant attention.

Based on all of the work conducted under this contract, the parallel work funded by the Federal Highway Administration (FHWA), and other research conducted at Purdue University and Michigan Technological University, the following may be concluded with respect to the mechanisms and prevention of premature joint deterioration.

- Two primary mechanisms appear to be driving distress:
    - Freeze-thaw damage incurred in saturated concrete. This typically appears as thin flakes.
    - Paste deterioration due to chemical attack, primarily the formation of expansive calcium oxychloride. Distress may appear as cracking at regular intervals parallel to the saw cut and/or as loss of paste, leaving clean aggregates in the voids.

- The following can reduce the risk of distress:
    - Use of a low w/cm ratio, ~ 0.40 to 0.42 to reduce permeability
    - Appropriate use of supplementary cementitious materials
    - Ensuring an adequate air void system behind the paver
    - Selection of cementitious systems with high Si/Ca ratios that are more resistant to oxychloride formation
    - Paying attention to drainage at all locations so that joints can dry out
    - Application of penetrating sealants that will slow water and salt penetration into the microstructure (Castro et al. 2011)
    - Limiting the use of aggressive salts to times and temperatures (typically <15ºF) when they are necessary for safety

INTRODUCTION

Joint deterioration has been reported in a number of locations in cold weather regions. Damage to concrete pavement joints is often observed as cracking and spalling at joints and eventually reduces the service life of pavement systems, including highways, city and county streets, and parking lots (Taylor et al. 2012). Not all roads have deteriorated, but the problem is common enough to cause some local authorities to reconsider the use of concrete in their pavements. No single mechanism can account for all occurrences of joint deterioration. Spragg et al. (2011) document that the factors that contribute to this damage include chemical reactions, inadequate air voids, poor mix design, inadequate constituent materials, or poor construction practices.

The work described in this report summarizes the tasks conducted under this research contract, which was part of a larger program encompassing multiple funding sources and research organizations.

LABORATORY INVESTIGATIONS

Laboratory tests were conducted to investigate the mechanisms that may be related to joint deterioration in concrete pavements. The following tests were conducted:

- Monitoring temperature and humidity change within a concrete slab
- Mechanisms of damage in the interfacial transition zone
- Influence of pore sizes on paste freezing and thawing durability
- Effect of subsurface permeability
- Effect of sawing

Monitoring Temperature and Humidity Change within a Concrete Slab

An instrumented concrete slab with dimensions of 20 × 20 × 8 inches was built using a typical concrete pavement mixture containing 20% fly ash. The temperature and humidity measurements were taken as follows:

- Two temperature measurements at the top of the slab (0.2 inches apart)
- Three temperature measurements at the corner of the slab (3 inches apart)
- Three temperature measurements at the side of the slab (3 inches apart)
- Two temperature measurements at the middle of the slab (6 inches apart)

The aim of the work was to observe temperature and internal relative humidity (RH) profiles in a slab buried in the ground and exposed to an Iowa winter in order to better understand the influence of the environment on concrete internal temperature and RH.

The instrumentation layout is shown in Figure 1 and Figure 2.

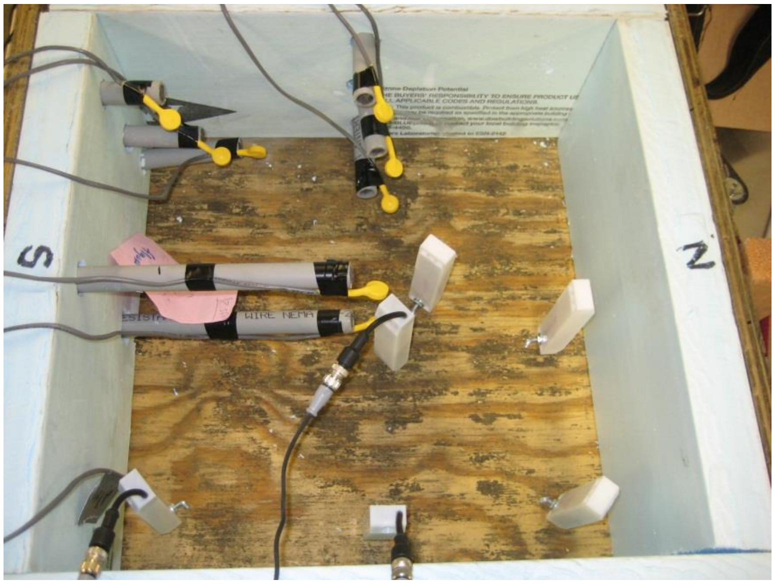


Figure 1. Temperature and humidity sensor layout

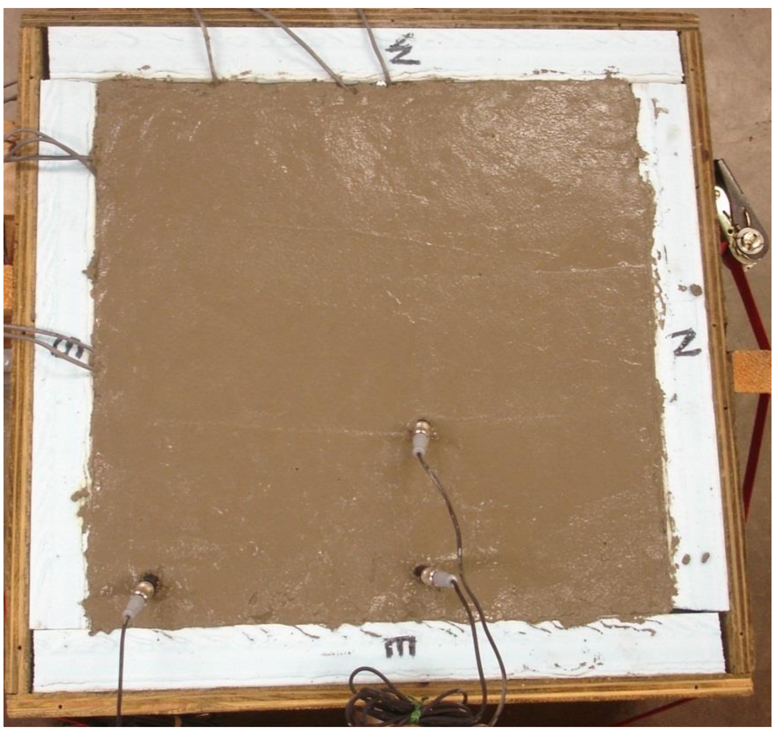


Figure 2. Instrumented slab after concrete was placed

The slab was cast in early October, moist cured for two weeks, and then placed into a freezer before being placed into the ground when aged one month (Figure 3).

Figure 3. Instrumented slab buried in the ground next to a residential driveway

Sodium chloride was applied to the top of the slab during snow events, as shown in Figure 4.

Figure 4. Sodium chloride applied on the top of the slab during a snow event

Temperature data were recorded every 15 minutes for four months. Figures 5 through 8 illustrate the data collected over the four-month period.

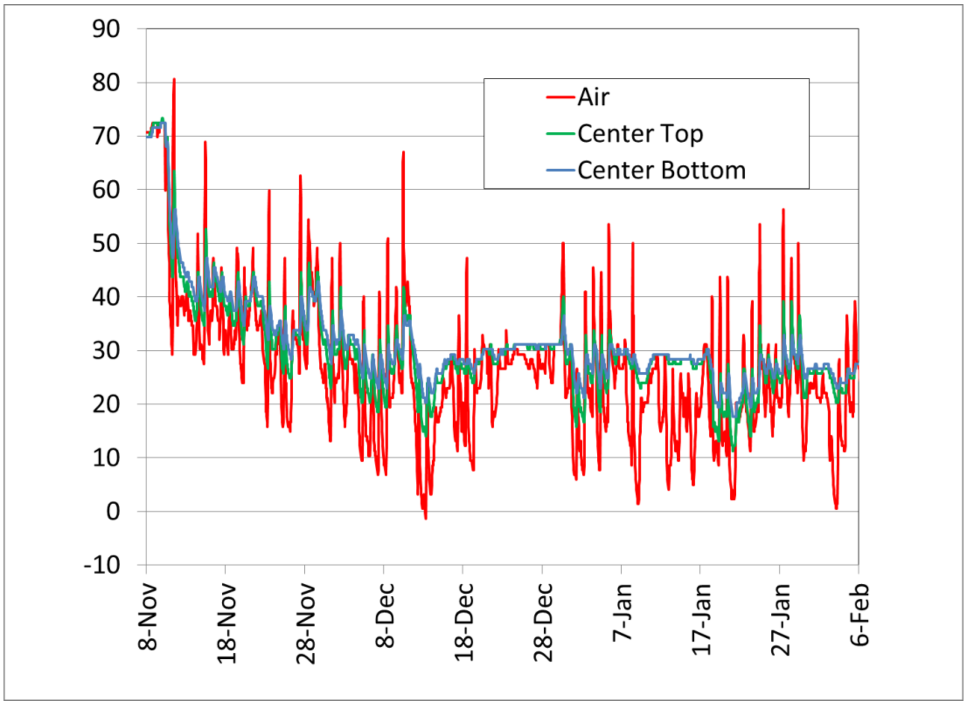


Figure 5. Temperature measurement from the center of the slab

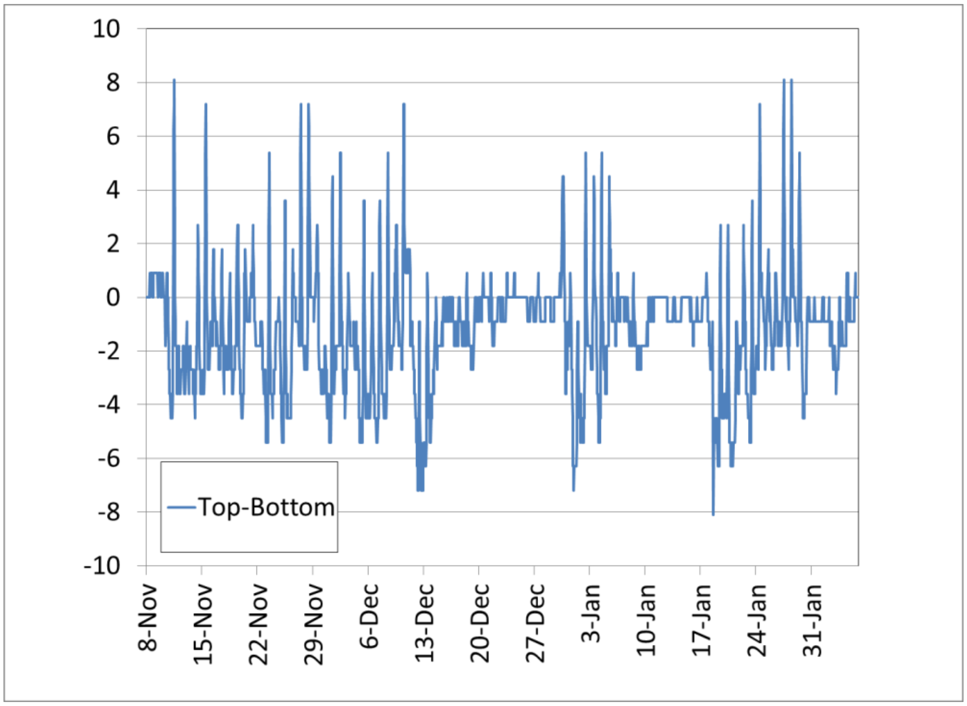


Figure 6. Difference between top and bottom temperatures in the center of the slab

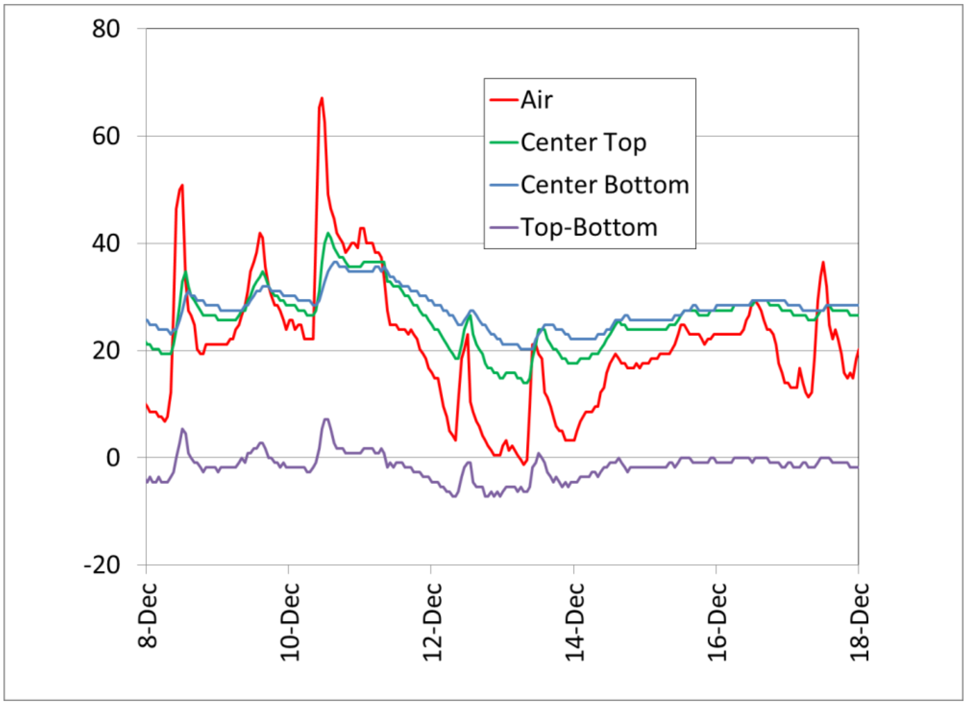


Figure 7. Temperatures in the center of the slab – detail for 10 days

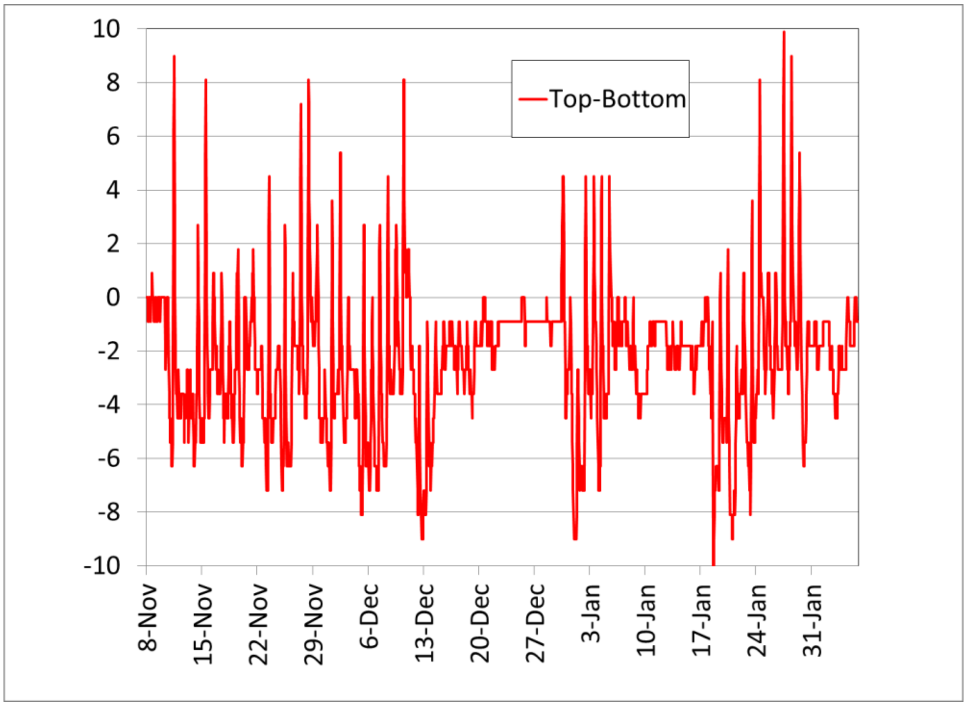


Figure 8. Difference between top and bottom temperatures at the edge of the slab

Observations from the plots above indicate the following:

- The temperature at the bottom of the 8 inch slab does not fluctuate as markedly as the top surface, as expected. However, as seen in the detail in Figure 7, when one of the greatest temperature swings occurred, the difference between the top of the slab and the bottom of the slab never exceeded about 8ºF.

- The edge of the slab did see higher differentials, likely because the soil at the edge of the slab was not thoroughly compacted, therefore likely acting as a better conductor of heat than the concrete. This is also likely to be true of the interior of a sawn joint that is more exposed to the air.

Analysis of the data indicates that the number of freeze-thaw cycles (a cycle from above 32ºF to below 32ºF and back) in the air was 70, in the top of the slab the number was 44, and at the bottom of the slab the number was 17.

The relative humidity sensors never reported a value less than 98%. This is notable because, despite the concrete appearing "dry" and being less than 85% saturated, evidenced by the fact that the surface did not exhibit damage, the internal RH was still high. This supports the contention that RH of the pore space is an inadequate measure of the risk of freezing-related distress.

Mechanisms of Damage in the Interfacial Transition Zone

As reported in Taylor et al. (2012), there is a strong indication that damage occurs preferentially in the interfacial transition zone (ITZ), resulting in cracks forming at about 1 inch increments parallel to the saw cut. The aim of the laboratory work described in this section was to investigate the mechanisms occurring within the ITZ.

Three possibilities were initially considered:

- Freezing and thawing of water in the ITZ leads to localized expansion
- Salt crystallization causes expansive forces
- Dissolution of the ITZ in the salt solutions, especially at low temperatures because some calcium compounds are increasingly soluble as temperatures drop

Valenza and Scherer (2006) discount the first two alternatives. The first is considered unlikely because the water that expands as temperatures drop would have to be held in the ITZ to cause pressure, and it is considered more likely that the water would simply be expelled back into the saw cut. In addition, the volume of freezing water in the ITZ would likely be too low to create significant stresses. The second mechanism is considered unlikely because osmotic pressure caused by freezing salt solution is about 160 psi, and the crystallization pressure is about 374 psi

(Correns 1949), while the typical tensile strength of concrete with a w/c ratio of 0.45 is about 650 psi (Bhanja and Sengupta 2005).

The aim of the experimental work was to test whether dissolution was occurring at the ITZ. This was considered likely because of the common observation in the field that aggregate particles were being cleanly separated from the paste, as shown in Figure 9.

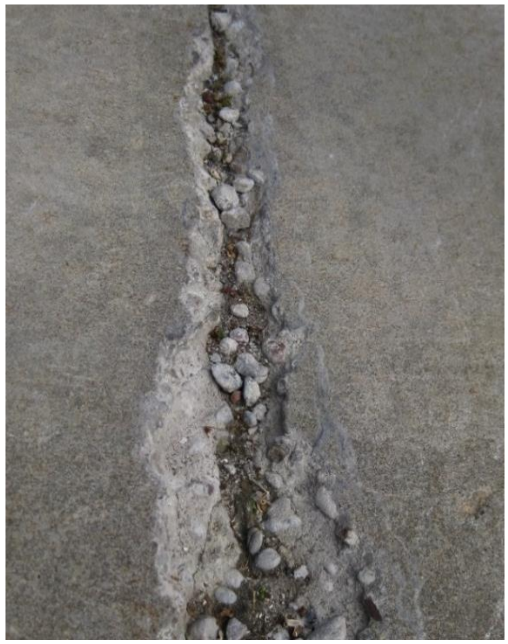


Figure 9. Field observation of joint deterioration, including exposed aggregates left behind

Laboratory test results on samples that exposed the ITZ yielded similar observations as in the field (Figure 10).

Figure 10. Laboratory sample exposed in 3% NaCl solution, showing cleanly exposed aggregate

The approach used was to prepare prisms from a single mixture and partially submerge them in water, 3% sodium chloride (NaCl) solution, or 3% magnesium chloride ($MgCl_2$) solution at 40°F for 56 days, followed by examination of the tested samples using microscopy. The low constant temperature was selected to remove the effects of freezing while enhancing the potential dissolution of calcium compounds. The temperature was also selected based on distress reported by Sutter et al. (2008) in similar tests. The mixture was selected to be typical of nominally durable pavement mixtures to preclude failure of the bulk paste confounding the observations. Two coarse aggregates were tested, gravel and crushed limestone, to observe the effects that aggregate type may have on performance.

The details of the mixture are shown in Table 1.

Table 1. Mix proportions

Parameter	**Value**
Cement	Type I
Fly ash	Class C, 20%
Binder content	564 lb/yd^3
w/cm	0.45
Target air content	6%
Coarse aggregate	1 in. gravel or crushed limestone
Fine aggregate	River sand

Concrete was mixed in accordance with ASTM C192 and cast into 4 by 3 by 16 inch beams. The beams were cured in a fog room for 28 days before they were cut by diamond saw into 1/2-inch thick slices (Figure 11).

Figure 11. Saw cut slice sample with a thickness of 1/2 inch

The slices were deliberately thin to ensure that some aggregate particles were exposed on both faces of the slice.

The slices were partially immersed, sawn face down, in a 1/4 inch layer of test liquid comprising either water, 3% NaCl, or 3% $MgCl_2$ at a constant 40°F (Figure 12).

Figure 12. Samples partially immersed in liquid while stored at 40°F

For each solution, four samples were tested. After 56 days, slices were cut into two halves to create vertical sections so that the effects of the solutions could be observed through the thickness of the samples. Selected samples were examined using a scanning electron microscope (SEM).

The observations from the samples are shown in Table 2 and Figures 13 through 15.

Table 2. Observations of samples after testing

Solution	Visual observations	SEM observations
H_2O	No distress (Figure 13, left)	No distress (Figure 13, right)
NaCl	No distress (Figure 14, left)	Minor microcracking throughout the paste system. No signs of Cl^- concentrations or dissolution of hydration products in the ITZ (Figure 14, right)
$MgCl_2$	Aggregate faces appear to be below paste surface level, indicating paste expansion (Figure 15, left)	No signs of Cl^- concentrations or dissolution of hydration products in the ITZ. However, cracks were observed around the aggregate particles. Cracking was more prevalent closer to the face of the sample exposed to the solution (Figure 15, right)

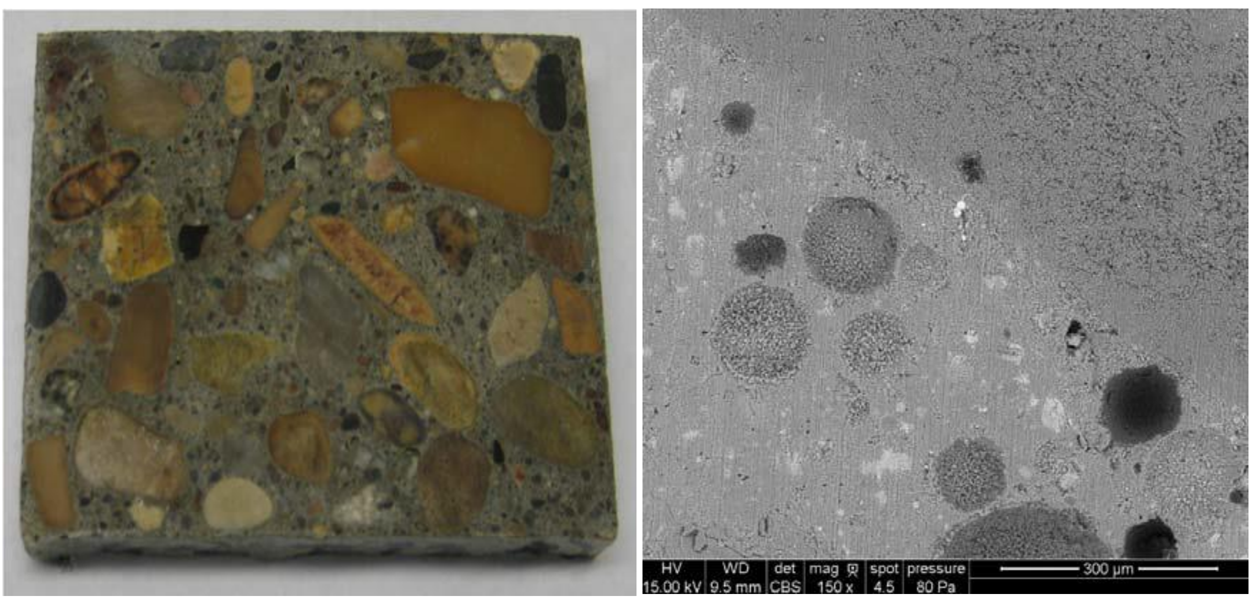


Figure 13. Typical sample tested in water after 56 days at 40°F: optical image (left) and SEM image (right)

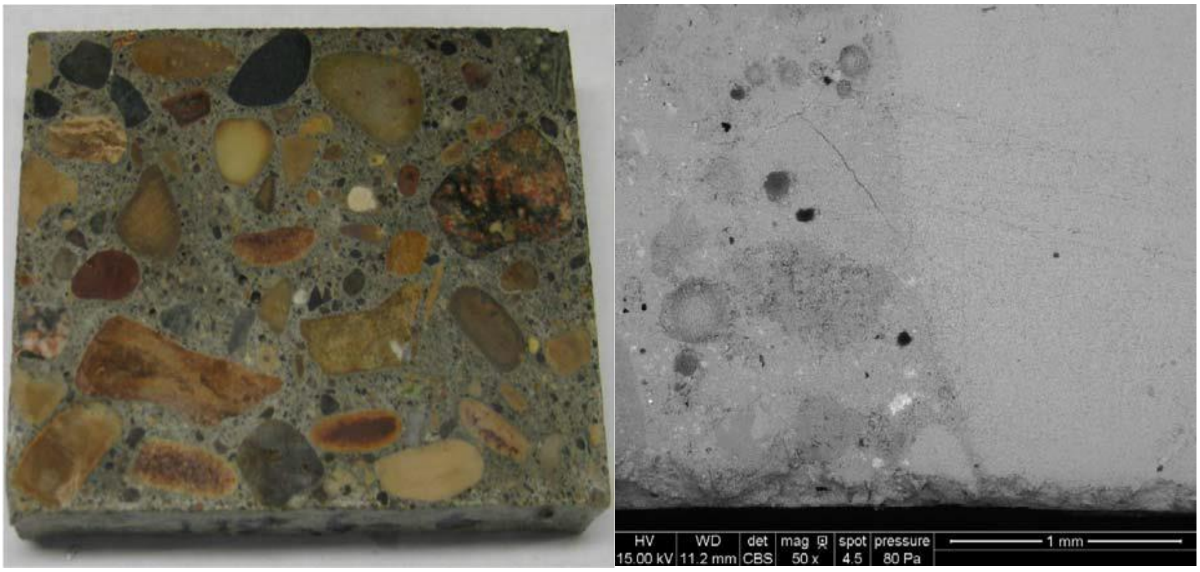


Figure 14. Typical sample tested in NaCl after 56 days at 40°F: optical image (left) and SEM image (right)

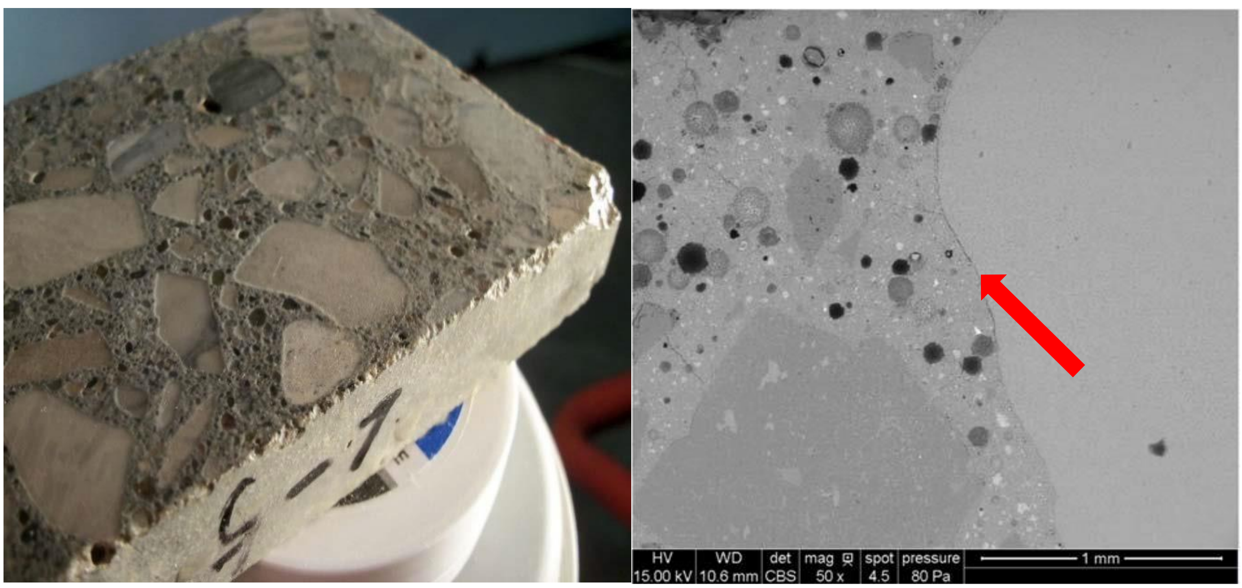


Figure 15. Typical sample test in $MgCl_2$ after 56 days at 40°F: optical image (left) and SEM image (right) with a crack adjacent to the aggregate indicated

These observations, along with references to previously reported work (Taylor et al. 2012, Sutter et al. 2008, Farnam et al. 2015), lead to the following conclusions:

- Exposure to water and NaCl above freezing temperatures results in negligible distress.
- The failure mechanism in $MgCl_2$ does not appear to be related to any of the three hypothesized above.
- The paste appears to expand in the presence of $MgCl_2$ and thus becomes debonded from the coarse aggregate particles that are not expanding. The mechanism of expansion is likely the

formation of calcium oxychloride ($Ca(ClO)_2$) in the paste, as reported by Sutter et al. 2008 and Farnam et al. 2015.

It is notable that this distress is occurring in samples that are not exposed to freezing conditions. This is consistent with the findings of Farnam et al. (2015) that calcium oxychloride will form at temperatures above 32ºF.

Influence of Pore Sizes on Paste Freezing and Thawing Durability

The pore structure of the cement paste affects water transport and thus the potential durability of a mixture. This may be considered in the same manner as the pore structure of aggregates influences D-cracking risk where the following is true:

- A coarse pore structure is durable under freeze-thaw conditions because water is free to enter or leave the system.
- A very fine pore structure is also durable because water cannot penetrate into the system.
- However, an intermediate pore structure may potentially be at risk because water can enter the pores but evaporate out only with difficulty (Pigeon and Pleau 1995). Such a system, then, is at a higher risk of reaching critical saturation, which leads to damage in freezing and thawing conditions.

The purpose of the work conducted in this study was to examine the parallels between paste porosity and nondurable coarse aggregates.

Mercury intrusion porosimetry (MIP) was utilized to assess the pore structure of a set of cement pastes with different water-cement (w/cm) ratios (0.30, 0.35, 0.40, 0.45, and 0.60), supplementary cementitious materials (SCMs) (fly ash, silica fume), and drying treatments (oven dry and air dry) (Zhang and Taylor 2015). Paste samples were cured in sealed containers for 24 hours after mixing while being continually rotated to minimize the effects of bleeding until well after set time.

Air-dried samples were kept in their sealed bottles for 7 days before conducting the cyclic freezing and thawing test. Oven-dried samples were kept sealed in their bottles at 75°F until aged 7 days. The lids were then removed, and the oven-dried samples were kept in an oven at 122°F until constant mass was achieved. Samples were then shipped to a commercial laboratory for MIP testing using applied pressures ranging from 0.50 psi (3.45 kPa) to 60,000 psi (413685.4 kPa).

Paste samples prepared from the same mixtures were also subjected to freeze-thaw cycles following the same preparation and curing procedures as the samples prepared for the MIP tests. The freezing and thawing test consisted of placing the dried samples in a freezer at 0°F (-18°C) for 12 hours. After that, samples were placed in a laboratory to thaw to 70°F (21°C). Most samples were distressed after one freeze-thaw cycle, but the sample with a w/cm ratio of 0.40 and with 20% C fly ash survived five freeze-thaw cycles before distress was observed.

The data collected are presented in Figures 16 through 19.

Figure 16 shows the pore size distributions for the oven-dried pastes made with plain cement and with w/cm ratios ranging from 0.30 to 0.60.

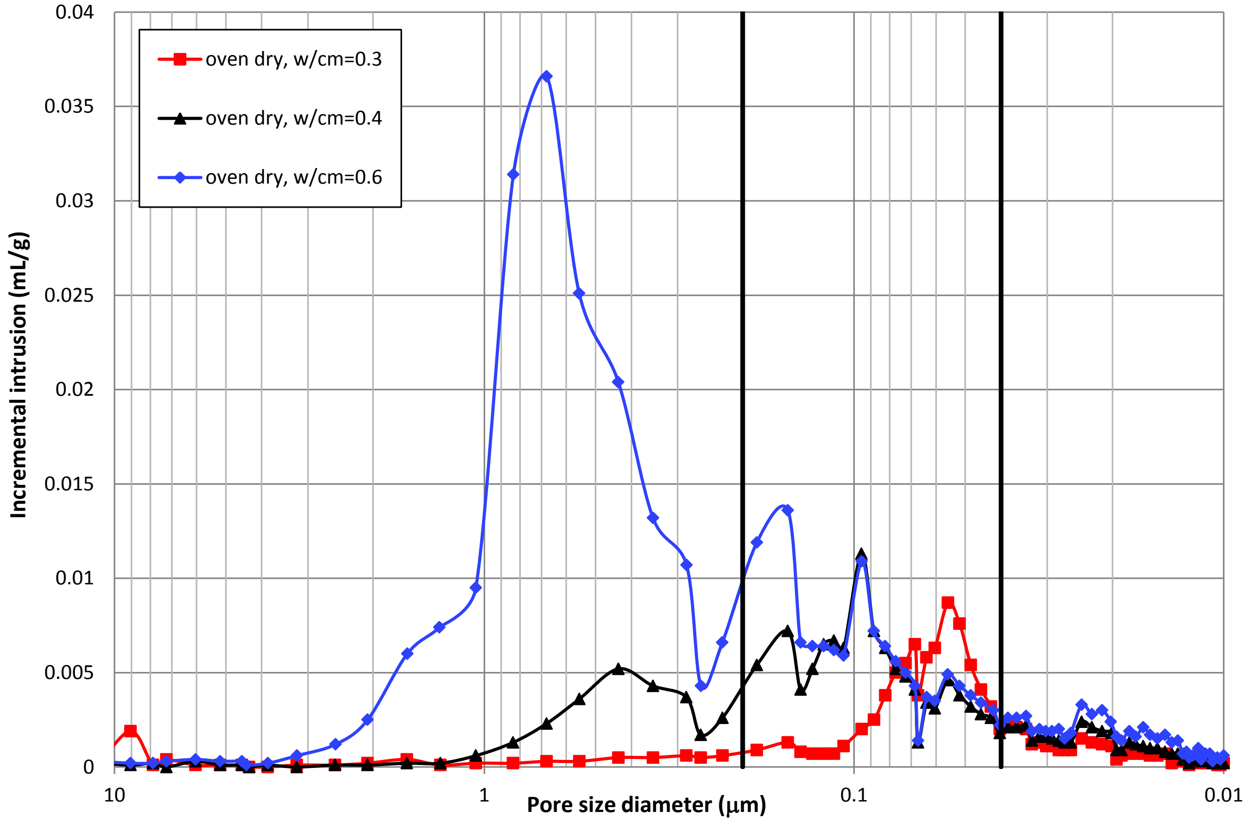


Figure 16. Pore distribution of oven-dried paste with various w/c ratios

The curves indicate the pore size distribution of each sample, and the area under each curve indicates the total porosity of that sample.

The darker vertical lines in Figure 16 are the range of values normally considered to indicate aggregates at high risk of D-cracking (0.20 to 0.04 µm). As expected, decreasing the w/cm ratio significantly decreases the porosity of the systems, as exhibited by the areas under the lines. In addition, decreasing the w/cm ratio pushes the peak of each line to the right, indicating that the systems contain finer pore systems. It is notable that the peaks for the mixtures with w/cm ratios equal to 0.3 and 0.4 are within the range where drying is difficult. While the mixture with a w/cm ratio equal to 0.6 also has a peak in the same range, the bulk of the curve is toward the coarse side of the envelope.

Freeze-thaw testing (Figure 17) indicated that the greatest distress was in the sample with a w/cm ratio of 0.4.

Figure 17. Oven-dried paste samples with different w/cm ratios after one freeze-thaw cycle

This is consistent with the model, which holds that open systems allow water to move freely, tight systems do not allow sufficient water to enter, and intermediate systems allow water to enter but not to leave readily.

Figure 18 provides the pore size distribution of oven-dried paste samples with a w/cm ratio of 0.40 and containing different binder systems.

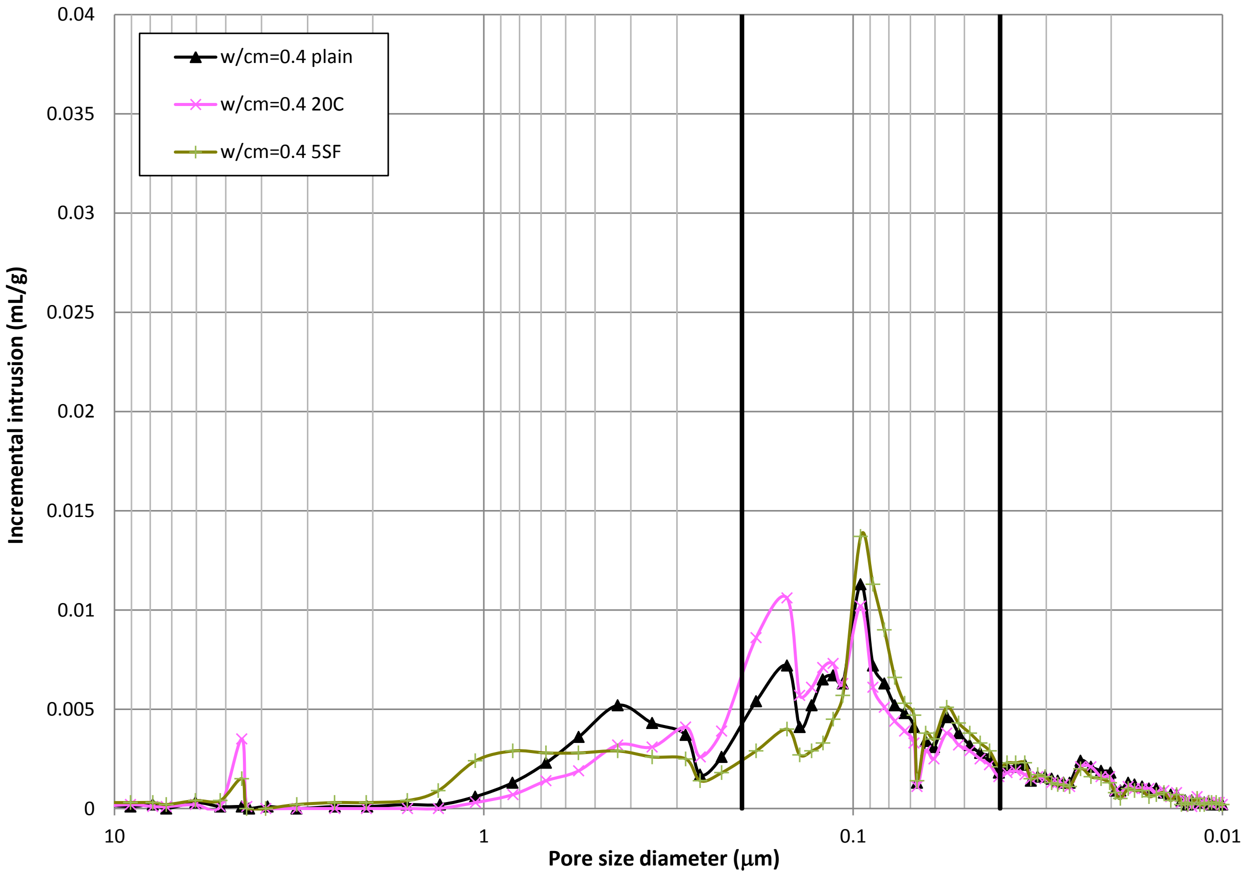


Figure 18. Pore distribution of samples with w/c = 0.4 and various binder systems after 7 days hydration

No significant differences were observed between the mixtures. This result indicates that w/cm ratio is the primary controller of the pore structure of the paste at two weeks of age. This is consistent with the literature, which has stated that SCMs do not significantly influence the pore size of the paste samples during the early stage of curing.

In the freeze-thaw testing, the plain sample had the most distress, and the sample containing 20% C fly ash had the least distress. It is possible that the damage incurred by drying is less marked in the presence of fly ash.

Figure 19 shows the pore size distributions of paste samples with a w/cm ratio of 0.60 and treated by oven or air drying.

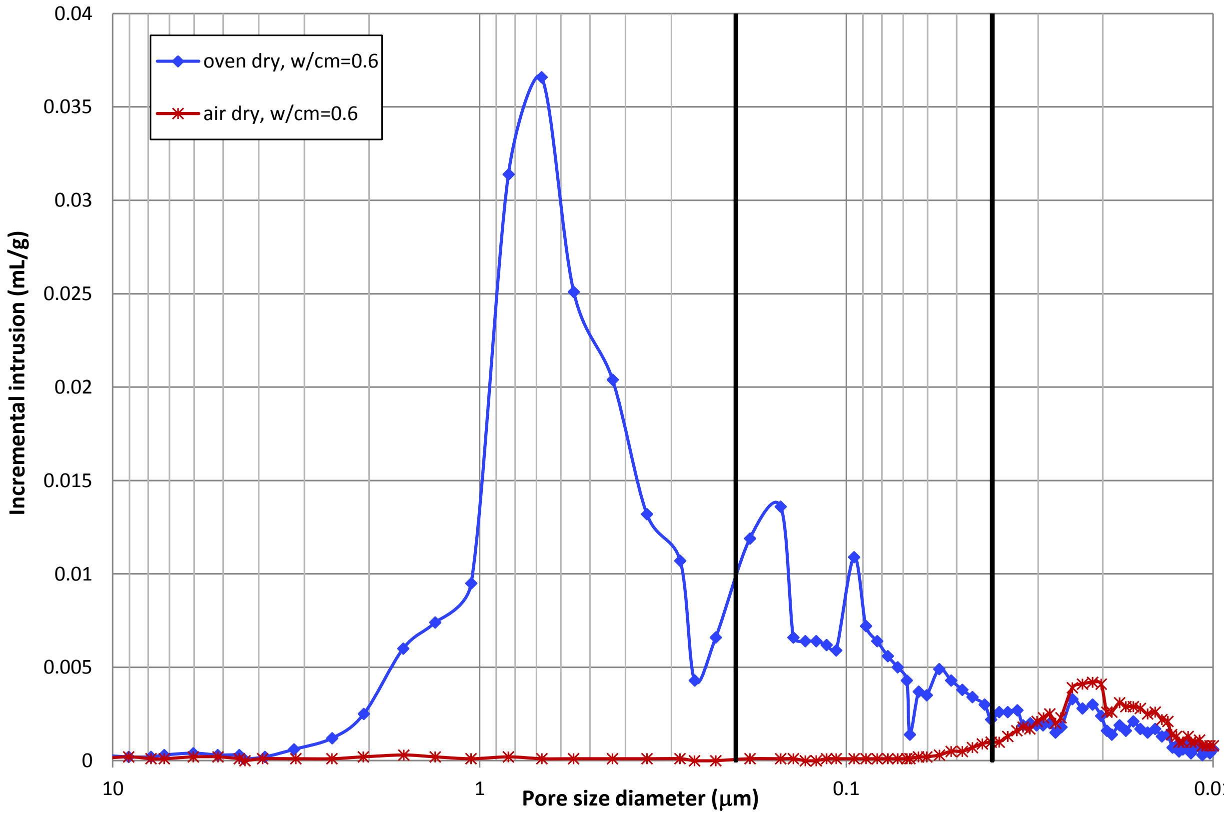


Figure 19. Pore size distribution of samples with w/c = 0.6, oven dry versus air dry

The data from the oven-dried sample show significantly larger pores and greater porosity than the data from the air-dried sample, as expected. This reflects the significant effect that the water remaining in the pores has on the information provided by a MIP test. Moreover, the air-dried samples were cured for 35 days and the oven dried samples were cured for 14 days, with the effect that the longer curing time resulted in more hydration product being formed, which thus reduced porosity.

In the freezing and thawing test, no visible damage was observed in the air-dried sample, but the oven-dried sample exhibited significant damage. This is likely due to damage incurred in the sample during oven drying.

The following conclusions can be drawn from this task:

- Increasing the w/cm ratio increased the total porosity and pore sizes of the hardened cement paste. Most notably, the peak pore sizes in the lower w/cm ratio mixtures were within the range indicated as problematic based on the mixtures’ ability to allow water to evaporate.

- The high w/cm ratio mixture had similar peaks in the fine zone but had a far larger peak on the coarse side, likely meaning that water is able to enter and leave the system readily, which thus allows the system to dry out enough to avoid freezing-related distress. This is not a motivation to specify high w/cm mixtures because of the associated negative effects, but it does mean that mixtures at w/cm of about 0.40 have to be provided some other protection such as an adequate air void system.

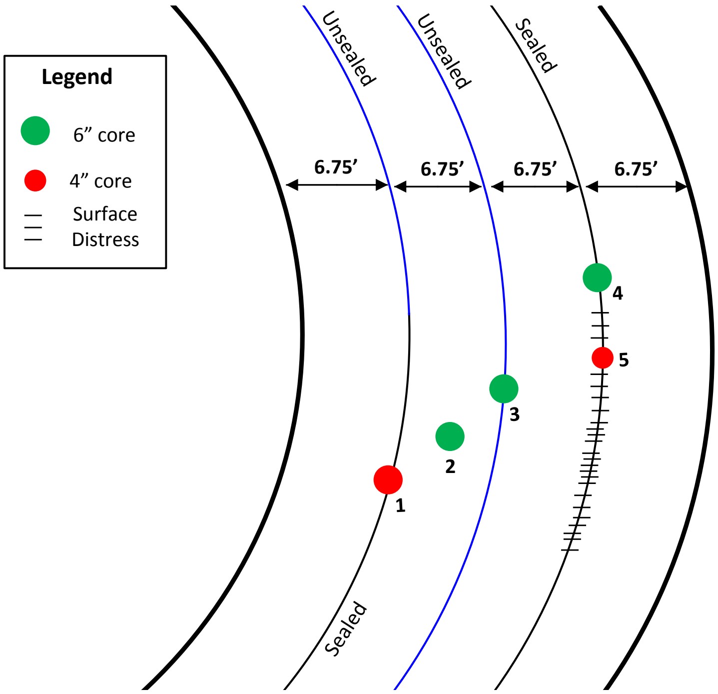
Effect of Subsurface Permeability

Water that is trapped in a pavement system increases the risk of distress due to mechanisms such as saturated freezing and thawing. This can be avoided by providing sufficiently permeable subsurface layers to drain water from the pavement system.

This task was aimed at increasing understanding of the relationship between concrete pavement performance and the permeability of subsurface layers. The results of field borehole permeameter tests conducted for this task on a city street indicate that a low-permeability subsurface layer may correlate with joint deterioration under freezing conditions. Laboratory falling head permeability tests conducted for this task on a similar base material in a frozen condition show that permeability decreases as moisture content increases and that freezing of the moist base material significantly reduces permeability.

Field tests were conducted on a city street in Iowa. The two-lane street serves office buildings and is approximately 0.8 km (1/2 mile) long. The street was reportedly paved using concrete in 1997 in one day using a full-width slipform paver running from southwest to northeast.

The extent of the distress was mapped, along with details of where joints had been sealed (Figure 20).



not to scale, west on the left

Figure 20. Plan view of coring and distressed locations

Five cores were extracted from the pavement over a period of two years. Core 1 from a sound joint and Core 4 from a distressed joint were sent for petrographic examination. Figure 21 illustrates a distressed joint, while Figure 22 shows Core 4 obtained from that joint.

west on the left

Figure 21. Field view of the location of Core 4, showing joint distress

Figure 22. Core 4 taken from the distressed joint

The core exhibits bottom-up distress, which indicates that saturation of the concrete was from a source of water at the bottom of the slab.

Field borehole permeameter test results for all locations conducted in different seasons are summarized in Table 3.

Table 3. Average hydraulic conductivity of base by season

Core	Location	Season	K (cm/s)	K (ft/day)	Time to drain ≤ 50% (days)	Time to drain ≥ 50% (days)
1	Joint Sealed Sound	Summer	0.0022	6.2	5.8	30.8
		Winter	0.0007	1.9	18.8	100.4
2	Mid-panel	Spring	0.0086	24.5	1.5	7.8
3	Joint Unsealed Sound	Summer	0.0011	3.0	11.9	63.6
		Winter	0.0008	2.2	16.2	86.7
4	Joint Sealed Distressed	Summer	0.0020	5.7	6.3	33.5

The results from the summer tests show a small difference between the distressed sealed joint (Core 4) and the sound sealed joint (Core 1), but the unsealed joint (Core 3) is less permeable than the sealed joints (Core 1 and Core 4). The subsurface layer below the middle panel (Core 2) is more permeable than the subsurface layer below the joints, which may be due to fine materials penetrating the joints into the base layer. The permeability during summer was higher than during winter in both samples, likely because ice is impermeable.

The permeability test results from all three locations are low compared with the sufficient permeable base requirement, which ranges from 0.0529 cm/s (150 ft/day) to 0.1058 cm/s (300 ft/day) (Rodden 2010). The time to drain more than 50% of the drainable water and the time to drain less than 50% of the drainable water were determined using the Pavement Drainage Estimator (PDE) Version 1.04, which was developed by White et al. (2004). Field permeability measurements indicate that the subsurface layer on this street is insufficiently permeable, which can cause deterioration of the joint.

The influence of freezing on the permeability of moist base material was then evaluated in the laboratory. Due to the limited amount of material that could be sampled from the field, a selected base material with a gradation similar to that of the base material from below the mid-panel was used in the laboratory permeability test. Samples were prepared at moisture contents of 0% to 10% at 2% increments and then compacted with standard proctor energy. The compacted samples were frozen at -18°C (0°F) for 24 hours before a falling head permeability test was conducted. The temperature was chosen to mimic the temperature experienced in Iowa that winter. An antifreeze windshield washer fluid with a freezing point of -29°C (-20°F) was used as the test fluid to prevent it from freezing during testing (Figure 23).

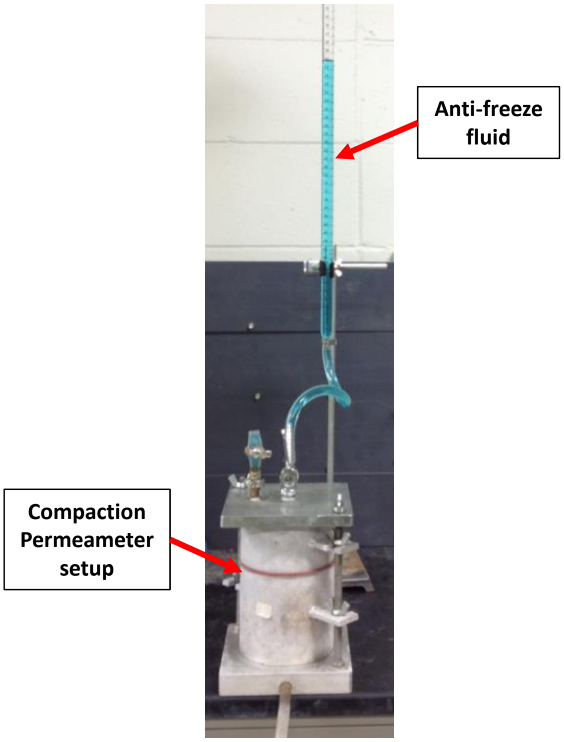


Figure 23. Laboratory falling head permeability test setup

Figure 24 illustrates the relationship between moisture content and the dry unit weight of the compacted specimens.

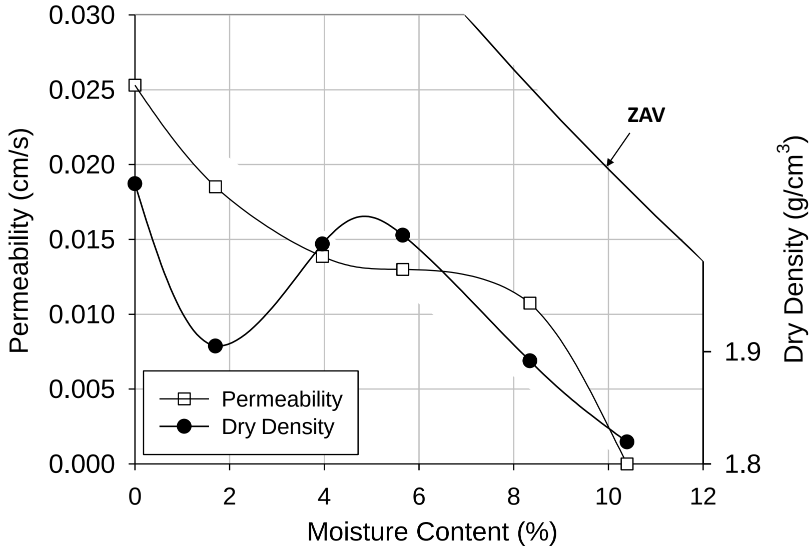


Figure 24. Moisture and permeability relationship under a frozen condition

The sample has a maximum dry unit weight when the moisture content is about 5%. Figure 24 also reports the permeability data as a function of moisture content. The permeability decreases as moisture content increases under a frozen condition, and the frozen, saturated sample was impermeable. This finding supports the hypothesis that freezing water within a moist sample increases pore blocking.

Table 4 summarizes the drainage coefficient of the base material using the data obtained from the laboratory tests.

Table 4. Estimated drainage coefficient based on laboratory permeability data under frozen conditions

Water content (%)	Dry density (g/cm^3)	Under frozen conditions		
		K (cm/s)	Time to drain ≤ 50% (days)	Time to drain ≥ 50% (days)
0.0	2.1	0.0253	0.5	2.7
1.7	1.9	0.0185	0.7	3.6
4.0	2.0	0.0139	0.9	4.9
5.7	2.0	0.0130	1.0	5.2
8.3	1.9	0.0107	1.2	6.3
10.4	1.8	0.0000	NA	NA

The PDE was used to estimate the time to drain less than 50% and more than 50% of the drainable water for a pavement system that has such base material. The PDE is a Microsoft Excel–based spreadsheet program that can be used to estimate the minimum required hydraulic conductivity of a pavement base layer and/or the time to achieve a given percent drainage. The dimensions of the pavements, the infiltration rate, and the effective porosity of the base material are required for estimating the required hydraulic conductivity (K) based on steady-state flow analysis. The following design parameters were used in this work:

- Infiltration rate per crack = 0.22 m^3/day/m (as recommended by Ridgeway [1976])
- Width of the pavement = 8.2 m (measured on site)
- Cross slope = 2.1% (obtained from design)
- Number of lanes = 2 (obtained from design)
- Thickness of base layer = 0.15 m (obtained from design)
- Effective porosity of the material = 30% (for open-graded materials, the porosity of the material equals the effective porosity)

The results indicate that the selected base material is slowly permeable under frozen conditions and that samples become less permeable with increasing moisture contents.

Effect of Sawing

An exercise was conducted in the laboratory to assess whether sawing practice influences the amount of damage in a joint. A 12 by 18 by 4 inch slab was cast outdoors using a standard paving mixture. A handheld saw fitted with a diamond blade was use to dry-cut joints in the slab starting too early (as indicated by the extreme raveling). The operator was asked to push hard on the blade and to induce a curve to mimic the worst possible practice (Figure 25).

Figure 25. Saw cutting the test slab

After the slab had been allowed to harden and gain strength, a full-depth section was cut perpendicular to the hand-sawn joints to observe the condition of the concrete at the bottom of the cuts.

Following examination under an optical microscope, the only evidence of damage was a small piece of aggregate cracked at the tip of one of the cuts (Figure 26).

Figure 26. View of damage at saw cut tip

SUMMARY

Based on all of the work conducted under this contract, the parallel work funded by the Federal Highway Administration (FHWA), and other research conducted at Purdue University and Michigan Technological University, the following may be concluded with respect to the mechanisms and prevention of premature joint deterioration:

- Two primary mechanisms appear to be driving distress:
  - Freeze-thaw damage incurred in saturated concrete. This typically appears as thin flakes. Saturation may be due to the following:
    - The presence of deliquescent deicing salts
    - Uncracked slabs or tight cracks under saw cuts, which prevents drainage
    - Poor drainage structures under the slab
    - Water ponding in low-lying elements
    - High water tables
    - A paste microstructure with insufficient air to slow saturation
    - A pore system that slows or prevents drying
  - Paste deterioration due to chemical attack. Distress may appear as cracking at regular intervals parallel to the saw cut and/or as a loss of paste, leaving clean aggregates in the voids. Paste deterioration may be due to the following:
    - Formation of expansive calcium oxychloride in the presence of calcium and magnesium chloride at temperatures > 35ºF
    - Ettringite deposition that accelerates saturation of air voids
    - Formation of expansive Friedels' salt
- The following can reduce the risk of distress:
  - Use of a low w/cm ratio, ~ 0.40 to 0.42 to reduce permeability
  - Appropriate use of supplementary cementitious materials
  - Ensuring an adequate air void system behind the paver
  - Selection of cementitious systems with high Si/Ca ratios that are more resistant to oxychloride formation
  - Paying attention to drainage at all locations so that joints can dry out
  - Application of penetrating sealants that will slow water and salt penetration into the microstructure (Castro et al. 2011)
  - Limiting the use of aggressive salts to times and temperatures (typically <15ºF) when they are necessary for safety

OTHER PRODUCTS OF THIS RESEARCH

A number of training sessions were conducted that were partially or fully funded by this project. Workshops targeted at municipal jurisdictions were held at the following locations:

- Des Moines, Iowa – January 11, 2013
- Eau Claire, Wisconsin – January 22, 2013
- Sioux Falls, South Dakota – February 14, 2013
- Indianapolis, Indiana – February 28, 2013
- Plymouth, Michigan – March 7, 2013
- Long Island City, New York – March 26, 2013
- Lakeville, Minnesota – April 18, 2013
- Bloomington, Illinois – April 10, 2014
- Fargo, North Dakota – April 17, 2014

The agenda for the six-hour sessions included the following topics:

- Mechanisms of joint deterioration
- Drainage issues and solutions
- Achieving what is needed: guide specifications for mixture and construction practices
- Quality assurance and testing
- Industry-led discussion
- Partial-depth repairs: thin overlays and reestablishing load transfer

The workshop materials included PowerPoint presentations on the above topics and the following documents, which were provided on a CD to each participant:

- Investigation of Deterioration of Joints in Concrete Pavements
- Guide for Optimum Joint Performance of Concrete Pavements
- Design Guide for Improved Quality of Roadway Subgrades and Subbases
- Guidelines for Minimizing the Deleterious Chemical Effects of Deicers on Portland Cement Concrete
- Concrete Pavement Mixture Design and Analysis (MDA)
- Concrete Pavement Mixture Design and Analysis (MDA) Commentary
- Field Reference Manual for Quality Concrete Pavements
- Testing Guide for Implementing Concrete Paving Quality Control Procedures
- Guide for Partial-Depth Repairs of Concrete Pavements
- Concrete Pavement Preservation Manual

In addition, the following publications have been produced as a result of the work conducted under this project:

Arribas-Colón, M., Radliński, M., Olek, J., and Whiting, N. *Investigation of Premature Distress Around Joints in PCC Pavements: Parts I & II*. Publication FHWA/IN/JTRP-2012/25 & FHWA/IN/JTRP-2012/26. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2012.

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Spragg, R., Castro, J., Li, W., Pour-Ghaz, M., Huang, P., and Weiss, W. J. Wetting and Drying of Concrete in the Presence of Deicing Salt Solutions, *Cement and Concrete Composites*, Vol. 33, Issue 5, May 2011, pp. 535-542.

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Zhang, J., and Taylor, P. Pore Size Distribution in Cement Pastes in Relation to Freeze-Thaw Distress, *ASCE Journal of Materials in Civil Engineering*, Vol. 27, Issue 3, March 2015.

Zhang, J., Taylor, P., and Shi, C. Investigation of Approaches for Improving Interfacial Transition Zone-Related Freezing-and-Thawing Resistance in Concrete Pavements, *ACI Materials Journal*, Vol. 112, Issue 5, September-October 2015, pp. 613-618.

Zhang, J., White, D., Taylor, P., and Shi, C. A Case Study of Evaluating Joint Performance in Relation with Subsurface Permeability in Cold Weather Regions, *Cold Regions Science and Technology*, Vol. 110, 2015, pp. 19-25.

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