JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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Synthesis: Accelerating Implementation of Research Findings to Reduce Potential Concrete Pavement Joint Deterioration

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16. Abstract

Distress has recently been observed in the joints of some concrete pavements, primarily in the wet-freeze states. This distress often begins in longitudinal joints, followed by transverse joints and results in the significant loss of material from the joint area. Although it may only affect approximately 10% of the concrete pavements system-wide, it greatly reduces the service life and increases maintenance costs of the pavements it effects. Primary issues that emerged from studies on this phenomenon include the importance of the timing of joint sawing, the width of the joint opening, degree of concrete or joint sealing, drainage and degree of saturation of the concrete at the joint, quality of the air void system, role of deicing chemicals, quality of curing, and the degree of restraint at the joint. Although this broad collection of issues implies that we still lack complete understanding of all causes of joint deterioration, it also makes it pretty clear that the observed damage is a result of combination of several factors. This study synthesizes completed research related to concrete pavements joint deterioration and provides information to advance the knowledge and understanding of the variables involved in in this deterioration process and suggests the best practices that can lead to its reduction or mitigation.

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EXECUTIVE SUMMARY

SYNTHESIS: ACCELERATING IMPLEMENTATION OF RESEARCH FINDINGS TO REDUCE POTENTIAL CONCRETE PAVEMENT JOINT DETERIORATION

Introduction

Over the last several years, the Indiana Department of Transportation (INDOT) initiated multiple research projects focused on identifying the origins and failure mechanisms responsible for premature joint deterioration in concrete pavements, as well as on the development of potential guidelines for eliminating or slowing down this distress. Similar studies have been performed by other states or groups of states through the pooled fund study mechanism.

A number of potential causes and mechanisms responsible for the observed distress have been proposed, and a few methods have been suggested to detect, repair, or potentially mitigate this distress. Unfortunately, to date no unified, comprehensive approach has been developed to document the steps and design changes needed to implement revisions for the construction or maintenance of these joints.

The objective of this study was to develop a synthesis document that compiles and analyzes recorded laboratory and field experiences related to concrete pavement joint deterioration. The findings serve as a basis to develop recommendations for potential joint damage detection, repair, mitigation, and preventive techniques that can be used to eliminate—or at least substantially reduce—the occurrence of joint deterioration in the future.

The intent of this synthesis is to advance the knowledge and understanding of the variables involved in joint deterioration and suggest best practices that can lead to its reduction or mitigation.

Findings

The following primary issues emerged from analysis of the joint deterioration studies presented in this synthesis: the importance of the timing of joint sawing, the width of the joint opening, the degree of concrete or joint sealing, drainage and the degree of saturation of the concrete at the joint, the quality of the air void system, the role of deicing chemicals, the quality of curing, and the degree of restraint at the joint. Although this broad collection of issues implies that we still lack full understanding of all causes of joint deterioration, it also makes clear that the observed damage results from a combination of several factors that can be generally classified into two broad categories:

1. classic freeze-thaw damage due to increased levels of saturation for pavement joints with no or low salt concentrations, and
2. chemical reactions between chloride bearing salts (especially $CaCl_2$ and $MgCl_2$) and the cementitious matrix (specifically calcium hydroxide, $Ca(OH)_2$) for high salt concentrations.

The following list provides a short summary of the main findings from the previous projects. The numbers in parentheses at the end of the individual list entries identify sections of the synthesis document (this report) that provide the specifics of these findings.

1. Increase the Specified Volume of Air Entrainment and Reduce the Variation in Air Content (3.1)
2. Reduce the Volume of Cementitious Paste in Concrete Pavements (3.2)
3. Reduce the Values of Water-to-Cementitious Materials Ratio Used in Concrete Pavements (3.3)
4. Use a Formation Factor to Specify the Transport Properties of Concrete (3.4)
5. Use Supplementary Cementitious Materials (SCM) to Reduce Susceptibility to Salt Damage (3.5)
6. Use a Topical Treatment for Concrete That Repels Water or Seals the Concrete (3.6)
7. Reduce the Tie Bar Size and Spacing to the Necessary Level (3.7)
8. Remove the Backer Rod or a Cavity in the Design of Pavement Joints (3.8)
9. Consider the Use of Unsealed Joints (3.9)
10. Use a Capillarity Break Below the Pavement (3.10)
11. Reduce the Strength Required to Open a Pavement to Traffic (3.11)
12. Increase the Use of Maturity to Accept Concrete Pavement at Early Ages While Long-Term Strength Is Used in Design (3.12)
13. Improve the Use of Methods to Detect Water Ponding in Concrete Pavements (3.13)
14. Examine the Proportion of Salts in Blended Systems (3.14)

Implementation

This project was intended to be a state-of-the-art synthesis on concrete pavement joint deterioration. The findings presented in this report will allow INDOT to benefit from a systematic review of numerous study results and will prevent duplication of efforts, resulting in potential cost savings.

The preliminary results from this study were presented to INDOT personnel in the form of technical recommendations at the Joint Deterioration Workshop held on April 27, 2015 (see Appendix to this report). Following the workshop, some of the suggested recommendations were implemented (e.g., a change in the types of deicing salts used). Implementation of other findings will require joint efforts between INDOT and contractors, resulting in specification changes. Premature joint deterioration significantly impacts a wide range of issues, from the selection of the type of pavement material, to the cost of pavement repair and maintenance, to the cost to the user. To avoid costly mistakes, this problem must be addressed through the systematic process of making fact-based decisions regarding all aspects of pavement construction and maintenance. The numbered list provided in the Findings section above serves as a starting point for implementation activities. The options listed there can be used either independently or in combination to address specific technical issues.

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1. SUMMARY OF RECOMMENDATIONS

Concrete pavements are often specified due to their longevity. While a long-term maintenance free pavement is desired, there have been growing concerns regarding observations of distress at some joints in some concrete pavements, mostly in the wet-freeze states. During the last decade, several research projects have been conducted which were focused on identifying the mechanisms responsible for premature joint deterioration in concrete pavements. While a number of potential mechanisms responsible for the observed distress have been proposed, they can generally be classified as either:

1. classic freeze-thaw damage due to increased levels of saturation for pavement joints with no or low salt concentrations, and
2. chemical reactions between chloride bearing salts (especially $CaCl_2$ and $MgCl_2$) and the cementitious matrix (specifically calcium hydroxide, $Ca(OH)_2$) for high salt concentrations.

Chapter 2 will provide background on these two distress mechanisms.

While these mechanisms are being better understood, to date there has been no unified, comprehensive approach developed to document steps and design changes needed to implementing changes in mixture proportioning, construction, maintenance or salting practices that impact these joints.

Chapter 3 presents a series of implementable items that can be utilized to reduce the potential for joint deterioration in concrete pavements and to mitigate cases of joint deterioration in the future (it should be noted that some of these have already been implemented as a result of this project or previous, related projects). These items were presented to INDOT on April 27, 2015 (see slides in Appendix). This document also discusses a few methods to detect or potentially prevent/mitigate this distress. The following list provides a short summary of the main findings from the previous projects.

1. Increase the Specified Volume of Air Entrainment and Reduce the Variation in Air Content (3.1)
2. Reduce the Volume of Cementitious Paste in Concrete Pavements (3.2)
3. Reduce the Water-to-Cementitious Materials Used in Concrete Pavements (3.3)
4. Use a Formation Factor to Specify the Transport Properties of Concrete (3.4)
5. Use Supplementary Cementitious Materials (SCM) to Reduce Susceptibility to Salt Damage/ Use a Performance Test for Mixture Design to Limit Calcium Oxychloride Damage (3.5)
6. Use a Topical Treatment for Concrete That Repels Water or Seals the Concrete (3.6)
7. Reduce the Tie Bar Size and Spacing to the Necessary Level (3.7)
8. Remove the Backer Rod or a Cavity in the Design of Pavement Joints (3.8)
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14. Examine the Proportion of Salts in Blended Systems (3.14)

Chapter 4 provides background on each of the projects performed as a part of reaching these conclusions.

Chapter 5 provides summary of findings regarding the role of the drainage system

2. SUMMARY OF THEORETICAL CONSIDERATIONS FOR SATURATION AND DEICING SALT DAMAGE

2.1 Summary of Degree of Saturation

The classic freeze-thaw damage due to increased levels of saturation for low salt concentrations is addressed in items 1–4 and 6–10 from the list of recommendations in Chapter 1. While there are many thoughts on classic freeze thaw behavior, Figure 2.1 describes a sorption-based model for reaching a critical degree of saturation Fagerlund, 1977a, 1977b; Li, Pour-Ghaz, Castro, & Weiss, 2012; Lucero, 2015; Todak, 2015). Fagerlund (1977a, 1977b) pioneered the use of this sorption based approach and considers that concrete would not be able to withstand freezing when saturation levels exceed a certain critical level of saturation (e.g., 75–91%). This value has been measured to be 86% for mixtures representative of a typical concrete pavement (Li et al., 2012). However, more recent research has shown that this value can vary from 78–91% (Todak, Lucero, & Weiss, 2015). The critical degree of saturation will be assumed to be 85% for the examples discussed in this document.

Bentz, Ehlen, Ferraris, and Garboczi (2001) modified the sorption based approach assuming a single sorption rate by assuming a weather event (e.g., rain) of longer than a particular time (6 hours) was required to reach the second level of saturation and this was used to predict freeze-thaw damage in concrete pavements.

Lucero, Bentz, Hussey, Jacobson, and Weiss (2015) used neutron radiography to examine the relationship between the initial rate of absorption and pores that were being filled. Lucero et al. (2015) proposed that the initial absorption (shown in blue) corresponds to the filling of gel and capillary pores while the secondary rate of sorption (shown in red) was related to the filling of larger pores like air voids. The impacts of the sorption-based model on concrete specifications have been discussed by Todak et al. (2015).

The findings from Lucero et al. (2015) have indicated that the transition between the initial absorption and secondary absorption (commonly referred to as the nick point) can be described by the degree of saturation that fills in all the pores in a concrete with the exception of the air voids (this would include the gel and capillary pores). The Powers-Brownyard (1948) model can be used to determine the degree of saturation at the nick point. This degree of saturation is a function of the entrained air volume (Figure 2.2a). It can be noticed that concrete with more air has a lower degree of saturation (i.e., is further away from reaching critical saturation). More recent research has focused on extending the Powers-Brownyard model to a thermodynamics based model that uses Gibbs Energy Minimization Software (GEMS) to enable a wider range of material chemistries to be used (i.e., concretes with supplementary cementitious materials (Azad, Suraneni, Isgor, & Weiss, 2017; Glosser, Azad, Suraneni, Isgor, & Weiss, 2017). While the extension of the Powers-Brownyard model is in its infancy, this approach shows substantial promise.

Experiments have shown that when water is in contact with concrete (a 50 mm thick sample was used)

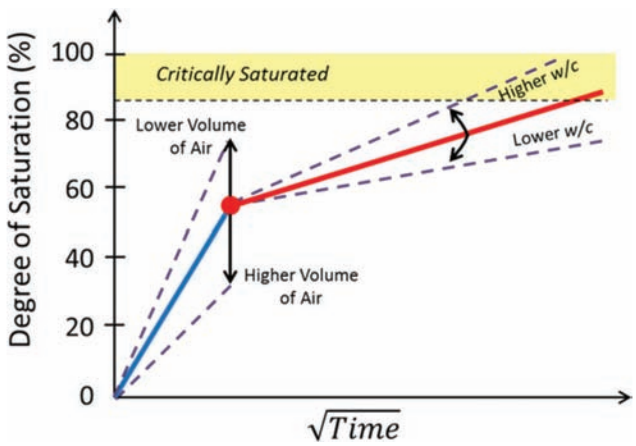

Figure 2.1 A conceptual illustration of the sorption-based model.

the nick point will generally be reached during the first 24 hours (Lucero et al., 2015). Because of this, the prediction of service life for concrete pavements would not need to consider the initial absorption and the prediction can begin assuming that the matrix is saturated (i.e., S_{nick}). With this assumption, the secondary rate of sorption can be used to predict the time required to reach the critical degree of saturation (t) as shown in Eq. 2.1:

$$S_{CR} = S_{NICK} + \Delta S\sqrt{t} \tag{2.1}$$

where, S_{CR} is the critical degree of saturation, S_{NICK} is the degree of saturation between the initial and secondary absorption, which occurs when all the pores except the air voids are filled, ΔS is the secondary rate of sorption and t is time.

While S_{NICK} is dependent on the entrained air volume (Figure 2.2a), the secondary rate of absorption is strongly related to the quality of the matrix. Figure 2.2b illustrates the impact of the secondary sorption rate on the time to achieve critical saturation for a concrete made with an air content of 5.5% and a water to cement ratio (w/c) that varied from 0.39 to 0.45 (with S_{NICK} varying from 66% to 70%, respectively). The range of secondary sorption was measured by Castro, Bentz, and Weiss (2011) with 0.033 being representative of a mixture with a w/c of 0.39 and 0.053 being representative of a mixture with a w/c of 0.45.

Figure 2.3a provides an illustration of the influence of air content on the time it takes to saturate the concrete. It can be seen that the volume of air has a substantial influence on the time to reach critical saturation (shown as a dashed, horizontal line). Figure 2.3b illustrates the influence of w/c on the time to reach critical saturation, where the impact is due to the change in the rate of water absorption.

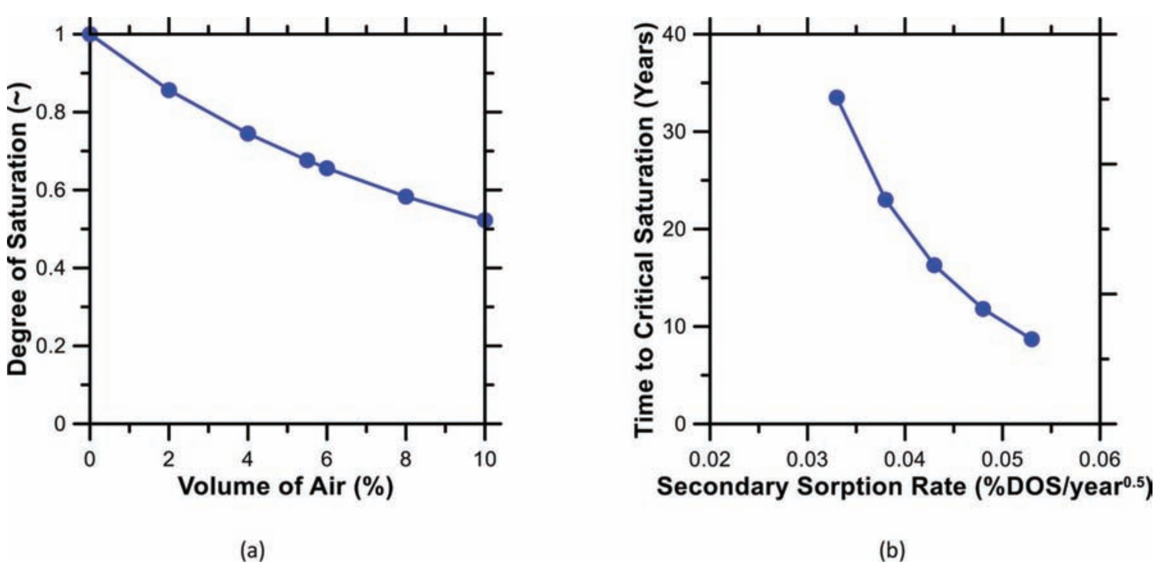

Figure 2.2 Influence of air content on degree of saturation at the nick point (a) and influence of the secondary rate of sorption on the time to reach critical saturation (b).

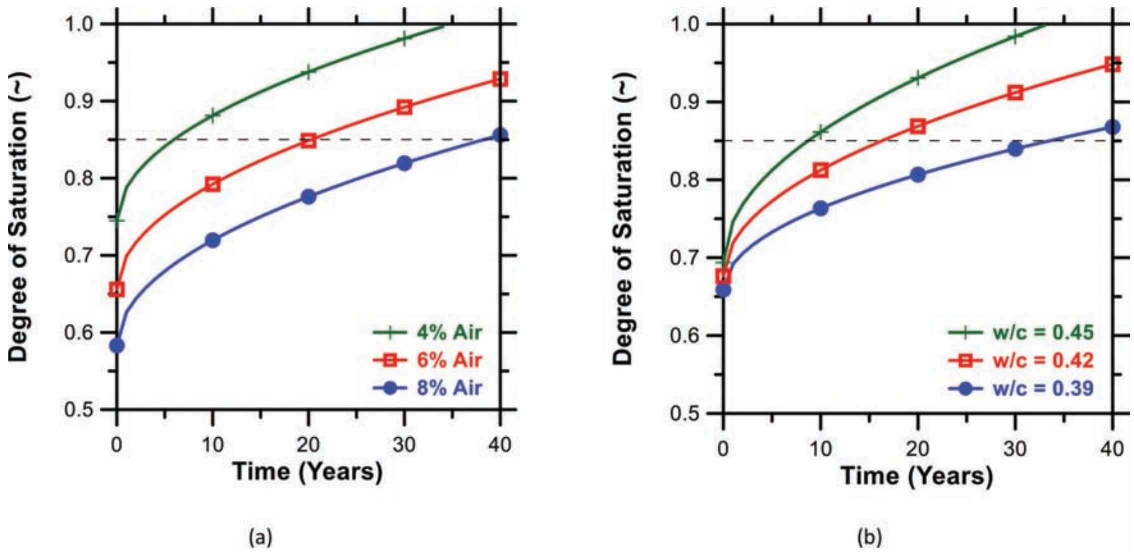

Figure 2.3 Illustration of the air content on the degree of saturation and the time to reach a critical degree of saturation (a) and the influence of water to cement ratio on the degree of saturation and the time to reach a critical degree of saturation (b).

2.2 Summary of the Reaction between Chloride Bearing Deicing Salts and the Cement Matrix

The effects of chemical reactions that occur between chloride bearing salts and the cementitious matrix for high salt concentrations are related to all of the issues addressed by items 1, 2, 5, 6, 8, 11, 12 and 14 listed in Chapter 1. Item 14 discusses a test method to detect or potentially prevent/mitigate this distress.

Some deicing salts (specifically $CaCl_2$ and $MgCl_2$) can react with cementitious materials (specifically calcium hydroxide ($Ca(OH)_2$) in the cementitious matrix) resulting in secondary reaction products in concrete that can diminish durability (Farnam, Washington, & Weiss, 2015; Mesbah, Cau-dit-Coumes, Renaudin, Frizon, & Leroux, 2012). While the chemical reactions that occur between the salt and matrix can be quite complex, there are simple approaches that can be taken to reduce the potential for deicing salt related damage to occur (Suraneni, Azad, Isgor, & Weiss, 2016a). These approaches include the use of supplementary cementitious materials (SCMs) like slag or fly ash to reduce the calcium hydroxide in the mixture and the use of topical treatments like penetrating sealers that provide a physical barrier between the salt and calcium hydroxide. A summary of the chemical reactions that can occur is presented below.

The first type of reaction that may be observed occurs between the chlorides in the deicing salt and the aluminate phases present in concrete is the reaction to form Friedel's or Kuzel's salts. The reaction for the formation of Friedel's salt is shown in Eq. 2.2 where calcium chloride ($CaCl_2$) reacts with tricalcium aluminate ($3CaO{\cdot}Al_2O_3$) from the binder to form Friedel's salt ($3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$). Similarly, calcium chloride can react with the hydration reaction product calcium monosulfoaluminate hydrate (AFm, $3CaO.Al_2O_3.CaSO_4.12H_2O$) to form Friedel's salt and gypsum (Eq. 2.3).

Freidel's Salt ($3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$)

$$CaCl_2 + 3CaO{\cdot}Al_2O_3 + 10H_2O \rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O \quad (2.2)$$

$$CaCl_2 + 3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O \rightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O + CaSO_4{\cdot}2H_2O \quad (2.3)$$

Calcium monosulfoaluminate hydrate ($3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O$) can also react with chlorides resulting in the formation of Kuzel's salt ($3CaO{\cdot}Al_2O_3{\cdot}0.5CaSO_4{\cdot}0.5CaCl_2{\cdot}11H_2O$), ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$), and aluminum hydroxide ($Al_2O_3{\cdot}3H_2O$) (Eq. 2.4) (Mesbah, Cau-dit-Coumes, Renaudin, Frizon, & Leroux, 2012). While the Friedel's and Kuzel's salt reactions can occur over a wide range of concentrations and temperatures, the formation of these phases is generally not considered to be very detrimental to the performance of concrete, other than reducing the space available for fluid movement into and out of air voids which would increase the degree of saturation (Farnam, Washington, & Weiss, 2015).

Kuzel's salt ($3CaO{\cdot}Al_2O_3{\cdot}0.5CaSO_4{\cdot}0.5CaCl_2{\cdot}11H_2O$)

$$\begin{aligned} 9[3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O] + 6Cl^- + 28H_2O \rightarrow \\ 6[CaO{\cdot}Al_2O_3{\cdot}0.5\,CaSO_4{\cdot}0.5\,CaCl_2{\cdot}11\,H_2O] + \\ 2[3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O] + \\ 2[Al_2O_3{\cdot}3H_2O] + 6OH^- \end{aligned} \quad (2.4)$$

The second type of reaction that may be observed occurs between calcium chloride and the calcium hydroxide to result in the formation of calcium oxychloride ($CaCl_2{\cdot}3Ca(OH)_2{\cdot}12H_2O$) as shown in Eq. 2.5.

Calcium oxychloride is expansive and can result in damage to the cement matrix.

Calcium Oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$)

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O \tag{2.5}$$

Greater amounts of calcium oxychloride form at higher salt concentrations (Bentz et al., 2001; Lucero et al., 2015) and at temperatures greater than freezing as shown by the red line in Figure 2.4 (Farnam, Todak, Spragg, & Weiss, 2015).

Recent research by Qiao, Suraneni, & Weiss (2018c) has expanded the isopleth for salts with a 20% $CaCl_2$ concentration by mass for different molar ratios as shown in Figure 2.5. It can be noticed then, when limited calcium hydroxide is present, the calcium oxychloride forms immediately (and nearly completely) upon cooling below the liquidus line, and higher concentrations require a more substantial reduction in temperature for the reaction to be completed.

While the previous equations have focused on calcium chloride as deicing salt, it should be noted that magnesium chloride ($MgCl_2$) deicing salt can also produce calcium oxychloride. $MgCl_2$ first reacts with $Ca(OH)_2$ to form brucite ($Mg(OH)_2$) (Eq. 2.6a). The magnesium exchanges with the calcium (Eq. 2.6b and 2.6c) resulting in a reaction similar to that shown for calcium chloride in Eq. 2.5. While the temperature for magnesium oxychloride formation is approximately 15 °C greater than calcium oxychloride (Farnam, Wiese, Bentz, Davis, & Weiss, 2015), samples exposed to $MgCl_2$ show both magnesium oxychloride and calcium oxychloride formation.

$$Ca(OH)_2 + MgCl_2 \rightarrow CaCl_2 + Mg(OH)_2 \tag{2.6a}$$

$$(3 \text{ or } 5)\ Mg(OH)_2 + MgCl_2 + 8H_2O \rightarrow (3 \text{ or } 5)\ Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O \tag{2.6b}$$

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow 3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O \tag{2.6c}$$

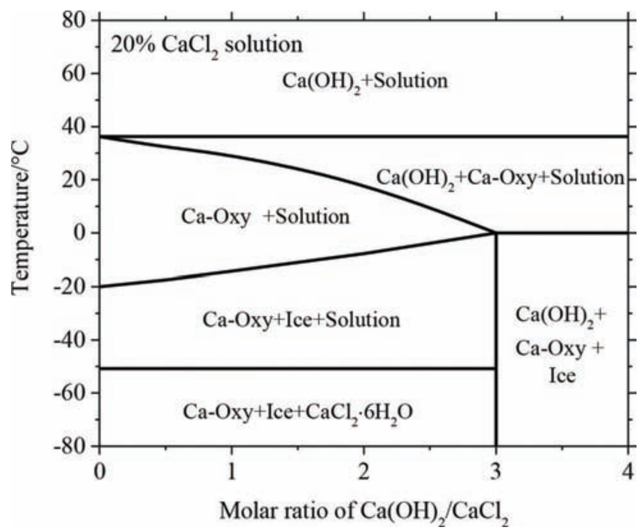

Figure 2.5 Phase isopleth section of the $Ca(OH)_2$-$CaCl_2$-H_2O system with varying $Ca(OH)_2/CaCl_2$ molar ratios (Qiao et al., 2018c).

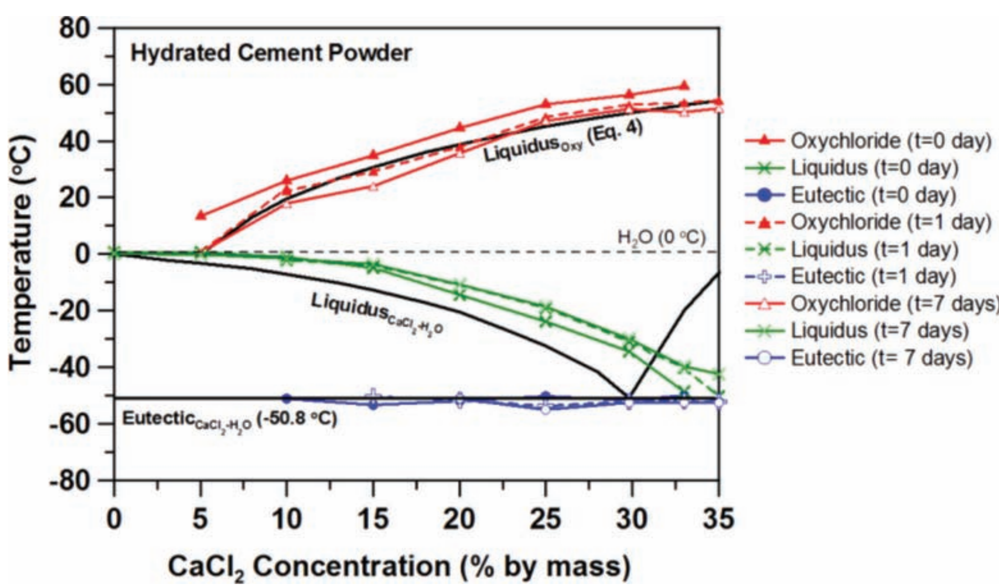

Figure 2.4 Phase diagrams illustrating the temperature for calcium oxychloride formation when hydrated cement paste encounters calcium chloride solution.

2.3 Summary of the Influence of Deicing Salts on Transport Properties of Concrete

It is important to note that the reaction that occurs between the chlorides in the deicing salt can dramatically reduce fluid transport in concrete. This can be seen in data from Figure 2.6 where the initial rate of absorption (sorptivity) can be dramatically reduced after the formation of calcium oxychloride formation (at concentrations higher than approximately 12% $CaCl_2$ at 23 °C). The reduction in a type I cement is more gradual than a type V cement due to the formation of the Friedel's and Kuzel's salt (Villani, Farnam, Washington, Jain, & Weiss, 2015). Lucero et al. (2017) demonstrated that the reduction in the rate of sorption was related to limited solution ingress due to the formation of new mineral phases (Eq. 2.2, 2.3, 2.4, 2.5 and 2.6) in the matrix that effectively 'seals off' the core of the concrete. This can also explain why chloride ingress rates are often much lower in systems that have been exposed to calcium or magnesium chloride (Bu, Luo, & Weiss, 2014).

2.4 Summary of the Damage of Cementitious Materials Exposed to Deicing Salts

There has been an increase in reports of premature deterioration around joints and saw cuts in concrete pavements (Glosser et al., 2017; Castro, Bentz et al., 2011; Suraneni et al., 2016a; Mesbah, 2012). The damage most commonly manifests itself in two forms (Weiss & Farnam, 2015). The first form is commonly associated with fluid saturation and classic freeze-thaw damage. In the first form cracks develop that are oriented parallel to the joints and occur within approximately 100–150 mm (4–6 in.) from the walls of the original joint. These cracks develop in response to spalling that begins at the base of the saw cuts used to construct the joints. The second mechanism is commonly associated with salt-matrix reaction and consists of the loss of concrete 'flakes' ranging from 3–6 mm (⅛–¼ in.) that are removed from around the joint. This damage tends to dislodge aggregate as calcium oxychloride preferentially forms around the aggregate since calcium hydroxide tends to deposit at the surface of the aggregate during hydration. In advanced stages of deterioration, both mechanisms may likely operate and large areas of material loss and spalling may occur around the joints.

The salt damage due to the chemical reactions has been quantified in the three cases of NaCl, $CaCl_2$ and $MgCl_2$ (Qiao, Suraneni, & Weiss, 2018a; Qiao, Suraneni, & Weiss, 2018b; Qiao, Suraneni, Tsui Chang, & Weiss, 2018). Figure 2.7 shows the different damage of cementitious materials when exposed to different deicing salts. $MgCl_2$ shows the greatest damage to the cement pastes (in Figure 2.7) and NaCl shows the least.

2.5 Summary of the Potential Methods to Mitigate the Damage of Cementitious Materials Exposed to Deicing Salts

The following recommendations aim to minimize the potential for joint deterioration in pavements where exposure to deicing chemicals are expected: (1) use concrete mixture designs that provide low w/c to reduce concrete fluid transport, (2) use SCMs to minimize the calcium hydroxide content of paste and reduce the potential to form oxychloride phases, and (3) have entrained air void systems with appropriate parameters for frost resistance.

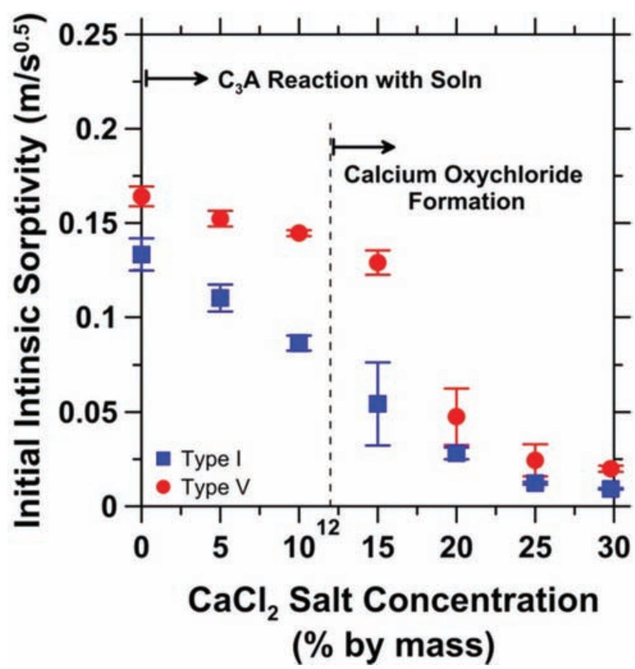

Figure 2.6 Reduction in the rate of water absorption due to reactions with salt.

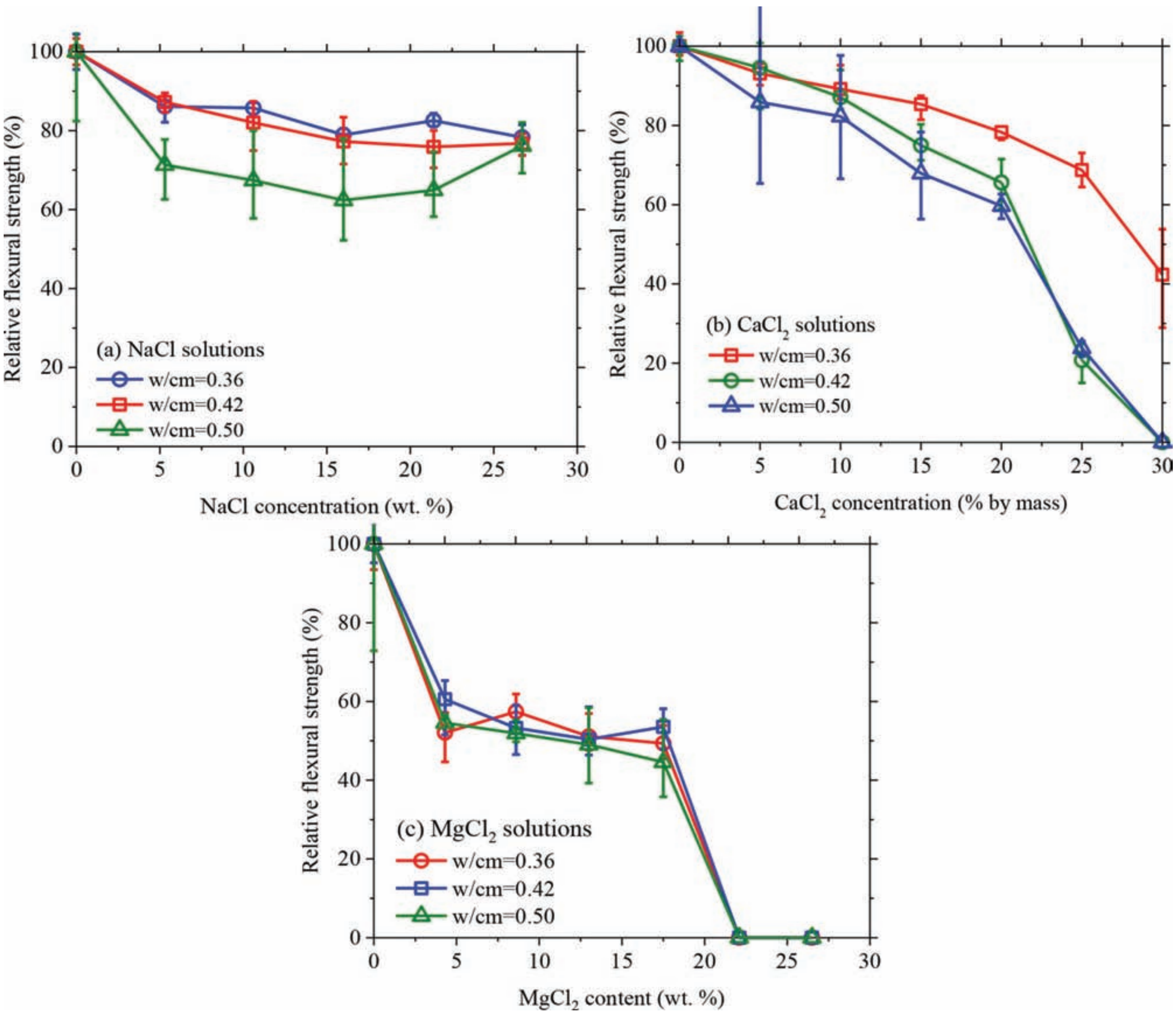

Figure 2.7 Relative flexural strength of pastes with different w/cm exposed to 21.6% NaCl (a), 20% $CaCl_2$ (b) and 17.5% $MgCl_2$ (c) solutions after a 50-5-50 °C thermal cycle, respectively (Qiao et al., 2018a, 2018b; Qiao, Suraneni, Tsui Chang, et al., 2018).

SCMs reduce calcium hydroxide in concrete due to both dilution and pozzolanic reaction (Weiss & Farnam, 2015). Figure 2.8a illustrates experimental results and Figure 2.8b illustrates results from experiments and a thermodynamic model indicating the benefits of using SCMs to reduce the potential for calcium oxychloride formation (Suraneni et al., 2016a; Suraneni, Azad, Isgor, & Weiss, 2016b). The addition of SCM reduces the calcium hydroxide which in turn reduces the calcium oxychloride formation (Monical, Unal, Barrett, Farnam, & Weiss, 2016; Monical, Villani, Farnam, Unal, & Weiss, 2016). Furthermore, Qiao et al. observed the smaller reduction in flexural strength of cement pastes with fly ash when exposed to NaCl, $CaCl_2$ and $MgCl_2$ solutions, as shown in Figure 2.9 (Qiao et al., 2018a, 2018b; Qiao, Suraneni, Tsui Chang, et al., 2018).

This suggests that concrete that has cement replaced with fly ash will be more durable and less prone to degradation. While increased SCM replacement works well for jointed plain concrete pavements and sidewalks that are unreinforced, the reduction in the pH of the concrete matrix may influence corrosion of reinforcing steel in reinforced concrete.

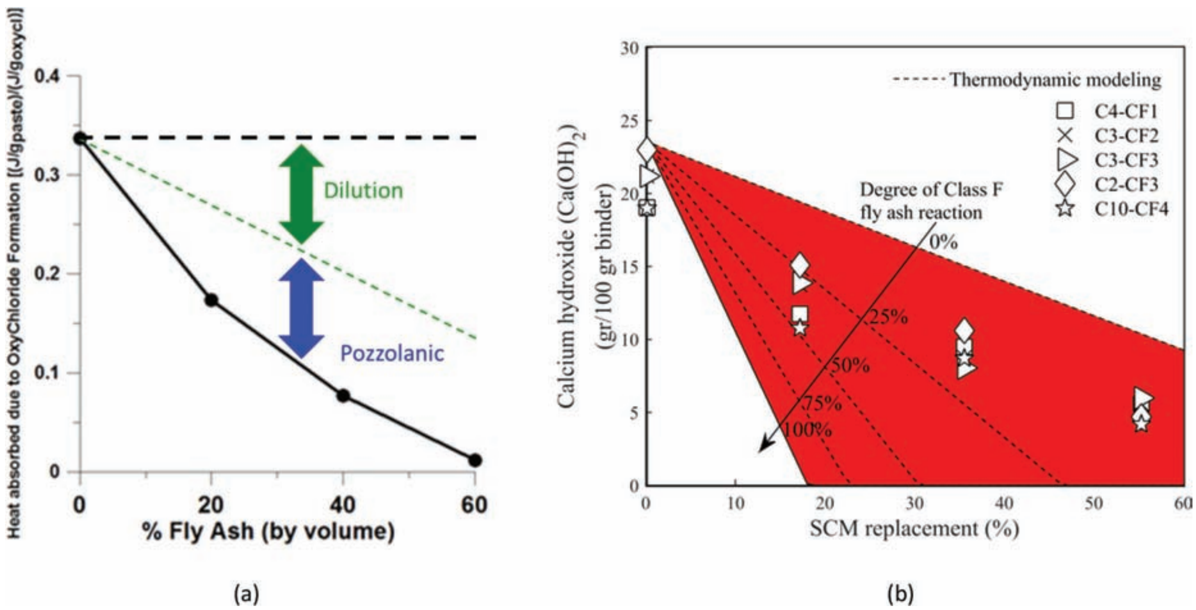

Figure 2.8 Illustration of the benefit of using SCM to reduce calcium hydroxide contents experimentally (a) and the benefits of using SCM to reduce calcium hydroxide through modeling (b).

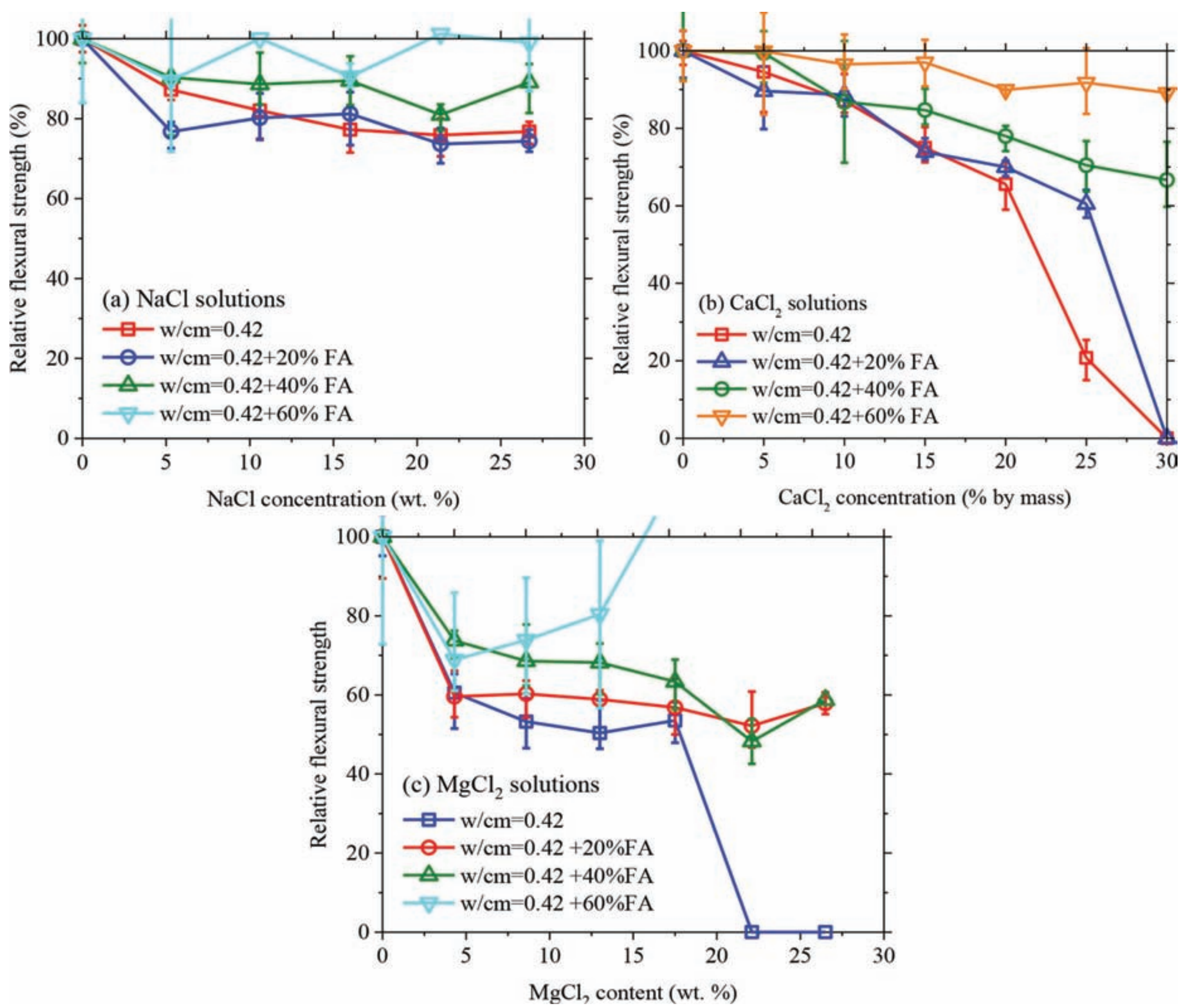

Figure 2.9 Relative flexural strength of pastes with fly ash exposed to 21.6% NaCl (a), 20% $CaCl_2$ (b), and 17.5% $MgCl_2$ (c) solutions after a 50-5-50 °C thermal cycle, respectively Qiao et al., 2018a, 2018b; Qiao, Suraneni, Tsui Chang, et al., 2018).

3. SUMMARY OF THEORETICAL CONSIDERATIONS FOR SATURATION AND SALT DAMAGE

This chapter provides some background for the recommendations provided to INDOT on April 27, 2015, as described in Chapter 1. The chapter will address each recommendation from Chapter 1 and will utilize concepts from Chapter 2 to provide the theory behind the recommendation.

3.1 Increase the Specified Volume of Air Entrainment and Reduce the Variation in Air Content

It is widely known that the freeze-thaw durability of concrete is dependent on the entrained air system (Mindess & Young, 2002). Air entrainment can be defined by using the quantity (or volume of air) and the quality of air (or the spacing/specific surface area) of the air void system. *The first recommendation is to increase the lower bound on the air content in the current specifications from 5.0% to 5.5% and to allow contractors to design mixtures at 7.0% air.* The goal of this recommendation is to reduce the potential for a mixture to have a low air content which exacerbates pavement joint damage.

Entrained air can improve freeze-thaw durability by reducing the degree of saturation in concrete (Li et al., 2016). Air entraining admixtures stabilize air bubbles generated during mixing to add large (approximately 0.05 to 1.25 mm), stable, air-filled voids to the paste portion of the concrete (Mindess & Young, 2002). These air-filled voids reduce the initial degree of saturation (Todak et al., 2015), as shown in Figure 3.1a. This graph indicates that a 1% change in the volume of air will have approximately a 5% reduction in the degree of saturation at the nick point (S_{NICK}). Figure 3.1b illustrates that as the volume of air increases the time to reach critical saturation (which can be assumed to be time to failure) increases. Increasing the air content will extend the life of the concrete by increasing the time required to critically saturate the concrete. Further, increasing the air content will provide additional air voids, which can accommodate the formation of deleterious phases while also enabling the air to function as entrained air in a partially saturated system.

Variability is an important factor in the freeze-thaw performance of concrete. INDOT is currently participating in a national pooled fund study headed by Oklahoma State University examining the use of improved methods for quantifying the quality of the air void structure. This work also considers the role of variability in pavement performance. In subsequent work on this project, the variation in air content has been related to the time to reach critical saturation (Weiss, Ley, Isgor, & Van Dam, 2017). Figure 3.2 uses Monte Carlo simulations to illustrate the impact of variability on the simulated time to reach critical saturation. Figure 3.2a illustrates that for a mixture with 7% air, 10% of the mixtures fail at 20 years despite the average performance predicting nearly double the service life. Figure 3.2b illustrates that for the same air content (6%) the time to critical saturation increases (more than doubles) when the 10% failure limit is used. This clearly indicates that while having sufficient average air specified is key, controlling the variation in the air content in the field is significant. For example, recent work by Weiss has suggested that this could be tied to pay incentives and disincentives.

3.2 Reduce the Volume of Cementitious Paste in Concrete Pavements

It is widely known that the freeze-thaw durability of concrete is dependent on the entrained air system (Mindess & Young, 2002). *The second recommendation is to enable contractors to optimize the binder content and reduce the paste content.* Minimum cement contents

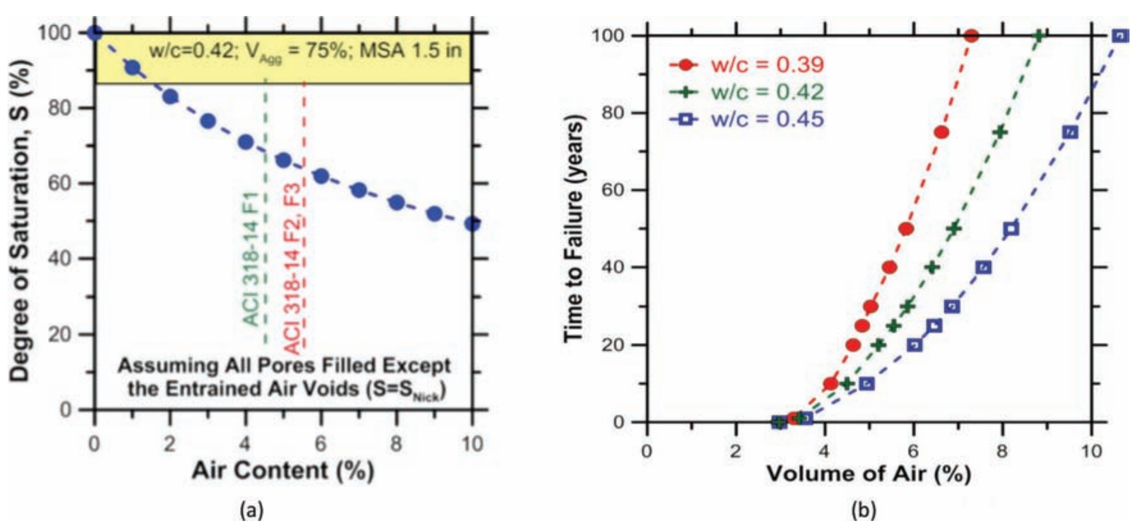

Figure 3.1 The influence of air content on the initial degree of saturation (a) and the influence of air content on the time to reach critical saturation (b).

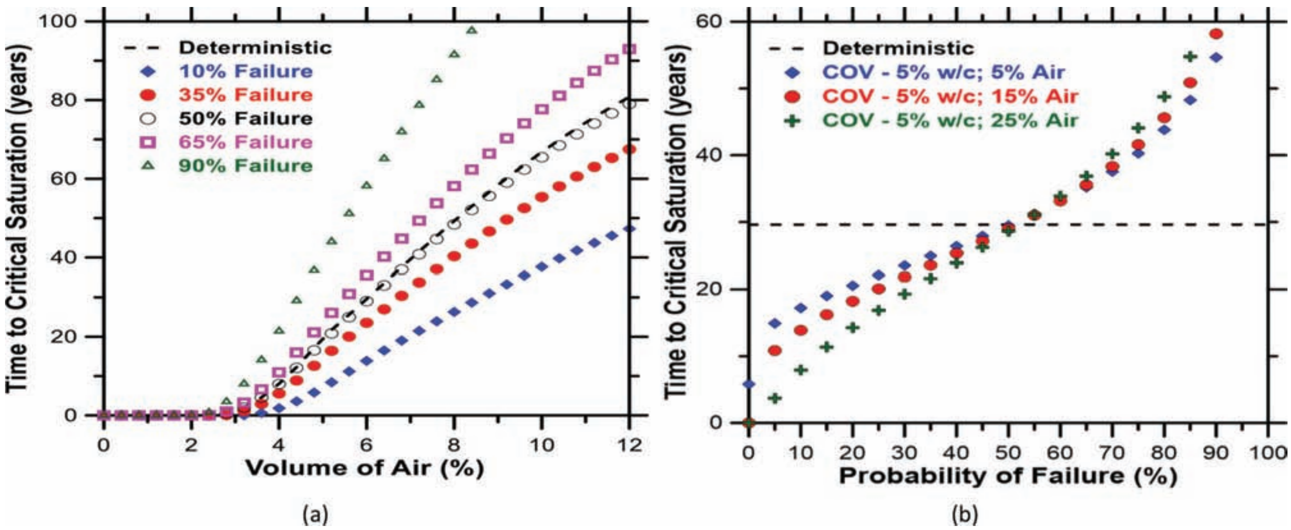

Figure 3.2 The influence of the volume of air on the time to saturation when variation is considered (w/c = 0.42, 6% air, and variation in w/c of 5% COV and in air of 15% COV) (a). The influence of variation in the air content on the time to critical saturation when the COV of the air is varied (note 5% COV refers to air between 5.4 and 6.6%, 15% COV refers to variation from 4.2 to 7.8% and 25% refers to variation from 3 to 9% in the total volume of air) (b).

should be eliminated from the specification unless there is a specific reason for them to be included. Further, contractors should be encouraged to optimize the aggregate gradation (Cook, Ghaeezadah, & Ley, 2018; Shilstone, 1990). The goal of this recommendation is to reduce the portion of gel (and correspondingly gel and capillary porosity) and to increase the volume proportion associated with air. For example, a change in the minimum cementitious content from 564 lb/yd^3 to 451 lb/yd^3 results in a decrease in the critical degree of saturation by approximately 5%. This will have the same impact as mentioned in section 3.1 on the service life. Further, recent work by Weiss has shown that it may be more technically correct to base the specified air content on the volume of paste (e.g., 18% of the paste is entrained air).

In addition to the benefit in reducing the volume of paste on the freeze-thaw performance, there is also a benefit of reducing the volume of paste as it relates to salt damage. The amount of calcium hydroxide that develops in a mixture (per cubic yard) is related to the content of cement in the mixture. As a result, mixtures with a higher cement content will develop a greater amount of calcium oxychloride and are subject to more joint damage.

3.3 Reduce the Water-to-Cementitious Materials Used in Concrete Pavements

It is widely known that the w/c is directly related to many properties of concrete. Figure 3.3a shows that both air content and water to cement ratio contribute to the degree of saturation when the gel and capillary pores are filled (i.e., S_{NICK}) when the same amount of cement is used in a mixture. As the w/c increases and air content decreases the concrete is closer to critical saturation after only a short time of exposure to water. The w/c can also impact the slope of the secondary rate of absorption (the red line in Figure 3.3b) for a straight cement mixture. Preliminary data has shown that this can be substantially reduced for mixtures with supplementary cementitious materials. Finally, the Powers-Brownyard model (Powers & Brownyard, 1948) can be used to describe the relative proportion of the phases in the cement paste. Figure 3.4 provides a graphical illustration of the relationship between the w/c and the phases that form in the cement paste (for a pure cement paste system) at complete (100%) hydration for sealed systems. It can be noticed that at w/c greater than 0.42, mixing water remains after complete hydration which ultimately results in the formation of capillary porosity. This capillary porosity increases the degree of saturation at the nick point and increases the rate of fluid absorption. *The third recommendation is to reduce the upper limit of water to cement ratio to 0.44 for both paving and flatwork specifications.*

3.4 Use a Formation Factor to Specify the Transport Properties of Concrete

As mentioned in Section 3.1 and 3.3, the water content (volume) and w/c have an impact on concrete pavement durability. A primary reason for this is that both are related to transport properties. INDOT has been a leader in the development of a new procedure to measure transport properties called the formation factor. The formation factor has significant advantages over the use of resistivity measurements alone. *The fourth recommendation is to move toward a pay factor that is based on the formation factor as assessed by resistivity.*

A variety of different test methods is currently used to assess transport. The formation factor can be related to the RCPT test (Weiss, Barrett, Qiao, & Todak, 2016),

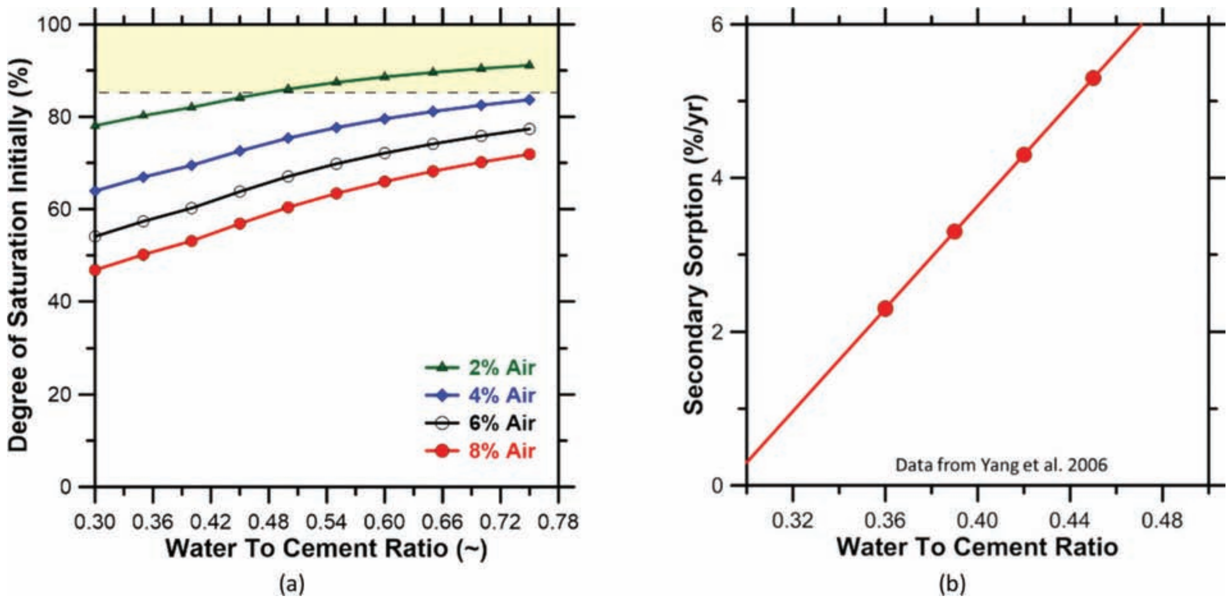

Figure 3.3 Influence of w/c and air content on S_{Matrix} (a) and the influence of water to cement ratio on the secondary sorption (b) (Weiss et al., 2017).

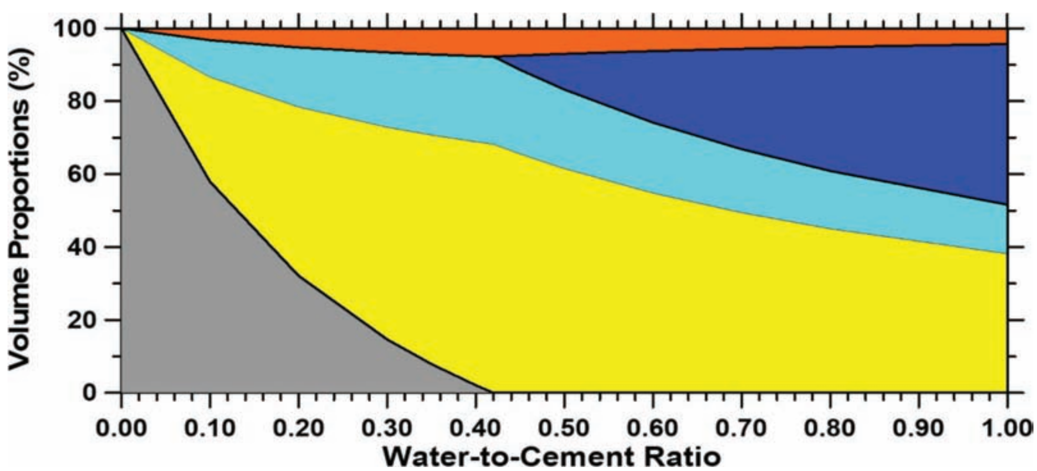

Figure 3.4 Volume proportions of cement paste phases at 100% degree of hydration (gray is unhydrated cement, yellow is solid hydration products, aqua is gel porosity, blue is capillary porosity and orange is vapor space due to chemical shrinkage).

the sorption test (Moradllo, Qiao, Isgor, Reese, & Weiss, 2018), permeability (Rajabipour, 2006), and diffusion for both cases that do and do not include chloride binding (Weiss, Spragg, Isgor, Ley, & Van Dam, 2017; Qiao, Coyle, Isgor, & Weiss, 2018). While the formation factor is clearly related to a wide range of transport properties, Figure 3.5 illustrates that the inverse of the formation factor is directly related to the w/c. The inverse of the formation factor is plotted as this is directly related to permeability. Since the formation factor can be measured quickly and is independent of the chemistry of the cementitious material, it provides a strong field test that can be used in quality control. Weiss and co-workers are currently working toward the development of a formation factor specification that can be used in conjunction with a freeze-thaw and salt damage model. Using the formation factor as a quality control measure (pay factor) will benefit in controlling the process of batching and placement and will provide incentive for contractors to focus on consistent production of concrete.

3.5 Use Supplementary Cementitious Materials (SCM) to Reduce Susceptibility to Salt Damage

The use of SCMs such as fly ash, slag, and silica fume leads to a reduction in CAOXY contents due to a reduction in the CH ($Ca(OH)_2$) contents. Figure 3.6a shows that the benefits of SCMs generally come from two factors, dilution and the pozzolanic reaction between the SCM and the calcium hydroxide. *The fifth recommendation is to modify specifications to enable greater use of SCM and use of SCM later in the construction season (part a).*

In a subsequent study, the performance of a wide range of cement and fly ash combinations was simulated. Figure 3.6b shows that a replacement level of 35% fly ash is needed to reduce the CAOXY value to an average value of 15 g/100 g paste. (Note the value of 15 g CaOxy/100 g paste is a target until more definitive values are obtained from field studies). However, it should be noted that this is an average value, with some mixtures still showing higher CAOXY values. If a replacement level of 40% fly ash were specified none of the mixtures that were physically tested showed CAOXY values higher than 15 g/100 g paste. Further 90% of all US cements –fly ash simulations resulted in CAOXY values less than 15 g/100 g paste (as seen in Figure 3.7b).

It should also be noted that a test method has been developed as AASHTO T365 based on the use of low temperature differential calorimetry. This standard can be required as a qualifying procedure to confirm that the proposed binder combinations have a reduced potential for calcium oxychloride formation. *The fifth recommendation is to require the use of a standard test to qualify the potential for calcium oxychloride formation at the time of mixture submission (part b).* This can be accomplished using the approach outlined in AASHTO PP-84 - Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures.

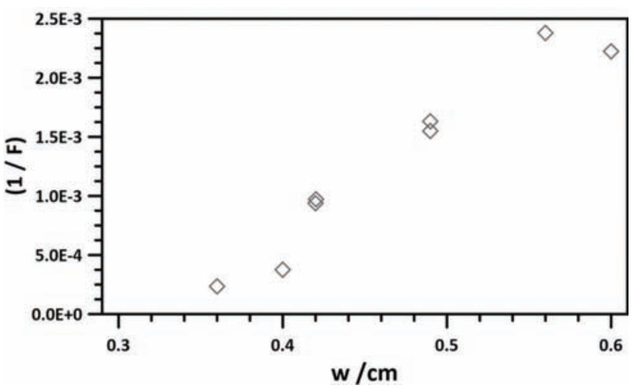

Figure 3.5 Relationship between the inverse of formation factor and w/c.

3.6 Use a Topical Treatment for Concrete That Repels Water or Seals the Concrete

It has been proposed that sealing the concrete instead of the joint may have benefits to reducing joint damage caused by fluid ingress or salt reactions (Weiss, Abraham, & Nantung, 2007). Topical treatments (e.g., sealers) have been shown to have varying levels of success in reducing joint damage in concrete pavements. While some penetrating topical treatments have shown advantages in preventing salt ingress, others appear to provide a physical barrier between the calcium hydroxide and the salt, which can reduce or prevent calcium oxychloride formation (Wiese et al., 2015). Some topical treatments (film-forming treatments) have been shown to be permeable to fluids during temperature changes which would not have a very beneficial impact calcium oxychloride formation (Harris, Farnam, Spragg, Imbrock, & Weiss, 2015; Coates, Mohtar, Tao, & Weiss, 2009). Figure 3.7a shows the results of samples that were topically treated with soy methyl ester polystyrene (SME-PS) and concrete that was untreated or treated with silane. It can be noted that the samples treated with the SME-PS show improved performance. Unlike many of the other suggestions that can only be conducted on newly constructed pavements, the use of topical sealants can also provide a solution to remediate pavements that have been deemed susceptible to joint damage in order to mitigate this potential. *The sixth recommendation is to use a topical treatment for concrete that repels water and limits salt ingress.*

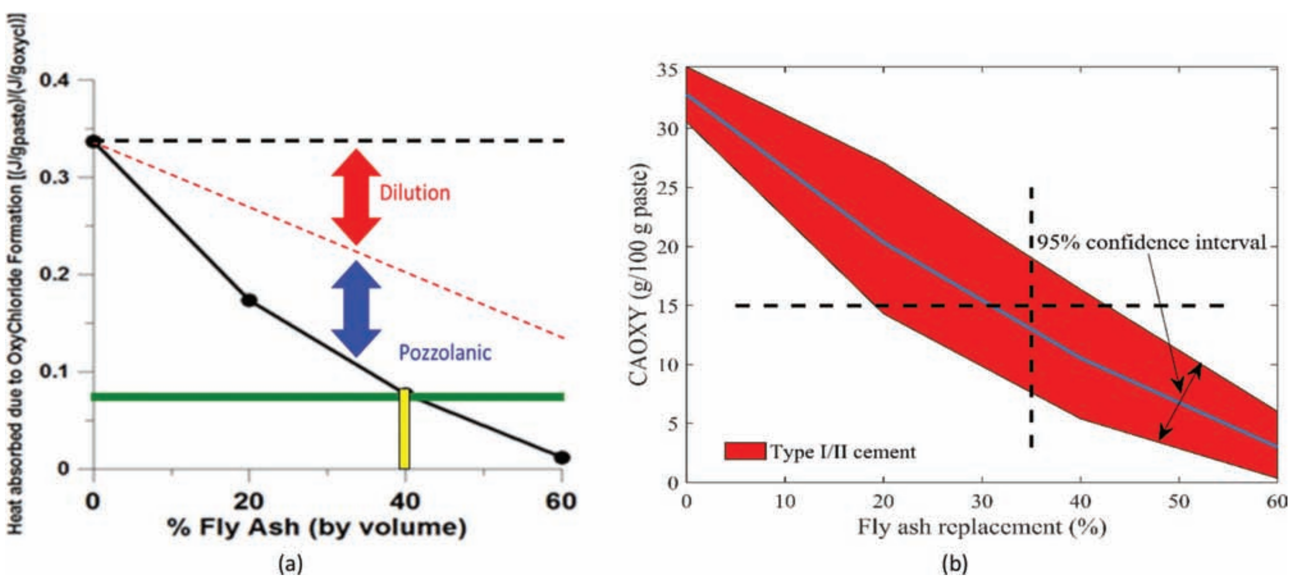

Figure 3.6 An illustration of the influence of one SCM (fly ash) on the reduction of calcium oxychloride formation (a) and an illustration of the reduction and variation of CAOXY contents as a function of fly ash replacement level (b).

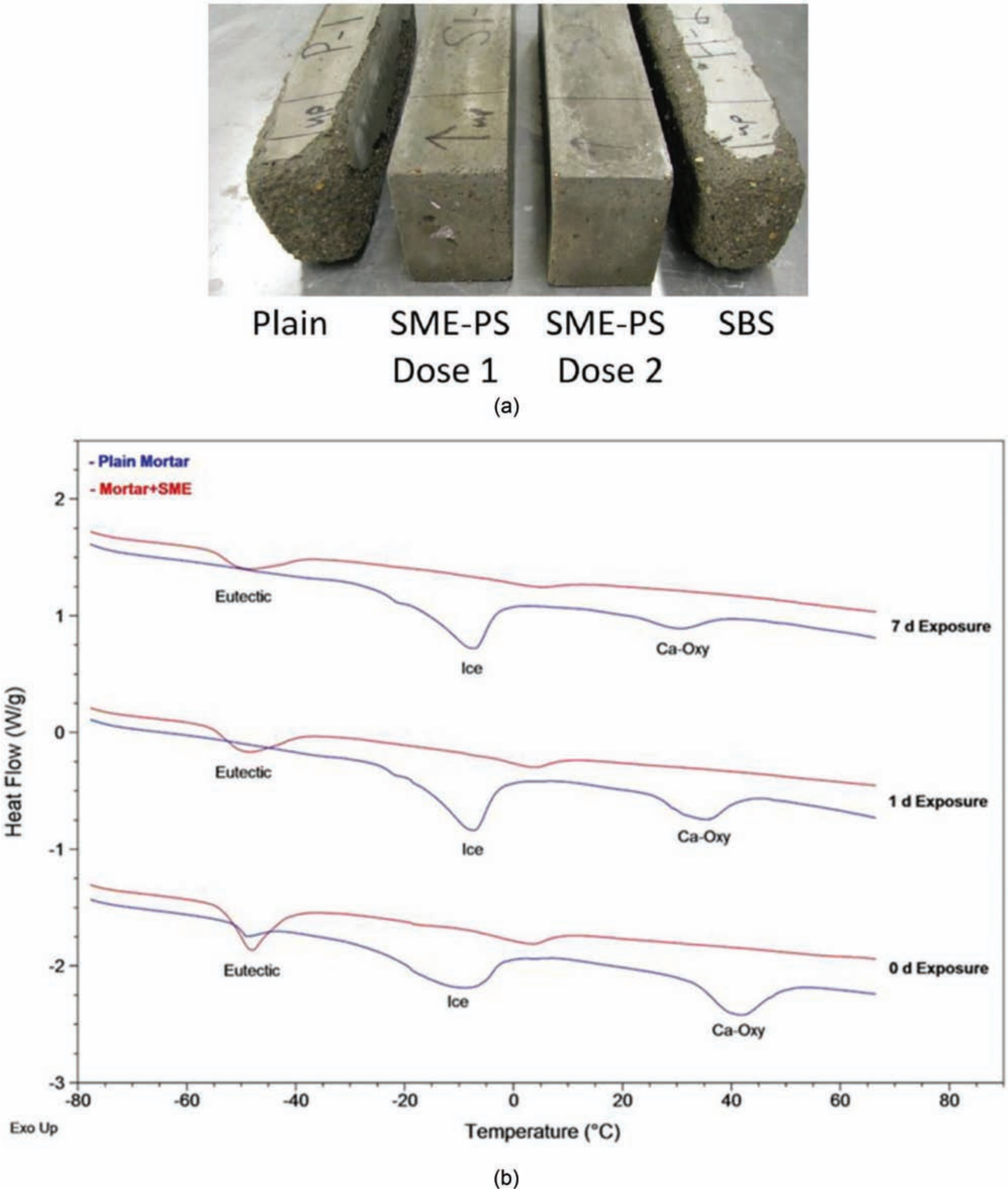

Figure 3.7 Behavior of concrete with different sealers when exposed to freezing conditions while sitting in water (a). Low temperature differential scanning calorimetry (LT-DSC) for plain mortar sample and mortar sample with SME at different exposure times to 29.8% $CaCl_2$ solution (calcium oxychloride is shown as Ca-Oxy in the figure) (note PS is an abbreviation for polystyrene, SBS is an abbreviation for siloxane based sealer) (b).

The formation of calcium oxychloride is a chemical phase transition that can be characterized using low temperature differential scanning calorimetry (LT-DSC) (Weiss et al., 2017). Heat flow curves are shown in Figure 3.7b for systems with and without a topical treatment (in this case SME). Three endothermic peaks can be seen for plain concrete samples saturated with $CaCl_2$ solution associated with (1) eutectic solid melting at approximately -50.8 °C, (2) ice melting at a temperature between -50.8 °C and 0 °C, (3) calcium oxychloride melting (shown as Ca-Oxy in the figure) at a temperature above 0 °C. The samples with SME showed no peak that corresponded to calcium oxychloride formation. This is mainly because SME can create a physical barrier between the deicing salt and calcium hydroxide.

3.7 Reduce the Tie Bar Size and Spacing to the Necessary Level

Over the last two decades, pavements have become thicker and stronger. These factors make it more difficult for the concrete to crack at the longitudinal and transverse saw cuts. In addition, the size of the tie bars used and the reduction in their spacing has led to the cracks that form in the longitudinal saw cut to be narrower than cracks in previous pavements. This is a concern since the cracks are not opening to a sufficient width to allow the joints to drain. This phenomenon has been discussed in SPR-3200. *The seventh recommendation has been implemented which was to reduce the tie bar size and spacing.*

3.8 Consider the Removal of Backer Rod or a Cavity in the Design of Pavement Joints

In many pavements experiencing damage, water (or fluid) has been found to intrude at defects in the joint sealant (Figure 3.8 a,b). This intruding water can fill in the available space below the joint sealant that is not filled by a non-absorptive backer rod. Further, many backer rods were found to actually be absorptive. When this intruding water finds its way into the joint, the joint sealant can actually minimize evaporation thereby providing a depression for the water to sit in enabling the concrete to become saturated. Figure 3.8c illustrates that slabs exposed to deicing salt solution without the benefit of treating the concrete (through SCM addition or a topical treatment) can be damaged. *The eighth recommendation is to remove the backer rod and either leave the joint empty or to fill the joint (e.g., with hot pour materials).* By removing the void beneath the joint sealant, the potential for water saturation in the concrete is greatly minimized, thereby increasing the life of the concrete pavement.

3.9 Consider the Use of Unsealed Joints

In many pavement texts, joint sealants are promoted as a way to keep debris out of the pavement joint thereby promoting long-term durability (Yoder & Witczak, 1975). Taylor et al. (2011) discussed that while joint damage can occur due to debris trapped in joints, however, they did not think that the damage due to debris would be significant in concrete pavements experiencing joint damage. Traffic speed may be one reason that debris is not observed on interstate pavements. While an open saw-cut does allow the evaporation of water, which can be accelerated by traffic speed, joint sealants that have failed but remain in the joint, limit air flow, which limits evaporation. A suggestion was made as a part of SPR-3523 to consider the potential for eliminating the sealed joint configuration and using a smaller single saw cut. It was suggested that a concrete topical treatment (concrete sealant) may be effective to reduce damage. This was to be evaluated as a part of SPR-3506 and SPR-3510. These projects will investigate the impact of the unsealed joints on the subgrade demands. *The ninth consideration is to consider the use of an unsealed joint.*

3.10 Continue the Use of a Capillarity Break below the Pavement

Two types of damage have been observed in pavements across the Midwest. Damage that originates from the top of the saw-cut/joint in the pavement and damage that originates from the base of the pavement propagating upward. In viewing images from numerous coring investigations, it appears that a common distinction between these types of damage is related to the material below the concrete pavement. In systems that exhibit damage that is primarily 'top-down', the material below the pavement is typically an open graded aggregate. In mixtures that exhibit damage that is both 'top-down' and 'bottom-up', the material beneath the pavement is frequently a fine grained, dense material (Figure 3.9). While many may believe that this difference is due to the drainability of the base, it should also be noted that it might be due to the open graded materials serving as a break in capillarity. As such, the open graded granular layer may help to break the capillary suction forces that draw water into the concrete pavement. *The tenth recommendation is for INDOT to continue the use of the capillarity break below the concrete pavements.*

3.11 Reduce the Strength Required to Open a Pavement to Traffic

Over the last two decades pavements have become thicker and stronger. These factors make it more difficult for the concrete to crack at the longitudinal and transverse saw cuts. This increased strength is related to the opening to traffic strength specifications. Recent work was performed as a part of SPR-3403 to illustrate that a 'one – size fits all' opening strength may be overly conservative for thicker pavements such as those used on the interstate. Figure 3.10 illustrates that as the pavement becomes thicker, the stress due to loading is reduced by the square of depth. *The eleventh recommendation is to permit a reduced strength for opening*. This recommendation has already been implemented in patches using a reduced opening strength and would be applicable to mixtures that incorporate larger volumes of SCM as the current specifications may

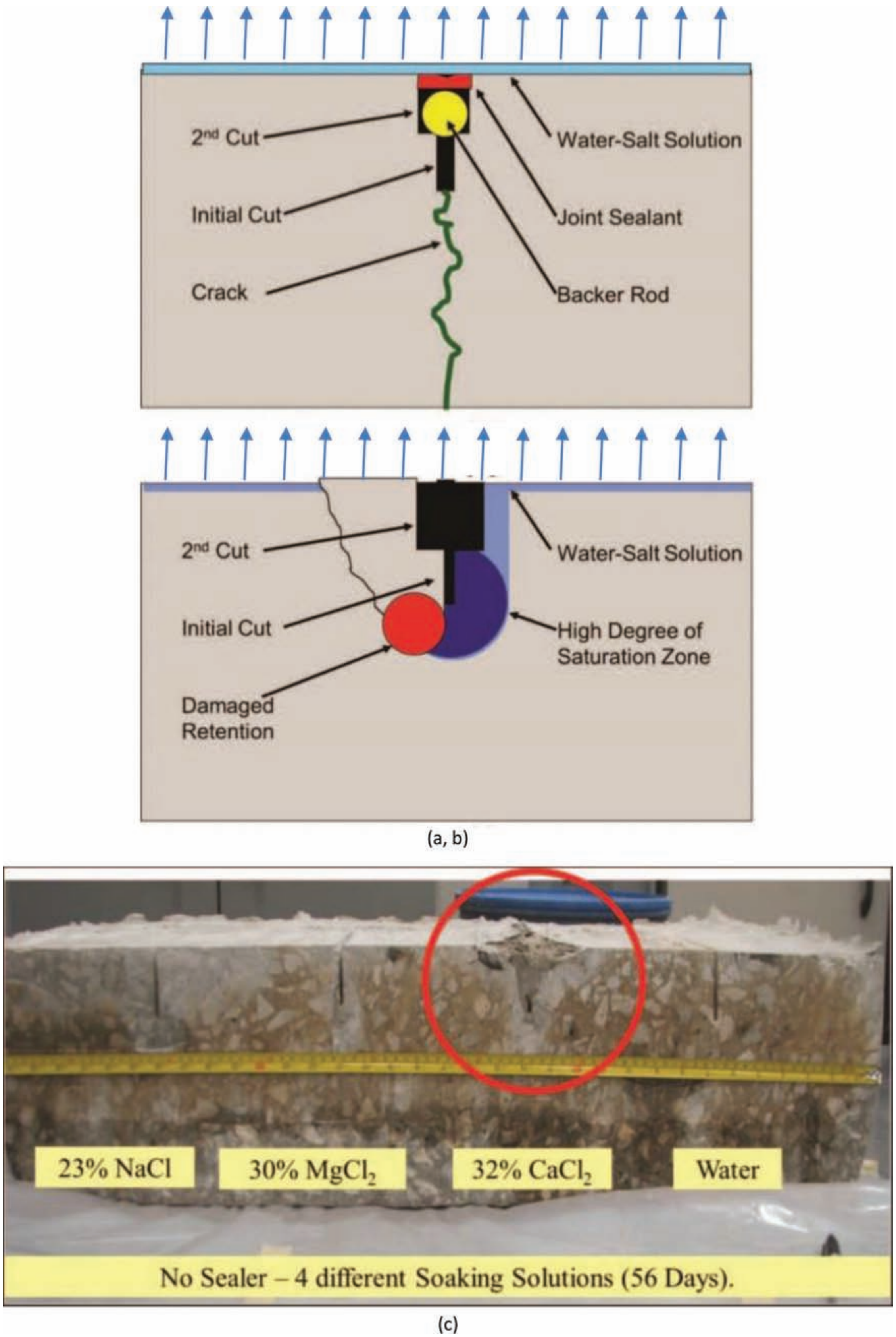

Figure 3.8 The influence of backer rod on fluid absorption (a), the influence of joint filling (b) and the influence of having no joint sealant on evaporation (c) (Mehta, Olek, Weiss, & Nantung, 2005).

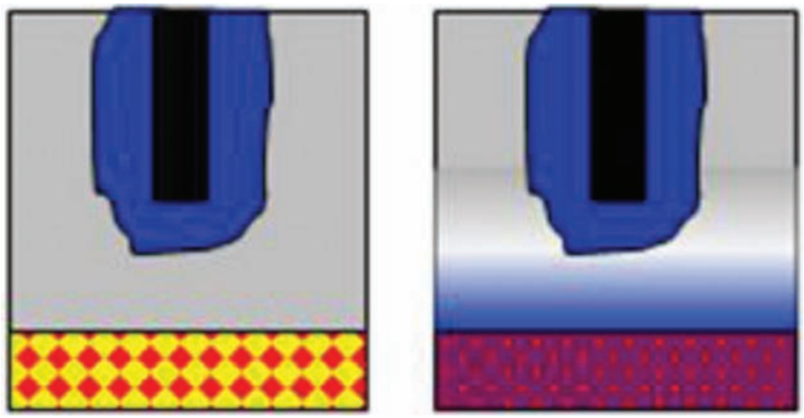

Figure 3.9 An illustration of the importance of a capillarity break in limiting the pavement deformation. Left: coarse base course. Right: fine base course.

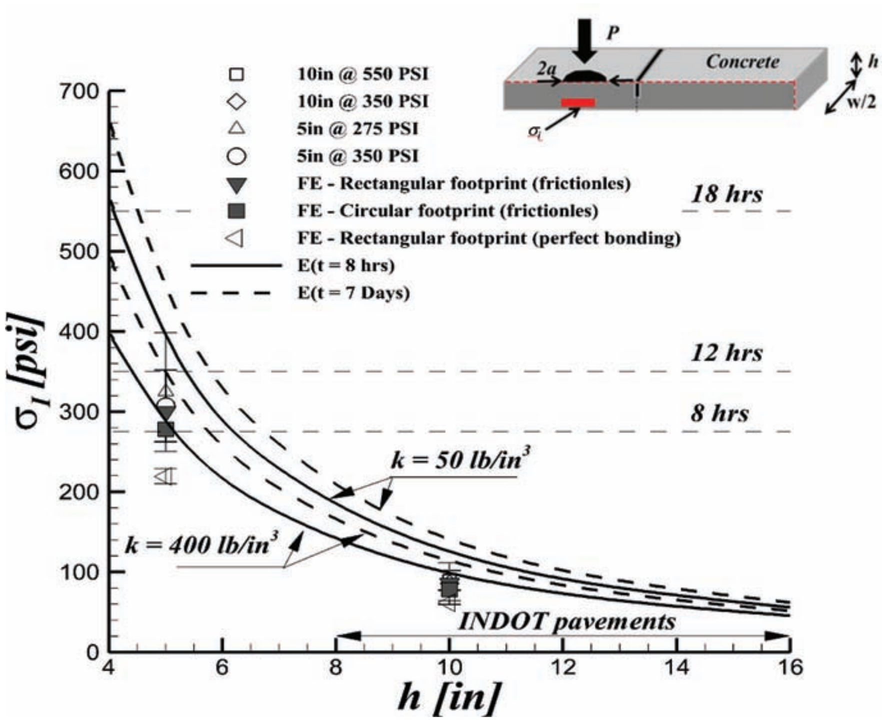

Figure 3.10 The impact of pavement thickness on the stress caused by mechanical loading.

inadvertently discourage their use. The impact of early age loading due to overloaded trucks should be considered.

3.12 Increase the Use of Maturity to Accept Concrete Pavement at Early Ages While Long-Term Strength Is Used in Design

Over the last two decades, pavements have become thicker and stronger. These factors make it more difficult for the concrete to crack at the longitudinal and transverse saw cuts. This increased strength is related to the opening to traffic strength specifications and the 7-day payment strength. Recent work performed as a part of SPR-3403 highlighted that the design strength is based on 28-day strength while acceptance and payment are based on 7-day values. A relatively modest increase in strength is assumed to occur from 7 to 28 days (570 psi to 600 psi) which may be acceptable for plain cement systems; however in systems with increased SCM levels, the strength may take longer to develop and the difference between 7 and 28 day strengths may be greater. As such, the mixtures containing SCM and lower cement contents (which are the mixtures that tend to result in greater durability performance with respect to joint damage) are at a disadvantage. *The twelfth recommendation is to permit the use of the maturity method by contractors to* *determine a project specific increase in strength from the time of acceptance to 28 days (as recommended in SPR-7299).*

3.13 Improve the Use of Methods to Detect Water Ponding in Concrete Pavements

Two methods have been used to detect premature joint deterioration: (1) electrical resistivity and (2) ground penetrating radar. Direct measurement of electrical resistivity of the concrete from the surface can also be used to determine if fluid exists in the joint beyond a threshold decided to be indicative of susceptibility to joint deterioration. It has been shown that areas exposed to water and salts have different electrical properties than areas that are not exposed to these conditions. This method will be influenced by many factors independent to each specific pavement. As described in SPR-3623, ground-penetrating radar can be used to gain a general understanding of the fluid level in the joint without requiring the removal of backer rod and silicon sealant. Currently, this process would only provide a binary solution to say whether fluid exists in the joint beyond a certain depth. However, refinement of the process and a statistical analysis of the differences between maximum amplitudes of regular and cross-polarized scans on a variety of pavements could provide the ability to determine the depth of fluid in a joint. *The thirteenth recommendation is to improve non-destructive testing techniques to determine joints where water and salt water have penetrated so that the joint sealant can be removed and replaced.*

3.14 Examine the Proportion of Salts in Blended Systems

As the calcium hydroxide (CH, $Ca(OH)_2$) content in the paste increases, so does the potential for calcium oxychloride (CAOXY) formation. CAOXY contents increase with the proportion of $CaCl_2$ solution in the salt blends as observed in Figure 3.11. At lower proportions of $CaCl_2$ solution in the salt blends, the reaction is controlled by the amount of $CaCl_2$. At higher proportions of $CaCl_2$ solution in the salt blends, the reaction is controlled by CH. The concentration at which this switch occurs depends on the amount of CH in the paste. A simple model has been developed to estimate the amount of CAOXY formed in the pastes, depending on the calcium chloride and CH contents. A strategy to reduce pavement damage could be to use deicing salt blends with lower calcium chloride concentrations; however, the use of salt blends with lower concentrations of $CaCl_2$ needs to be balanced with the possibility of reduced deicing performance at lower temperatures as well as public safety. *The fourteenth recommendation is to re-examine the proportions of brine being used and when possible to use as high a concentration of NaCl as safety concerns would permit.*

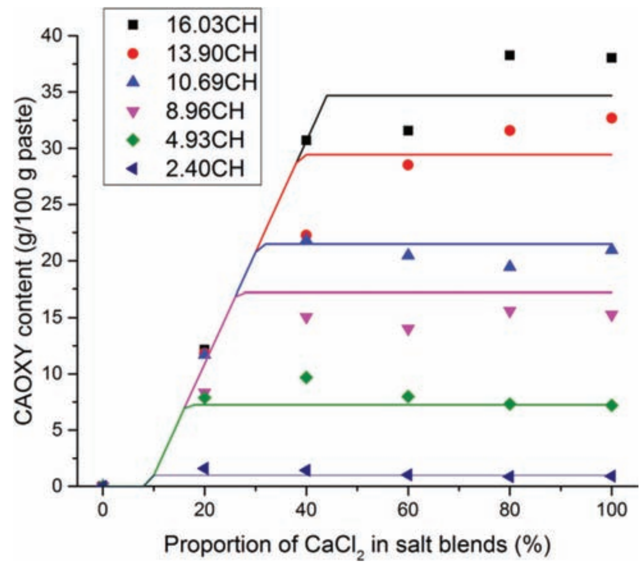

Figure 3.11 Application of a model to estimate CAOXY values for various CH and $CaCl_2$ values.

4. REVIEW OF PREVIOUS PROJECTS

Concrete pavements represent a large portion of the transportation infrastructure. While the vast majority of concrete pavements provide excellent long-term performance, a portion of these pavements has recently shown premature joint deterioration. Substantial interest has developed in understanding why premature joint deterioration is being observed in jointed portland cement concrete pavements (PCCP). While some have attributed this damage to insufficient air void systems, poor mixture design, or chemical reaction between the salt and the paste, it is the hypothesis of this work that a component of this damage can be attributed to fluid absorption at the joints and chemical reactions between the salt and chemistry of the matrix.

The following section describes research taken by the INDOT (as well as following work) to reduce damage at joints related to freeze-thaw effects.

4.1 SPR-2474: Interaction between Micro-Cracking, Cracking, and Reduced Durability of Concrete: Developing Methods for Considering Cumulative Damage in Life-Cycle Modeling (Yang, Weiss, & Olek, 2004)

4.1.1 Objectives of SPR-2474

Cracks in concrete pavements and bridge decks may occur due to either mechanical loading or environmental loading. In addition to reducing the overall strength and stiffness of concrete, these cracks can impact the durability. The hypothesis of this project was that these cracks can permit increased fluid ingress and thereby these cracks can dramatically reduce the durability of concrete. The accurate prediction of the performance of concrete structures should therefore account for the presence of cracking. This study worked to provide quantitative information on how damage influences water absorption, freeze-thaw behavior, and mechanical properties of concrete. It was concluded that further research should be implemented in the pavement design and life-cycle performance modeling processes.

4.1.2 Findings of SPR-2474

A field condition assessment of concrete pavements was conducted to assess the types of damage that occur in the field. Cores were taken from five concrete pavement sections. In damaged pavements, the rate of water absorption near the surface of the pavement was substantially higher (up to 54% higher) than that near the middle or bottom of the pavement due to the presence of microcracking.

Laboratory studies were conducted to assess how cracking (cracking that was carefully and systematically introduced) from loading or freezing and thawing influences fluid transport, electrical conductivity, freeze and thaw durability, and mechanical response of concrete.

It has been shown that water absorption and electrical conductivity are dependent on the characteristics of the cracking that was developed in the concrete. Freeze and thaw damage results in a well-distributed crack network that increased the water absorption in a linear proportion to the extent of damage. Cracking induced by mechanical loading tended to be well localized and affected only the region around the crack. As such, load induced damage does not appear to influence the water absorption or electrical conductivity at loading levels up to approximately 90% of peak load due to the discontinuous nature of the crack pattern.

This project showed that in spite of recent attention to durability performance models for concrete, little information exists on the influence of less than ideal curing conditions on the durability of concrete structures. For example, lack of sufficient curing can result in the development of microcracking in a material. Currently, it is not common to relate insufficient curing to changes in the material that will reduce the long-term performance of concrete. Providing sufficient curing is essential for excellent long-term durability performance.

Data from this project was used subsequently to show the impact of a cracked network on the projected time to saturation which would correspond to the onset of freeze-thaw (Weiss, 2015). Figure 4.1a illustrates the impact of connected cracking on the time to reach critical saturation (or freeze-thaw life). The sample used in this simulation corresponds to a reduction in stiffness of 31%, which resulted in a sorption that was 1.9 times higher than that of the undamaged concrete. Figure 4.1b illustrates the projected time for the concrete to reach critical saturation as a function of the original air content of the mixture. It was suggested that if the stresses are kept below 50% of the peak strength, the damage that results in substantial changes in the life cycle performance can be reduced.

4.2 SPR-2863: Saw-Cutting Guidelines for Concrete Pavements: Examining the Requirements for Time and Depth of Saw-Cutting (Raoufi, Their, Weiss, Olek, & Nantung, 2009)

4.2.1 Objectives of SPR-2863

The research was divided into three major components. The first component included field investigations to assess the current saw-cutting practices in Indiana.

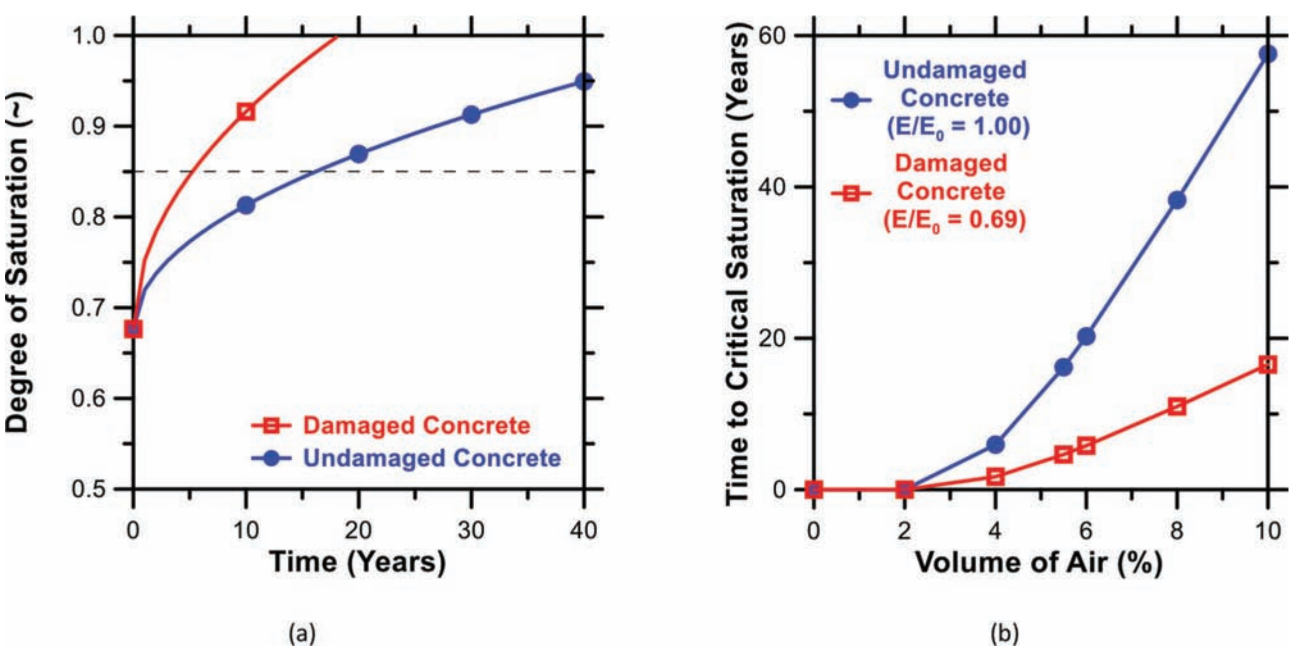

Figure 4.1 The influence of damage on the degree of saturation (a) and the influence of damage on the time to reach critical saturation (concrete with a 31% degradation in stiffness) (b).

The second component of this work included laboratory testing. The third portion of the work consisted of some preliminary approaches for assessing the potential for raveling using set-time and early entry saw-cut testing. The third component consisted of finite element analysis to assess the influence of the depth and time of saw-cut on residual stress development taking into consideration various ambient weather and environmental conditions. A simple methodology was developed to compute when a saw-cut needs to be placed, using a stress development for an unnotched specimen.

4.2.2 Findings of SPR-2863

Thier (2005) conducted studies of joint construction with an emphasis on saw-cutting. Raoufi, Radlinska, Nantung, & Weiss (2008) used a finite element model to simulate stress development at the saw-cut joints. It has historically been reported that saw-cutting needs to be performed before the stress reaches the tensile strength of the pavement to reduce the potential for random cracking; however this is un-conservative and a stress reduction factor is needed to prevent premature damage. Raoufi et al. (2009) related the stress reduction factor to the depth of the saw-cut being used as shown in Figure 4.2 to have stable cracking after saw-cutting. This indicates that deeper saw cuts require a greater reduction in the stress to strength ratio used for saw-cutting. It was also observed that higher stress-to-strength ratios can result in cracking at the base of the saw-cut when the stress in the pavement is high (Castro et al., 2011) and increase the rate of saturation and freeze-thaw damage (Weiss, 2015; Yang, 2004). This type of safety factor should be used where the stress development in an unnotched/unsawn section are used (e.g., programs like HIPERPAVE).

It has also been proposed that mechanical loading may play a role in damage at joints due to curling or shear from traffic, especially at early ages (Taylor et al., 2011). While the damage is widespread at ramps, intersections and closure pours, Wilson et al. (2016) have suggested that this is more likely related to locations where contractors switch to the use of straight cement mixtures due to the potential to open the pavement to traffic at an earlier time. As such, there is not currently evidence that traffic shear is responsible for the damage at joints.

4.3 SPR-3016: Investigation of Premature Distress around Joints in PCC Pavements: Parts I & II (Arribas-Colón, Radliński, Olek, & Whiting, 2012)

4.3.1 Objectives of SPR-3016

The objective of this study was to investigate possible causes of the premature deterioration, especially in the areas adjacent to the longitudinal and transverse joints. This deterioration typically manifested itself as cracking and spalling of concrete, combined with the loss of material in the direct vicinity of the joint. In addition, ‘‘bulb-shaped’’ damage zones were also observed under the sealed parts of the joints.

To reach this objective, the characteristics of the concrete in and near the deteriorated joints were compared and contrasted to the characteristics of the concrete in the non-deteriorated sections of pavement. The study was conducted in two different phases (Phase I and Phase II). Phase I provided important preliminary

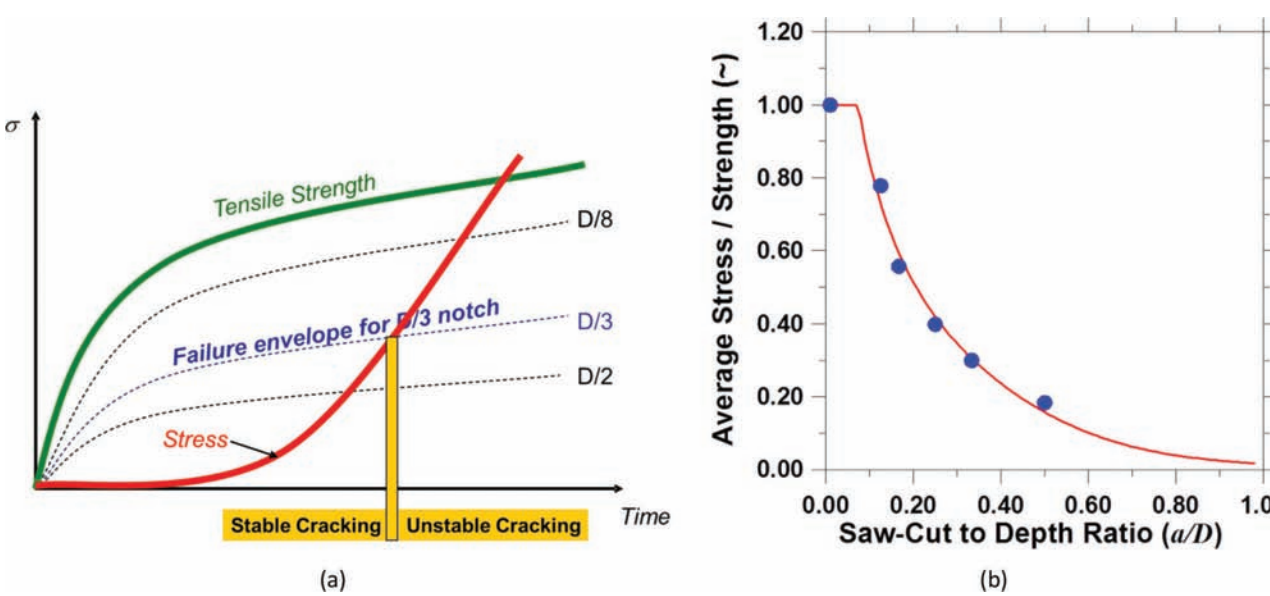

Figure 4.2 Strength and stress development for concrete pavements as a function of saw cut depth (a) and the saw cut stress to strength ratio (b).

information as to the potential causes of deterioration. Phase II directly compared sections that were (1) paved under one construction project by the same contractor, (2) that used similar mix designs and materials, and (3) were most likely exposed to similar environments and deicing practices but showed very different performances. In addition, where feasible, the base material was sampled and the drainage observed at each core hole.

4.3.2 Findings of SPR-3016

In general, the cores that came from the mid-span of the slabs included in Phase I had better air void systems than those extracted from locations near the joints. They also had good resistance to freezing and thawing cycles, relatively low rates of absorption, and were classified as having low or very low resistance in the rapid chloride ion permeability test. The only exception was the core containing slag aggregates.

The cores that came from the undamaged joints showed marginal to substandard air void system parameters, higher rates of absorption than the mid-span cores, variable F-T durability (with most specimens having durability factors above 60%) and low to moderate resistance in the rapid chloride permeability test. The cores that exhibited higher rates of absorption also exhibited lower durability factors (freeze-thaw test). Moreover, it was noted that cores from undamaged joints contained a considerable quantity of small (~10 mm) air voids filled with either ettringite, Friedel's salt, or a combination of both as shown in Figure 4.3. However, numerous empty air voids were also present in these cores.

The cores that came from the damaged joints mostly exhibited a poor air void system, showed evidence of some of the highest rates of absorption, displayed moderate to high chloride ion penetrability, and achieved relatively low values of the F-T durability factors. Additionally, it was noted that these cores contained numerous microcracks and infilled air voids (both small and large). The secondary (infilling) deposits contained ettringite, Friedel's salt, or a combination of both.

In general, the observed microstructural and chemical changes in Phase I cores were consistent with the appearance of concrete undergoing prolonged saturation (through-solution mechanism for creating deposits in the air voids).

Similar to those observed in Phase I of the study, the concrete samples collected in Phase II also contained a certain amount of infilling of the air void system by secondary deposits. Furthermore, it was observed that the existing air void system in the concrete from panels near the deteriorated longitudinal joint had neither spacing factors nor specific surface values within the range recommended for freeze-thaw durability. Contrary to this, nearly all of the concrete in lanes without damage had an adequate air void system at the time of sampling.

From the observation of the drains performed by the remote camera it was evident that not all of the drains were functioning properly and some were entirely blocked. However, more precise or direct correlations could not be made between the functioning of the drains and observed pavement performance.

Finally, the data collected during this study were limited and thus not sufficient to definitely and unambiguously determine the single cause of joint deterioration. Rather, the results seem to indicate that the observed deterioration is most likely caused by combination of several variables that may include type of deicers used, type of subgrade, structural design of the pavement, and type of the sealant in the joint.

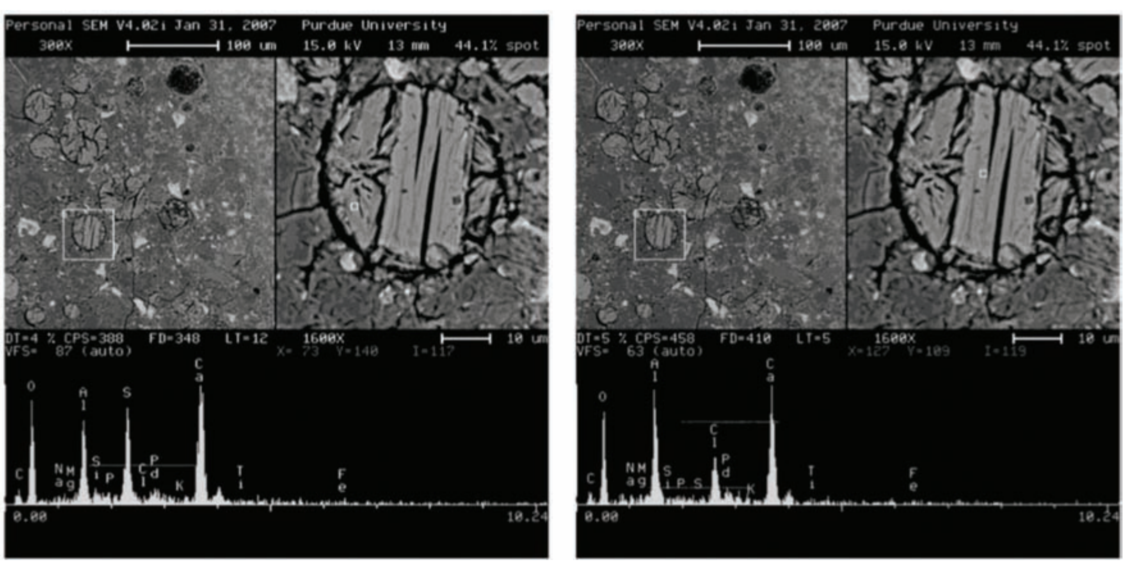

Figure 4.3 SEM image of a specimen from SR 67 showing an air void completely filled with mixture of ettringite (spectrum, left) and Friedel's salt (spectrum, right).

4.4 SPR-3091: Investigation of Anti-Icing Chemicals and Their Interactions with Pavement Concrete (Olek, Janusz, Jain, & Ashraf, 2013)

4.4.1 Objectives of SPR-3091

The primary objective of this study was to investigate the effects of deicing/anti-icing chemicals commonly used by the Indiana Department of Transportation (INDOT) on the durability of pavement concretes. The chemicals evaluated in this study included: sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), and Ice Ban®.

In order to find a solution to the previously stated problem, the scope of the work included the following four tasks: literature review, selection and testing of deicing chemicals, preparation and testing of laboratory concrete specimens, and data analysis. The present study investigated the effects of exposure of plain and fly ash concretes to different deicing solutions while being subjected to wetting/drying (W/D) and freezing/thawing (F/T) regimes.

4.4.2 Findings of SPR-3091

Overall, the best performance (in terms of reducing the negative impact on concrete) was associated with the use of sodium chloride solutions, followed by the combined solution of sodium chloride with magnesium chloride and sodium chloride with calcium chloride.

PC specimens subjected to 28% $CaCl_2$ solution and W/D regime developed very visible surface deterioration and 15% reduction in relative dynamic modulus of elasticity (RDME) after only 154 W/D cycles (Figure 4.4a). By comparison, similar reduction of RDME in specimens subjected to 25% $MgCl_2$ was observed only after about 300 W/D cycles.

The SEM-EDX analysis indicated formation of calcium oxychlorides in specimens exposed to 28% $CaCl_2$ solution under W/D regime. The changes in the matrix of specimens exposed to 25% $MgCl_2$ solution involved formation of M-S-H gel and $MgCl_2$ and $Mg(OH)_2$ deposits.

The fly ash modified concretes displayed better performance (in terms of lower mass loss and lower reduction in RDME) than plain concretes during the reported test period in both exposure regimes (Figure 4.4).

The only concrete property that was negatively impacted (although rather mildly) by the use of fly ash was scaling resistance. Since the rate of scaling can be strongly influenced by w/c values, air-void system parameter, and the concentration of deicers, careful control of these parameters should allow for safe usage of fly ash in concrete subjected to deicers.

Freeze/thaw exposure conditions typically resulted in more severe distress than W/D regimes, even though the concentrations of deicers used for F/T tests were about 50% lower than those used during W/D tests.

4.5 SPR-3093: Portland Cement Concrete Pavement Permeability Performance (Castro, Spragg, Kompare, & Weiss, 2010)

4.5.1 Objectives of SPR-3093

The main objective of this study was to evaluate the fluid transport properties of concrete pavements constructed in the state of Indiana. The scope of the research included a literature review of transport methods. The study then conducted an examination to obtain a baseline of information regarding the transport properties throughout the state. The study examined how the properties of solution influence the fluid sorption in concrete. The project used two methods

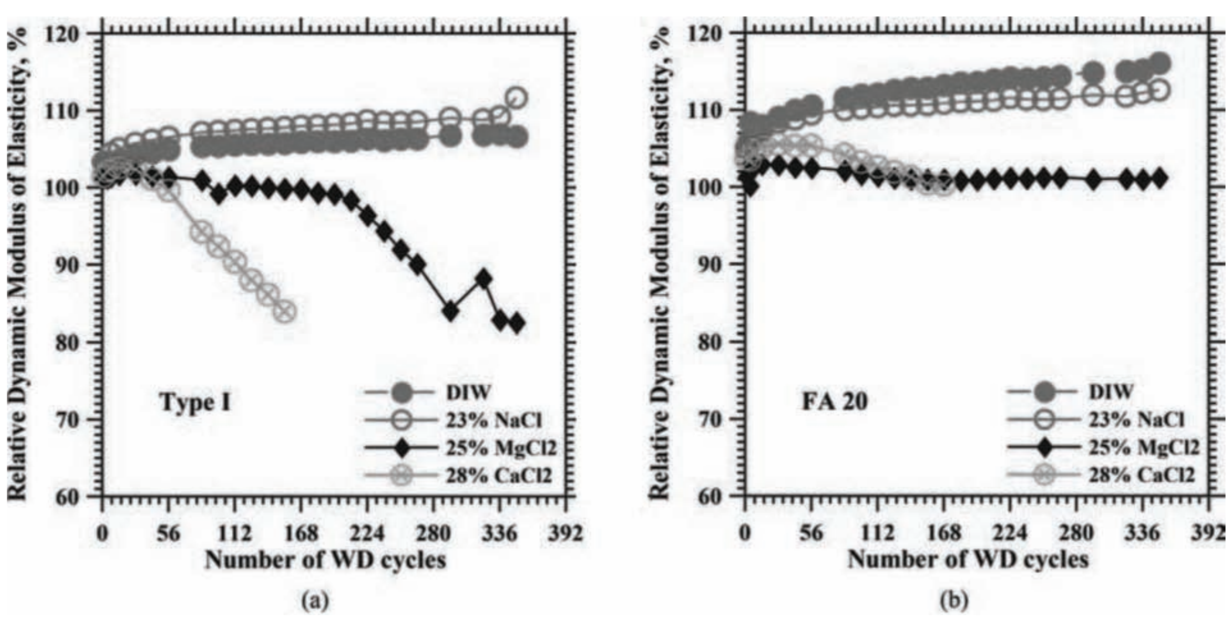

Figure 4.4 RDME values for (a) Type I and (b) FA 20 specimens exposed to W/D regime.

to characterize fluid transport using two primary tests that included water absorption and electrical conductivity. Mixtures were tested to illustrate the effect of curing conditions, water to cement ratio, and paste volume.

In addition to the measurement of transport properties, the relative humidity was assessed for concrete slabs exposed to different exposure conditions. The samples considered in this investigation included a sample stored at 50% relative humidity, covered concrete, a concrete with an exposed vertical surface, a concrete on a drainable base, a concrete on a non-drainable base, and concrete that was submerged.

4.5.2 Findings of SPR-3093

The report conducted a thorough literature review of numerous test methods that can be used to assess the transport properties of concrete. This included tests for absorption, permeability, and diffusion. The review considered the factors that influence transport properties including curing and sample preparation. The review included both gas and water permeability.

Transport was measured on mixtures from Indiana (see Figure 4.5). Mixture proportions were used that were similar to paving mixtures in Indiana. It was noted that samples dried to a lower relative humidity showed a greater volume of water absorbed. This led to studies that quantified the degree of saturation more directly. Drying water absorption samples at 105 °C resulted in substantial anomalies in water absorption, as such this method is not recommended.

Absorption samples should account for the volume of paste in the sample when this varies. Similarly, the viscosity and surface tension of the solution or the solutions the concrete was previously exposed to are important. The effect of sample conditioning was measured. Currently the ASTM absorption procedure (ASTM C1585-13) does not consider sample history nor does it provide appropriate conditioning. Further, the work identified that degree of saturation should be added to the standard test for use in freeze-thaw testing.

The influence of water addition to a concrete mixture was determined using electrical conductivity (resistivity). More recently, this has been adapted as formation factor testing. Pore solution conductivity was observed to be approximately linearly related to the degree of hydration presumably due to dilution. A correction must be applied to electrical conductivity or resistivity samples tested at different temperatures. Recent work (Coyle, Spragg, Amirkhanian, Suraneni, & Weiss, 2018; Coyle, Spragg, Suraneni, Amirkhanian, Tsui-Chang, & Weiss, 2018) has suggested an approach to perform these corrections.

Practical field sample exposure showed that the relative humidity in the concrete was always above 80% for the fall, winter, and spring. This indicates that the gel pores are frequently saturated and it is primarily the saturation of the capillary pores and air voids that is varying during the drying and wetting process. The samples that were exposed to precipitation events demonstrated higher relative humidities.

4.6 SPR-3200: Durability of Saw-Cut Joints in Plain Cement Concrete Pavements (Castro et al., 2011)

4.6.1 Objectives of SPR-3200

The main objective of this study was to evaluate factors influencing the durability of the joints in portland cement concrete pavement in the state of Indiana. Field observations indicated that deteriorating joints were observed to frequently have standing water (or solutions containing deicing salts) and damaged joint sealant (Mehta et al., 2005). Field observations include

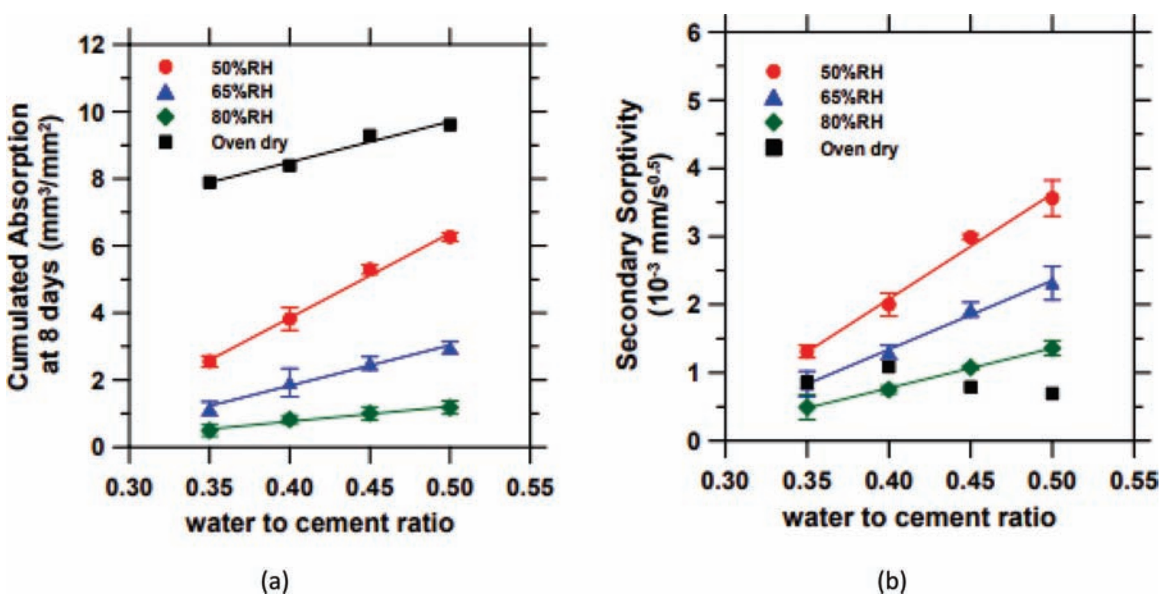

Figure 4.5 The influence of water to cement ratio and relative humidity on the cumulative absorption (a) and secondary sorption (b).

the flaking of concrete at the side of the joint as well as 'bulb-shaped' damage at the base of the saw-cut (Mehta et al., 2005). Specifically, studies were performed to compare the rate of absorption of water to the rate of absorption of deicing solutions. Further, a relationship was evaluated between the degree of saturation and concrete deterioration. Finally, the role of Soy Methyl Esters (SME) as a potential concrete sealant was evaluated.

4.6.2 Findings of SPR-3200

Studies were performed to compare the rate of absorption of water to the rate of absorption of deicing solutions. The rate of fluid absorption (i.e., deicing salt solutions) was related to the square root of ratio of surface tension and viscosity. As a result, salt solutions have a slower rate of absorption than plain water. It was also observed that concrete previously exposed to deicing salts also exhibited an altered rate of water absorption. This implies that field concretes can exhibit altered absorption properties depending on previous exposure to salt solutions. It was observed that salts altered the equilibrium relative humidity of the solution. As such, concrete containing deicing solutions will not dry (i.e., reduce mass due to water loss) until the humidity is lower than the equilibrium relative humidity of the salt solution. This suggests that concrete in the presence of a salt solution may become preferentially saturated.

A relationship between the degree of saturation and concrete deterioration due to freeze-thaw damage was obtained. It was observed that as proposed by Fagerlund (1977a, 1977b) once a critical degree of saturation was reached freeze-thaw damage was inevitable. This critical degree of saturation was approximately 86% saturation. Since the time of this research, this value has been observed to vary depending upon the quality of the air void system with systems having poorer air void spacing having a value closer to 80% (Mayercsik, Vandamme, & Kurtis, 2016). A model was extended from that of Fagerlund to predict the time to reach critical saturation. Figure 4.6 was developed based on subsequent work (Todak, 2015) to indicate how the time to critical saturation can be obtained.

Finally, the role of Soy Methyl Esters (SME) as a potential concrete sealant was studied. Penetrating concrete sealers (like soy methyl esters) reduce water absorption and the corresponding freeze-thaw damage. While absorption testing was able to show the benefits of sealers, differences were observed regarding the influence of sealer composition.

4.7 SPR-3506: Concrete Pavement Joint Deterioration (Whiting, Panchmatia, & Olek, 2016)

4.7.1 Objectives of SPR-3506

Concrete pavements design and construction has changed over the past 45 years. Changes in INDOT specifications, pavement materials and design, construction practices, and deicing materials were examined and related to the durability of concrete at the joints of

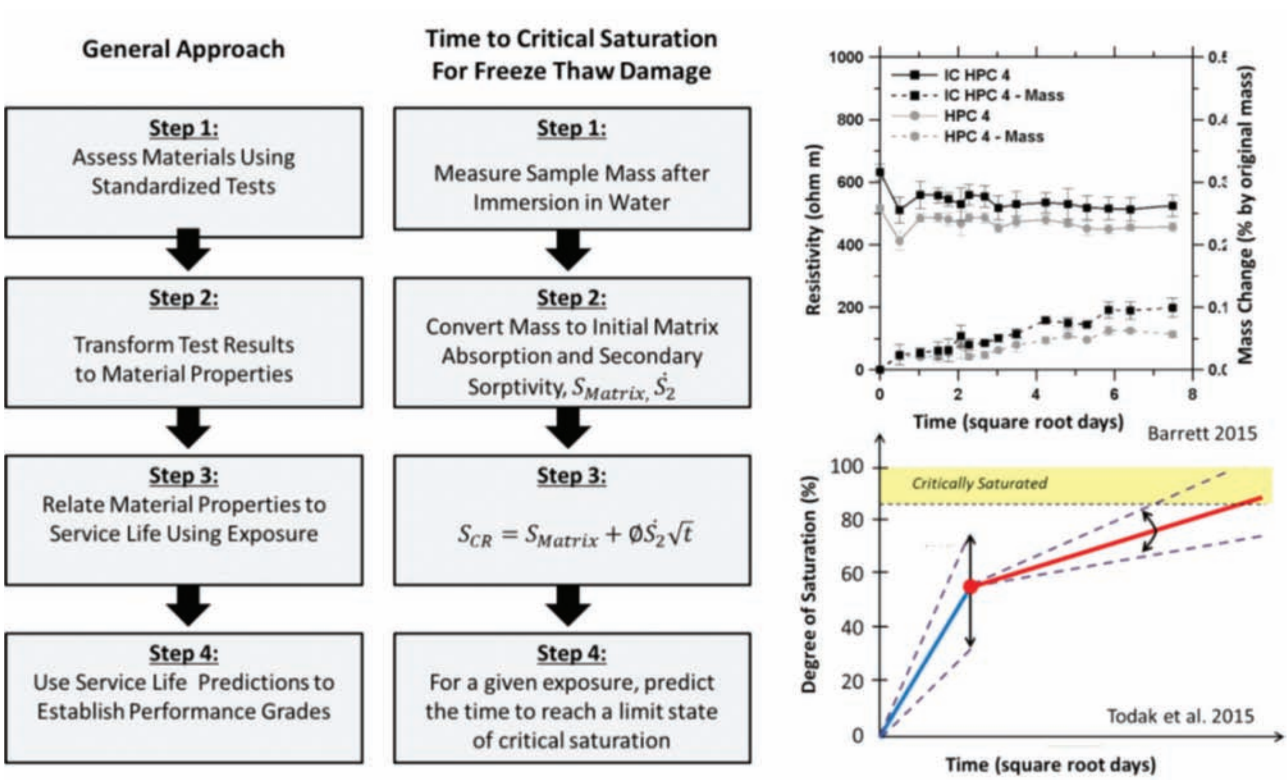

Figure 4.6 Extending the performance model approach to freeze-thaw damage.

existing pavements. Cores were taken from 11 pavements that represented different materials, construction practices, deicer exposure, and levels of deterioration to concrete with severe deterioration at the joints.

4.7.2 Findings of SPR-3506

Several variables were identified that influence the durability of concrete at the joints. These included the use of fly ash, joint sealer type, saw cut configurations, water-to-cementitious ratio (w/cm), 7-day flexural strength acceptance criteria, minimum cement content, tie bar spacing and size, target percentage air, and minimum percentage air before failure. This report illustrated that the physical properties and chemistry of cements have changed over the years. The fineness and amount of C_3S has increased. While this increases early age strength, it was reported to contribute to higher amounts of CH in the concrete and increase in the sulfates.

None of the concretes had a measured air void system that met all the criteria recommended for FT durable concrete; however, the air void systems were better at the mid-panel than at the joints. Infilling and lining of the entrained air voids with ettringite and some Friedel's salt was more common near the joints and could account for the reduced air void system. The FT testing did not correlate directly with the air void parameters, but generally, mid-panel samples tested as more durable than joints.

The following variables were determined to influence the durability of the concrete at the joints examined: the drainability of the base at the joints, original air void system, reduced air void parameters due to lining and infilling of the air voids with secondary minerals, compromised hydration of the concrete at the joint face, increased moisture at the joint. One pavement section that did not have fly ash had worse deterioration than the panels nearby that had fly ash.

4.8 SPR-3509 & SPR-3657: Electrical Testing of Cement-Based Materials: Role of Testing Techniques, Sample Conditioning, and Accelerated Curing (Spragg, Bu, Snyder, Bentz, & Weiss, 2013)

4.8.1 Objectives of SPR-3509 & SPR-3657

These projects examined the potential for using electrical testing on concrete as a potential surrogate for obtaining information on ion and fluid transport. Electrical measurements are particularly attractive for use in quality control as they are easy to perform, are performed rapidly, and can be directly related to fluid transport.

This work describes how electrical resistance measurements should be corrected for geometry to obtain a geometry independent resistivity or conductivity. Further, this work reviews and discusses several factors that influence the resistivity that is measured including porosity, pore connectivity, the role of temperature on degree of hydration (activation energy), temperature effects on conduction, ionic leaching, and the role of temperature and leaching on porosity. The goal of this work is to provide an overview of the main factors that should be considered when conducting electrical property testing, when using electrical properties for quality control/quality assurance, or if using these materials for acceptance.

4.8.2 Findings of SPR-3509 & SPR-3657

This work has indicated that geometry correction factors are needed to convert resistance measurements into the geometry independent value for resistivity or conductivity. The uniaxial cylinder test has a coefficient of variation of 4.4%, leading to a within-laboratory precision of 12.4% and a multi-laboratory precision of 37.38%.

Temperature can dramatically influence resistivity (Figure 4.7). A correction for measurements is needed when the sample is at a temperature other than the reference temperature. This can substantially influence the results, and a correction factor has been proposed that is based on the pore solution composition. The degree of saturation can dramatically influence resistivity. A saturation function is proposed that accounts for drying as well as the concentration of pore solution.

In general, for a standard 100×200 mm test cylinder, the ratio of surface resistivity to uniaxial resistivity is 1.8 to 1.9 for a homogenous material; however, if the material is heterogeneous (due to drying or leaching), this value changes.

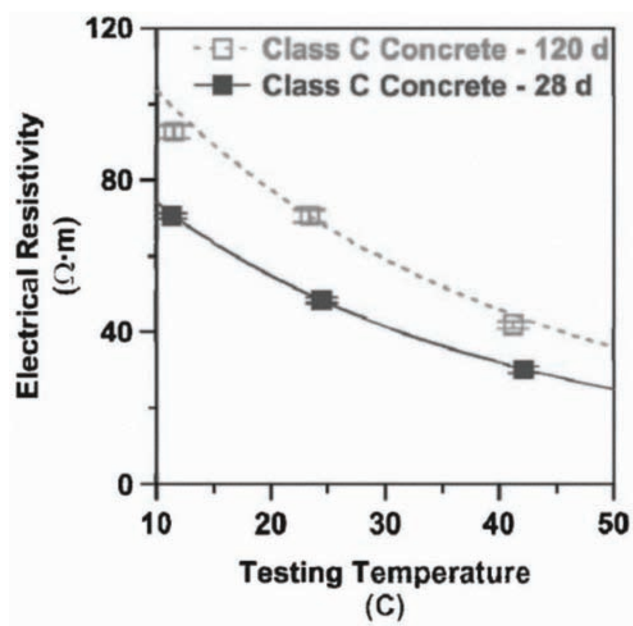

Figure 4.7 Influence of specimen temperature on measured resistivity. Dashed lines indicate a correction using an activation energy of conduction of 22 kJ/mol, error bars represent a standard deviation of 3 samples, reproduced from (Farnam, Washington, & Weiss, 2015).

This project has also illustrated the importance of ionic leaching (Figure 4.8). Specifically, when stored in lime-saturated water, alkalis and hydroxide ions can leach from the pore solution into the surrounding pore solution. Additionally, the report discusses how ionic leaching would impact different concretes differently.

It was shown that accelerated curing requires testing temperature correction and curing temperature correction. This leaching problem is also a temperature-related process, so specimens stored in limewater at different temperatures will show drastically different resistivity measurements, due in part to ionic leaching. Subsequently work by Coyle et al. developed an improved description of the influence of temperature (Coyle, Spragg, Amirkhanian, Suraneni et al., 2018; Coyle, Spragg, Suraneni, Amirkhanian, Tsui-Chang et al., 2018).

A direct correlation is discussed between electrical resistivity and the rapid chloride permeability.

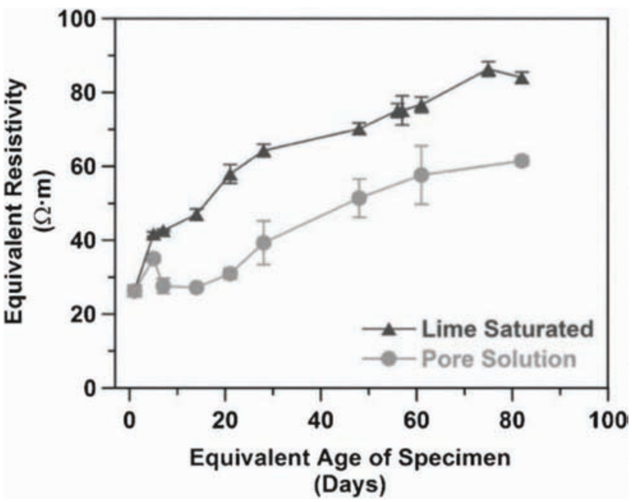

Figure 4.8 Electrical measurements conducted on a Class C concrete stored in lime-saturated water (standard curing) and in artificial pore solution using a solution to sample volume ratio of 2.0. Error bars represent the standard deviation of three specimens, reproduced from Spragg (2013).

This correlation was further extended after this project was completed (Shilstone, 1990).

4.9 SPR-3523: Evaluation of Sealers and Waterproofers for Extending the Life Cycle of Concrete (Wiese et al., 2015)

4.9.1 Objectives of SPR-3523

This project examined the role of soy methyl esters polystyrene blends (SME-PS) as a potential method to extend the service life of concrete pavements by limiting the ingress of salt solutions. The report discusses field application of the SME-PS blends for field investigation in Lafayette and Fishers. The report also discusses the development of a test to assess chloride solution ingress during temperature cycling.

4.9.2 Findings of SPR-3523

This project determined that in plain cement paste samples the $CaCl_2$ reacts with calcium hydroxide from the binder and produce calcium oxychloride, which is expansive and can cause degradation in concrete. The LT-DSC result showed three endothermic peaks. The endothermic peaks were associated with (1) eutectic solid melting at approximately -50.8 °C, (2) ice melting at a temperature between -50.8 °C and 0 °C, and (3) calcium oxychloride melting at a temperature above 0 °C. The sample containing SME showed no peak corresponded to calcium oxychloride formation. It was postulated that the SME can either limit $CaCl_2$ penetration into the mortar sample or it provides a physical barrier between the salt solution and calcium hydroxide thereby limiting reaction.

SME was applied on three experimental sections. The first section was a 15-year-old pavement. This was from US 231 just south of the intersection of W 400 S. The SME was applied on August 6, 2011, and tested November 26, 2014, after 3 years of service. The SME-PS appeared to work well in reducing the chloride ingress (Figure 4.9). No notable difference was observed

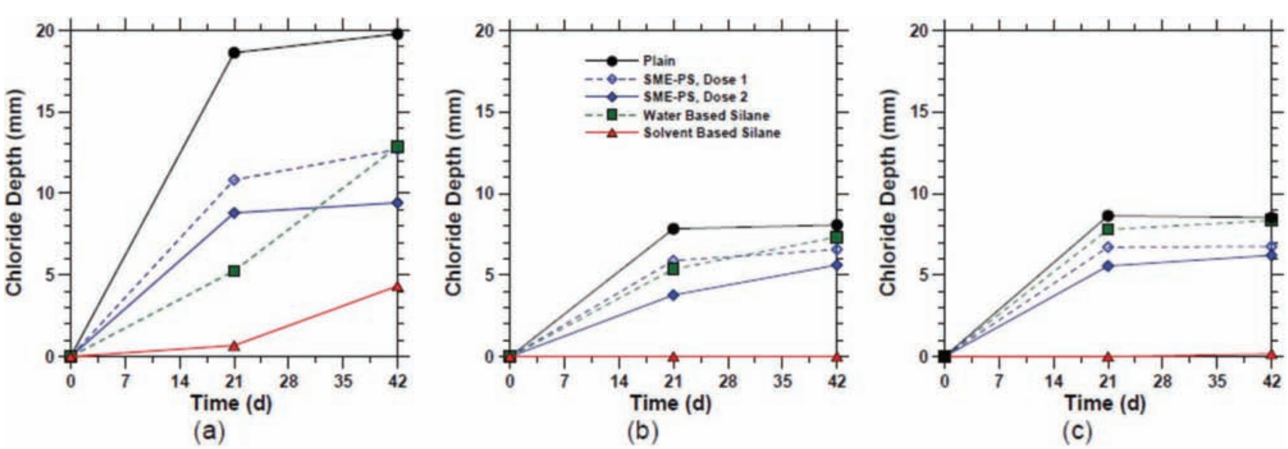

Figure 4.9 Chloride penetration depth for sodium chloride (a), magnesium chloride (b) and calcium chloride (c).

between samples that the joint was sealed with a full depth conventional joint sealer and the joints where the concrete was sealed with SME-PS. The sections where the concrete joint was left exposed without any treatment (i.e., no joint sealant or concrete sealant) showed substantially more ingress than the conventional joint sealer or the concrete sealer.

SME was applied on three experimental sections. The second section was a new pavement at 126th Street in Fishers between Enterprise Drive and Parkside Drive. This was tested after 4 years. The cores illustrated that the saw cuts were not as deep or consistent as anticipated. While some locations showed that the application of SME reduced the penetration of deicing salts while others showed little impact on the rate of chloride ingress. It should be noted however that in both locations no evidence of damage was observed presumably because the topical treatment provided a physical barrier between the salt and the calcium hydroxide.

One aspect of this project focused on the development of a testing procedure to assess the impact of sealers, pore blockers, and water repelling materials to delay or prevent chloride solution ingress. Preliminary testing has been performed to develop a methodology, which closely replicates concretes field exposure to fluids containing salts. Chloride pumping has been found to expedite the absorption of chlorides in concrete that are exposed to freezing conditions.

4.10 SPR-3623: Early Detection of Joint Distress in Portland Cement Concrete Pavements (Harris et al., 2015)

4.10.1 Objectives of SPR-3623

The objective of this project was to investigate the development of a nondestructive test method(s) that can be used to determine the level of damage that exists in D-1 pavement joints. The technique will be one sided and can be performed without the removal of the sealant or backer rod. This will provide an indication of whether damage is developing before it becomes visible at which time the cost of repair is high.

This project included the review of available techniques and previous attempts to detect damage, the use of nondestructive test on laboratory specimens with simulated damage documenting the results of these tests. Field evaluation was also planned.

4.10.2 Findings of SPR-3623

The electrical response was measured for mortars subjected to a temperature cycle from 23°C to -35°C with varying degrees of saturation and varying salt concentrations (Figure 4.10). The resistivity increased as the degree of saturation was reduced (Weiss, Snyder, Bullard, & Bentz, 2013) due to the reduction in the volume of the conductive medium and increase in tortuosity. The resistivity gradually increased as temperature was decreased until the phase transformation temperature (i.e., ice formation), after which time the resistance increased more rapidly. Direct measurement of electrical resistivity of the concrete from the surface can also be used to determine if fluid exist in the joint beyond a threshold decided to be indicative of susceptibility to joint deterioration. Like the GPR technique, this method will be influenced by many factors independent to each specific pavement. With further investigation and the compilation of a statistical data set, it may be possible to determine a relationship between resistivity attenuation, measured at a set angle with a set array of electrodes, and the depth of fluid within the joint. In both of these processes results should be compared to results on a section of known condition, preferable an area with an empty joint.

GPR was examined as a method to detect joint damage. GPR was used effectively to detect fluid accumulation in the saw-cut joint behind the joint sealant. The typical GPR waveforms are difficult and time consuming to interpret. Features of the wave form (amplitude and derivative) indicate the presence of fluid; however, the XX antenna configuration with the 400 MHz antennas was the most promising due to proportionality with the fluid present in the joint. A signal processing approach termed the complexity-invariance distance (CID) approach was used to obtain a single number that reflects the potential for fluid in the joint. Scalar waveform features and the computed CID can be used to estimate which joints may contain fluid, thereby providing insights into which joint sealant sections may need to be repaired or when a sufficient number of joints may contain fluid, which suggests that a larger joint maintenance effort be performed to seal the joints or the concrete (Figure 4.11).

4.11 SPR-3864: Performance of Concrete Pavement in the Presence of Deicing Salts and Deicing Salt Cocktails (Suraneni et al., 2016)

4.11.1 Objectives of SPR-3846

This project had two main objectives. First, the project intended to develop a standardized approach to use low temperature differential scanning calorimetry (LT-DSC) to assess the influence of cementitious binder composition on the potential for calcium oxychloride formation. Second, this work was to determine the influence of blended salt cocktails on the formation of calcium oxychloride.

4.11.2 Findings of SPR-3846

A test method was developed/formalized that uses low temperature differential scanning calorimeter (LTDSC) to quantify the chemical reaction that occurs between the cementitious matrix and the deicing salt to form calcium oxychloride. The LT-DSC test has been used to qualify the potential for calcium oxychloride formation in a cementitious matrix. Based on this research a test

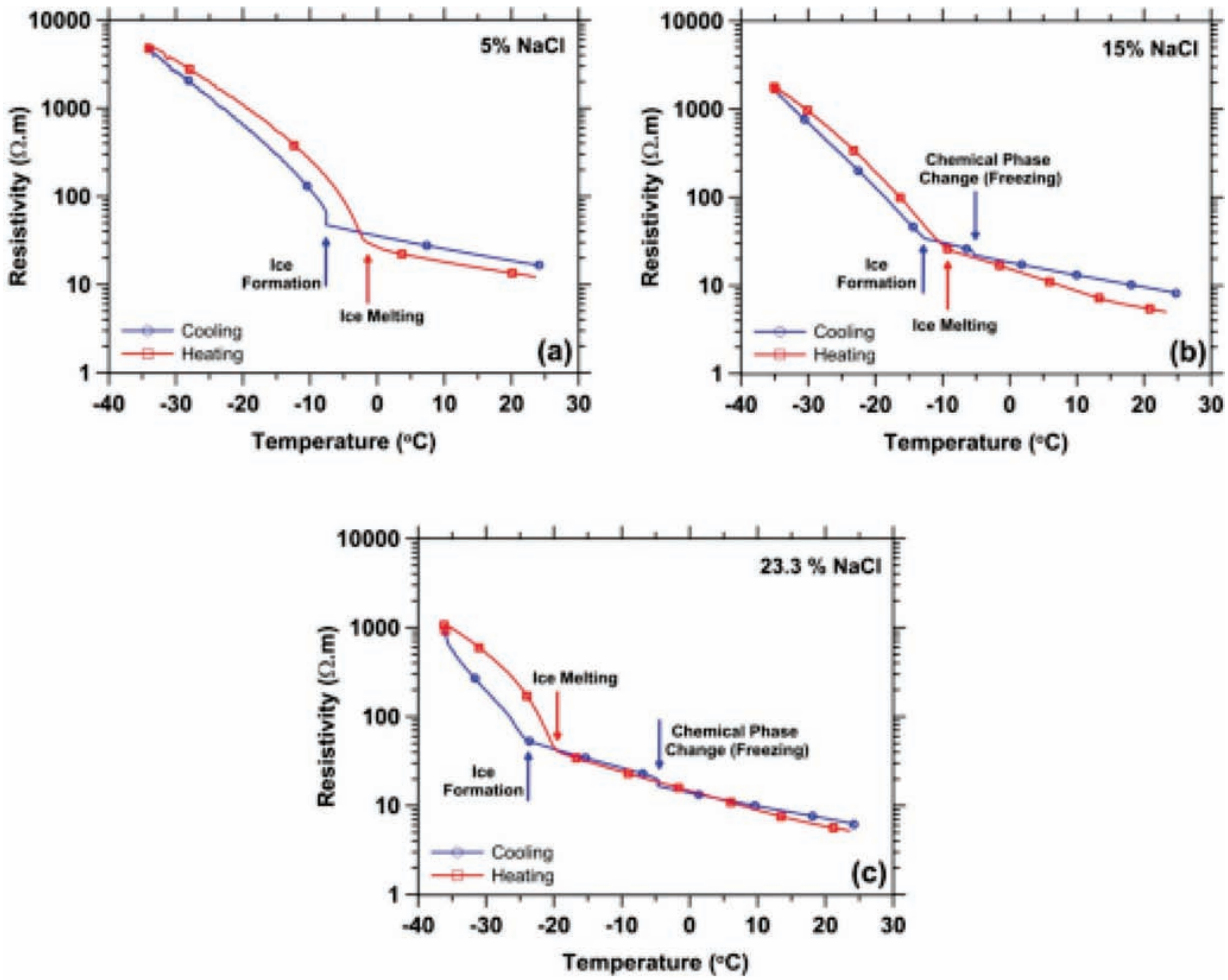

Figure 4.10 Resistivity as a function of temperature for samples saturated with solutions of 5% NaCl (a), 10% NaCl (b) and 23.3% NaCl (c).

method was standardized as an Indiana test method, and more recently this became an AASHTPO test method (AASHTO, 2017). Subsequent to this project, this test was extended to concrete (Suraneni & Weiss, 2018).

This report has shown that as the calcium hydroxide (CH) content in the paste increases, so does the potential for calcium oxychloride (CAOXY) formation. CAOXY contents increase with the proportion of $CaCl_2$ solution in the blends. A simple model has been developed to estimate the amount of calcium oxychloride formed in the pastes, depending on the calcium chloride and calcium hydroxide contents. This was related to the deicer blend that is used on the pavement. A simple example of this is seen in Figure 4.12.

This report quantifies how the replacement of a portion of cement with supplementary cementitious materials can improve performance. Subsequent to this work, a series of papers have been written to better quantify the performance of these systems as described in the following section.

4.12 Subsequent Work

A significant amount of work has been performed to better understand the behavior of cementitious materials exposed to chloride-based deicing salts. A short summary of the results presented here constitute a broad overview, and as such, a detailed presentation is not possible. Further details regarding the results can be found in the cited references.

Phase isopleths. LT-DSC results provide the temperatures of various transitions that occur in mixtures of $Ca(OH)_2$ and $CaCl_2$ – eutectic melting, ice melting, and CAOXY phase transition. These temperatures can be used to construct a phase isopleth (a slice of a ternary phase diagram; an example is shown in Figure 2.5). The effects of $CaCl_2$ concentration and $Ca(OH)_2/CaCl_2$ molar ratio on the eutectic temperature, the ice melting temperature, and the temperature at which CAOXY begins was determined. Using these phase isopleths

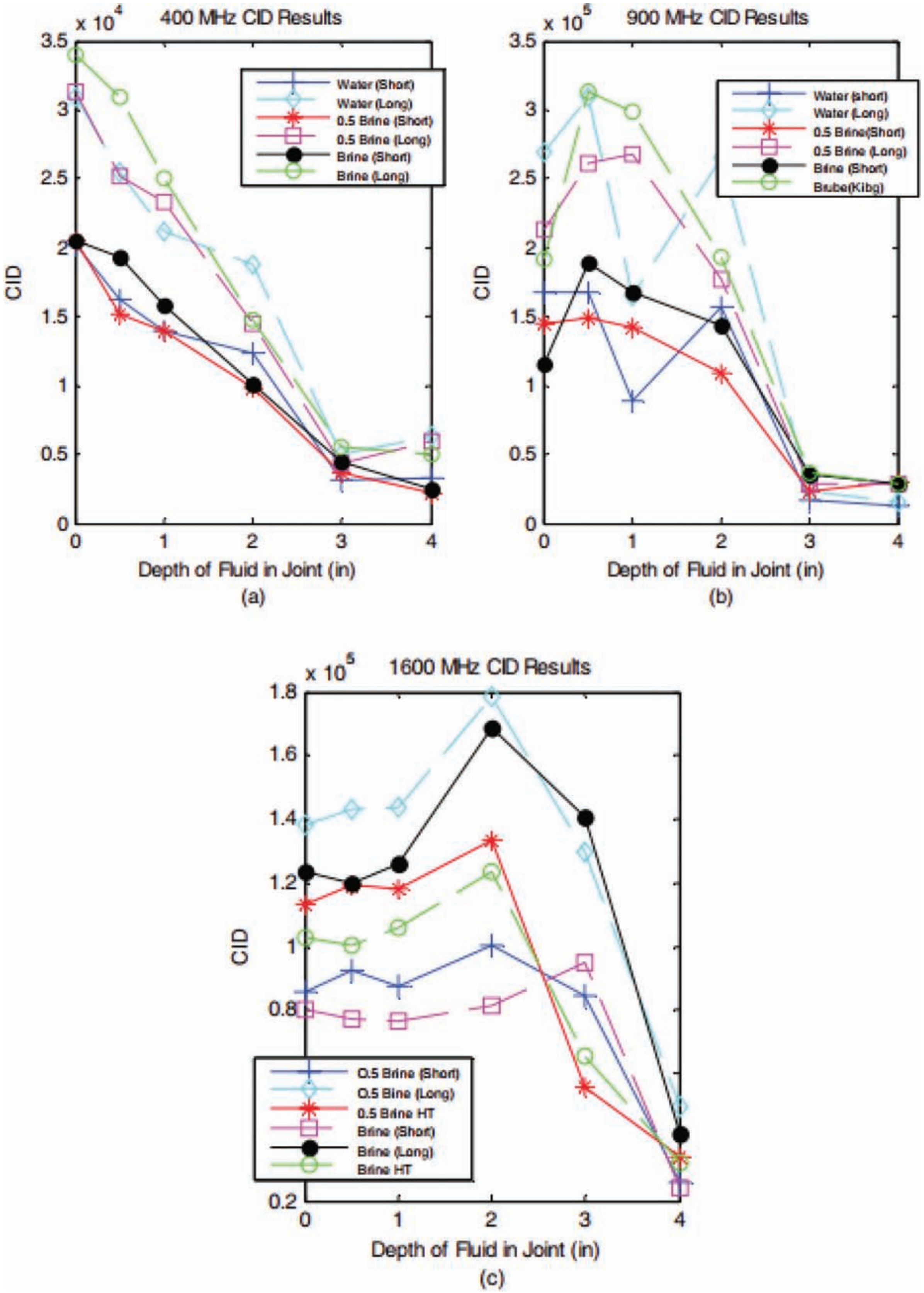

Figure 4.11 CID results for the 400 MHz antenna in the XX direction for differing depths of brine in the joint.

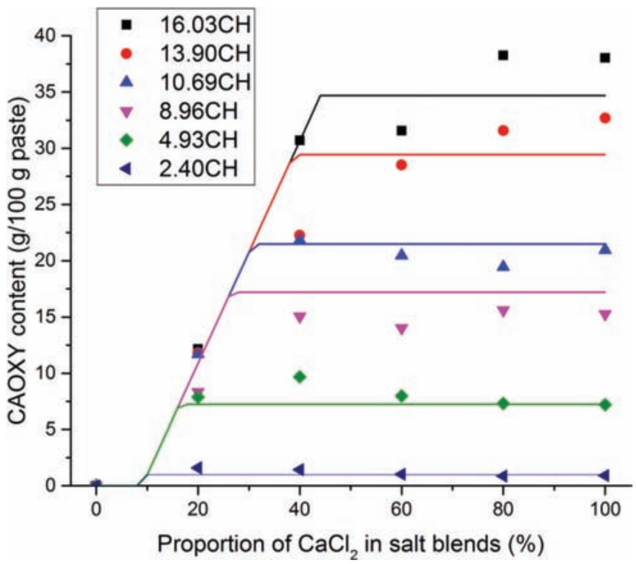

Figure 4.12 Application of the model to estimate calcium oxychloride values for various $Ca(OH)_2$ and $CaCl_2$ values. Experimental data is shown as points and modeled data is shown as straight lines.

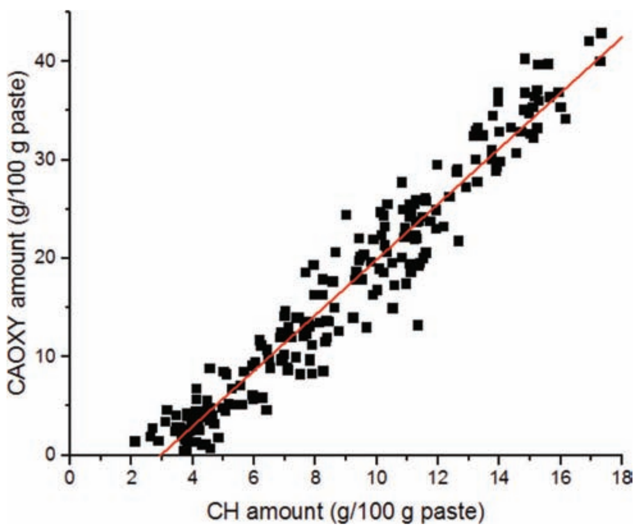

Figure 4.13 Relationship between CAOXY and $Ca(OH)_2$ amount shows a linear increase in CAOXY as $Ca(OH)_2$ increases.

together, it is possible to develop a ternary phase diagram of the system. In addition to isopleths with $Ca(OH)_2$, isopleths with cement paste and $CaCl_2$ solutions have also been developed. (Farnam, Dick, Wiese, Davis, Bentz, & Weiss, 2015; Qiao et al., 2018c).

Relationship between $Ca(OH)_2$ and CAOXY. In cement pastes mixed with 20% $CaCl_2$ solutions, the amount of $CaCl_2$ is much more than the amount of $Ca(OH)_2$, and all of the $Ca(OH)_2$ is consumed. Under these conditions, as can be seen in Figure 4.13, the amount of CAOXY linearly increases with the $Ca(OH)_2$ content. Therefore, $Ca(OH)_2$ contents can be used to predict CAOXY content, however, this must be done with some caution. As SCM amounts increase, CAOXY amounts decrease (as shown in Figure 2.8a). Using the nature of this relationship, the efficiency of each SCM in reducing CAOXY amounts can be quantified. The behavior for deicing salt blends can be determined based on models as shown in Figure 4.12 (Suraneni et al., 2016a; Monical, Unal et al., 2016; Suraneni & Weiss, 2018).

Volume change measurements. A volume change test method to determine the volume change of $Ca(OH)_2$ and cementitious materials exposed to $CaCl_2$ and other similar salts was developed. A continuous volume occurs due to changes in solution density with temperature and the sharp volume change only due to the CAOXY phase transition. This volume change depends on the $Ca(OH)_2$ content, salt concentration and the type of salt used. The volume change can be modeled using LT-DSC results. Volume change and LT-DSC results are broadly consistent, and the volume change is lowered when SCMs are used (Qiao et al., 2018a, 2018b, 2018c).

Flexural strength measurements. A test to determine the flexural strength reduction of cementitious pastes exposed to various deicing salts has been developed. Results are shown in Figure 2.4 and Figure 2.7 and have been discussed in the corresponding sections. The maximum damage to cement pastes is caused by $MgCl_2$ and the least damage is caused by NaCl. In all cases, the use of SCMs results in a reduction of the damage used (Qiao et al., 2018a, 2018b).

Thermodynamic modeling. Thermodynamic modeling can be used to determine degree of reaction of SCMs by comparing the experimental calcium hydroxide amounts with thermodynamic calculations. These results reveal that the degree of reaction decreases with the SCM replacement level, and that the degree of reaction values, especially for SCMs such as fly ash, are somewhat low (Azad et al., 2017; Glosser et al., 2017; Suraneni et al., 2016a; Monical, Unal et al., 2016).

Testing on mortar and concrete. TGA and LT-DSC testing has been done on mortars and concretes, and the results reveal that the tests are applicable on mortars and concretes. However, due to the large dilution caused by the aggregates, certain modification in the test protocols need to be made. Specifically, the tests need to be repeated on multiple samples in order to provide a more representative sample. In addition, the LT-DSC test needs to be performed with a higher power-liquid ratio, to counteract the dilution due to the aggregates (Suraneni & Weiss, 2018).

5. DRAINAGE

5.1 Research from Other Agencies

Researchers and agencies have examined several dozen concrete pavements exhibiting premature distress related to the joints over the past 15 years; however, very few have examined the base/subbase or considered how it may have contributed to the joint deterioration (Burnham & Rohne, 2011; Hansen & Kang, 2010; Hall, & Crovetti, 2000; Moulzolf, n.d.; Sargand, William, & Lankard, 2010; Vandenbossche, Ramirez, Geary, Gatti, & Mu, 2011; Van Dam, Sutter, Smith, Wade, Peterson, 2002a, 2002b, 2002c). Mn/DOT examined 12 pavements and found water remained in dense graded bases built without edge drains for more than 24 hrs, with some still wet after 3 days (Burnham & Rohne, 2011); and pavement joints showed less evidence of distress when the built on well drained subbases and when the joint sealer was intact.

5.2 INDOT Research

Research performed under two INDOT sponsored projects SPR-3016 (Weiss, 2015) and SPR-3506 (Whiting et al., 2016) looked at the drainage and/or the subbase materials at 60 core holes at 15 different pavement locations throughout Indiana. Figure 5.1 shows examples of good, slow and very poor drainage at the core holes.

The following summarizes the drainage and joint condition off the 15 pavement sections examined:

1. Two pavements showed no joint deterioration and had good drainage at both the joint and mid-panel.
2. Four pavements showed moderate to severe distress at the joint and all had slower drainage at the joint than at the mid-panel.
3. Six pavements showed very minor deterioration at the joints; three of these had good drainage at both the joint and mid-panel and three had slower drainage at the joint.
4. Three pavements that showed distressed concrete at the joints but had good drainage at both the mid-panel and joint also had construction problems that likely contributed to the concrete distress. One pavement was constructed during a snowstorm and two pavements were built in the 1960s, prior to AP aggregate specifications, with original joint spacing >20ft with mid-panel cracks and patching that was very common.

In conclusion, all pavements that showed moderate-to-severe joint deterioration also showed reduced drainage capacity of the subbase at the joint.

The material used as subbase can influence the drainage. SPR-3016 examined sections of I-94, near Michigan City, much of which was built using slag aggregate for the #8 drainage subbase layer. As shown in Figure 5.2, the slag aggregate can become larger chunks cemented together, changing the gradation of the subbase and at times becoming a solid mass. This mass was often cemented to the bottom of the pavement and occasionally found holding joints closed. These changes to the subbase likely compromised the drainability of the subbase, especially at the joints. It is possible that if slag aggregate is mixed with natural aggregate the problems of secondary cementation of the slag aggregate could be diminished and a certain amount of slag aggregate used for the drainage layer. However, until that is proven to be true it is recommended that slag aggregate be avoided in the drainage layer.

In addition to good drainage at the joints and in the drainage layer, maintaining good drainage in the edge drains and underdrains is critical to keeping the pavement joints and base dry. As shown in Figure 5.3 not all the edge and under drains on INDOT highways are being properly constructed or maintained in order to take and keep the water away from the pavement structure (Whiting et al., 2016).

Figure 5.1 Examples of subbase drainage at pavement core holes. Good, medium and poor drainage, from left to right, respectively.

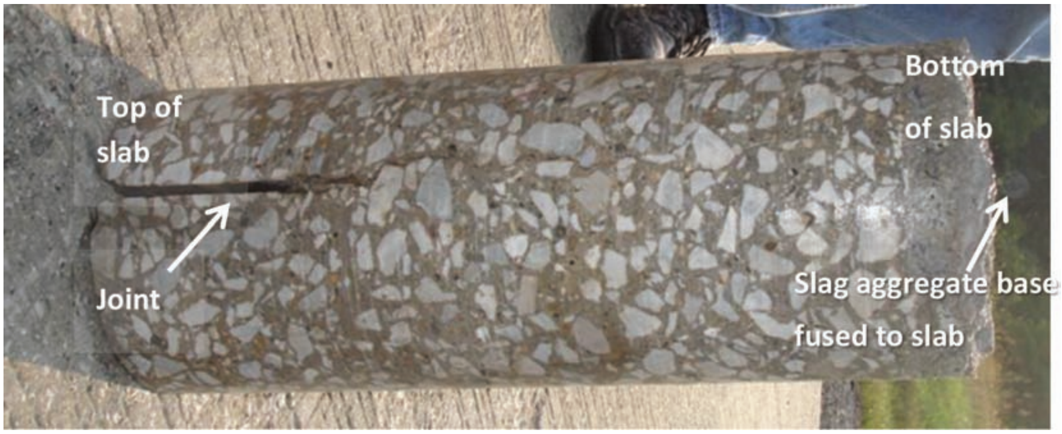

Figure 5.2 Core taken from I-94 with slag aggregate base fused to bottom of slab and joint crack held closed.

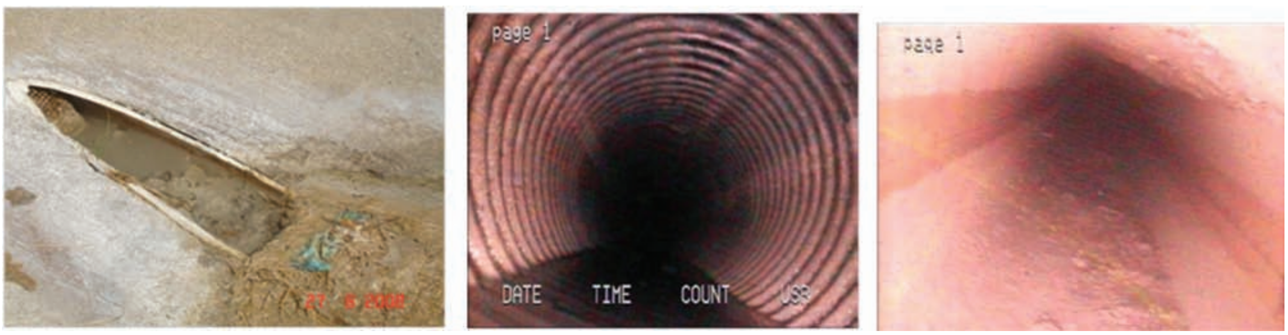

Figure 5.3 Example of blocked edge drain and water in drains in pavement sections along I-94 (Arribas-Colón et al., 2012).

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APPENDIX

Synthesized Recommendations: Slides from the Joint Deterioration Workshop, April 27, 2015

Joint Deterioration Workshop

11:30 Introductions - Holtz

11:45 Opening Remarks and Overview - Nantung

12:00 Project Recapping – Whiting

12:10 Project Recapping - Olek

12:20 Synthesized Recommendations – Weiss

12:35 Discussion of Recommendations - Holtz/Nantung

12:50 Action Plan

Main Overview

- Two main contributing factors
  - Water in joints leading to saturation Addressed by (1, 2, 3, 4, 7, 8, 9)
  - Chemical reaction occurs between the salt and the matrix Addressed by (5, 6, 10, 11)

- Recommendation – Red
- Impact – Green
- Trying to remain at 30,000 feet with details addressed in implementation phase

Concept: Examining the Volume of Air and the Water to Cement Ratio

Volume of Air

SCM Use

Concrete Sealer

W/C

F. Factor

Backer Rod

Reduce Tie

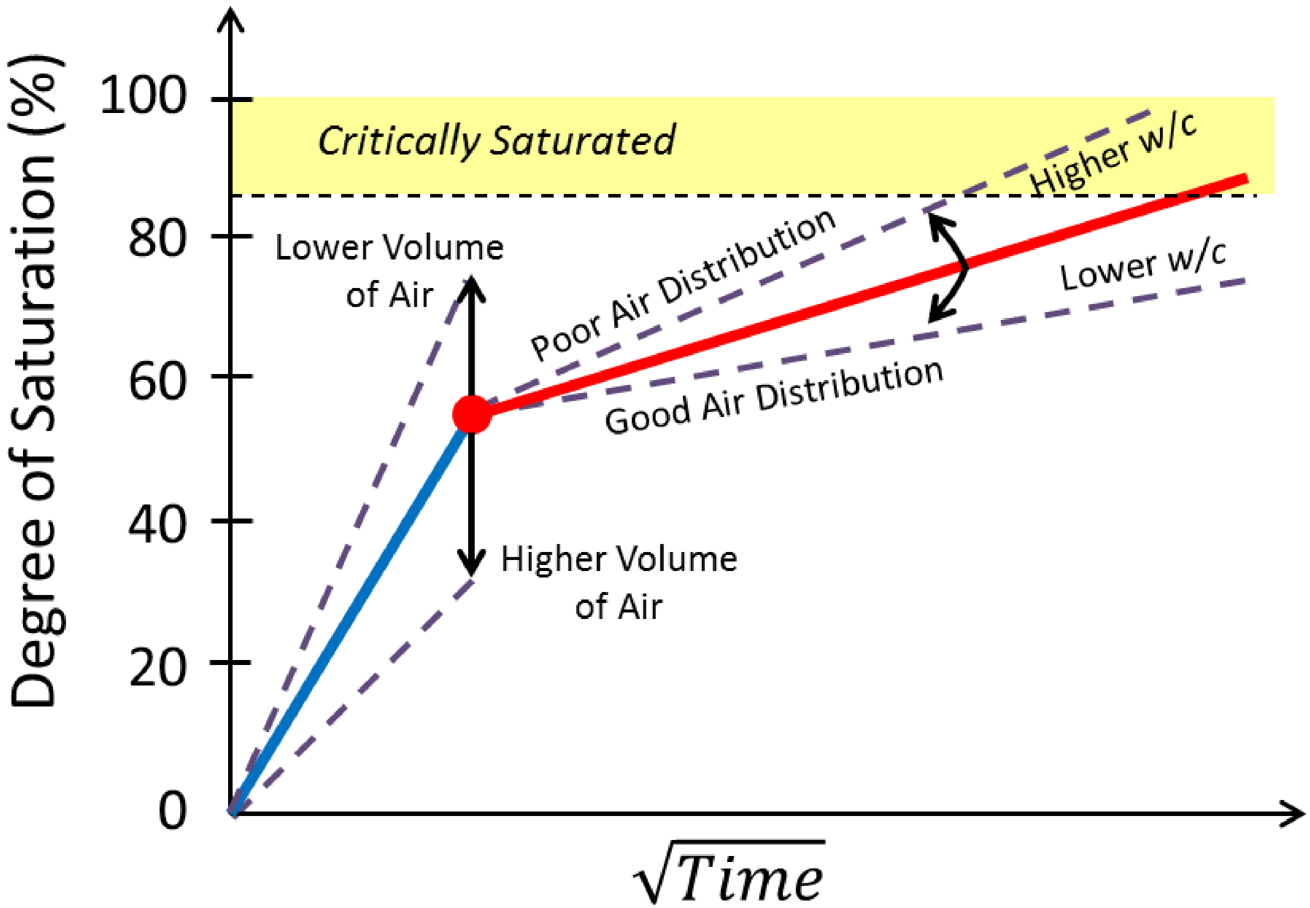
Bar Size/Spacing

Opening Strength

Strength Acceptance

Joint Sealant

Detection



NPFS: (co-PI Weiss) Improving Specifications to Resist Frost Damage in Modern Concrete Mixtures

1. Volume of Air

Volume of Air

SCM Use

Concrete Sealer

W/C

F. Factor

Backer Rod

Reduce Tie

Bar Size/Spacing

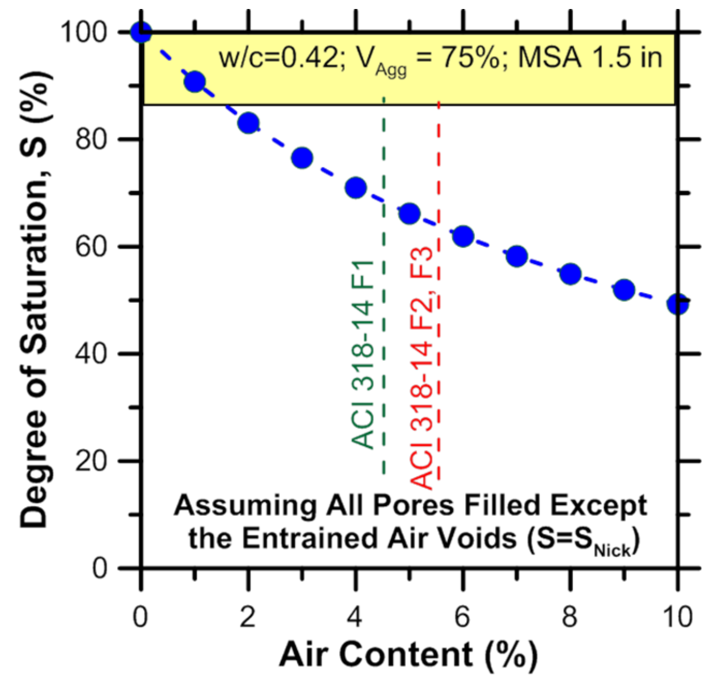
Opening Strength

Strength Acceptance

Joint Sealant

Detection

- Reduce the potential for low air
- Move lower bound on air from 5.0 to 5.5%
- Allow contactors to design for an air of 7.0%
- Change in air of 1%; 5% decrease in S_{nick}
- Impact – low risk, variable contractor target higher air



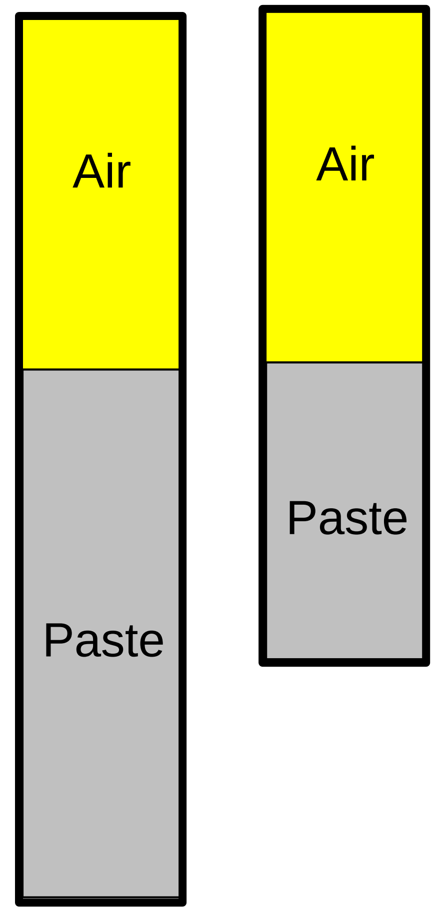
From General Discussion

NPFS: (co-PI Weiss) Improving Specs to Resist Frost Damage in Modern Concrete Mixtures

2. Volume of Paste (Minimum Cementitious Content)

- Volume of Air
- SCM Use
- Concrete Sealer
- W/C
- F. Factor
- Backer Rod
- Reduce Tie
- Bar Size/Spacing
- Opening Strength
- Strength Acceptance
- Joint Sealant
- Detection

- Allow contractors to optimize the binder and reduce paste
- Remove the minimum required cement content
- Change in cement from 564 to 451 lb/yd^3 decreases S_{nick} 5%
- Impact – Risk Low, Push Contractor to Optimize Aggregate, Verify Placeability



From General Discussion

3. Water to Cement Ratio

Volume of Air

SCM Use

Concrete Sealer

W/C

F. Factor

Backer Rod

Reduce Tie

Bar Size/Spacing

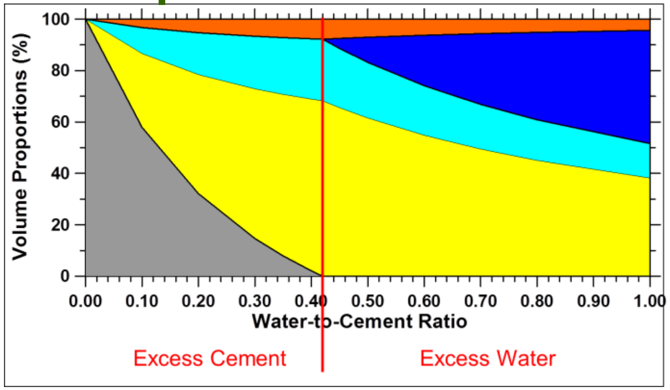
Opening Strength

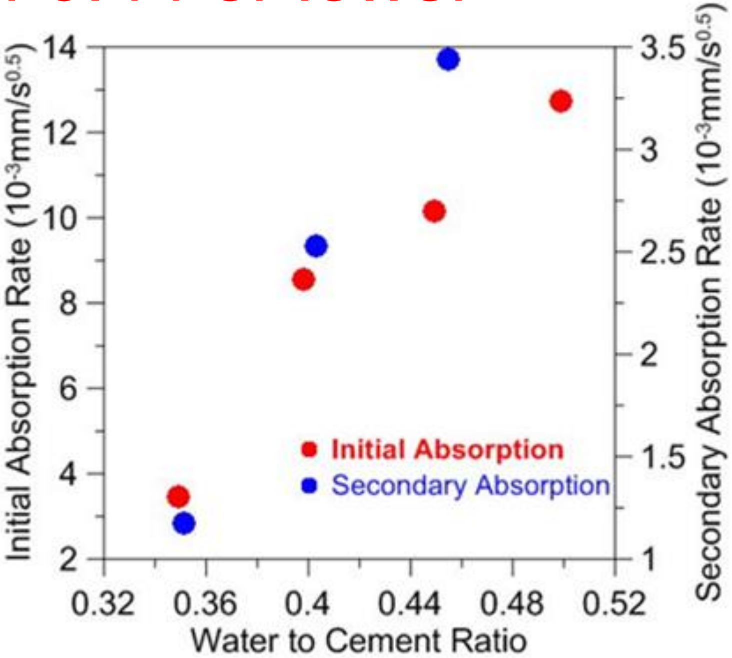
Strength Acceptance

Joint Sealant

Detection

- Change the current upper bound on w/c from 0.45 to a max of 0.44 or lower
- Impact - Low Risk





NPFS: (co-PI Weiss) Improving Specifications to Resist Frost Damage in Modern Concrete Mixtures

SPR 2474 (PI Weiss and Olek) Interaction Between Micro-Cracking, Cracking, and Reduced Durability of Concrete: Developing Methods for Considering Cumulative Damage in Life-Cycle Modeling

4. Consider Specification of a Formation Factor

Volume of Air

SCM Use

Concrete Sealer

W/C

F. Factor

Backer Rod

Reduce Tie

Bar Size/Spacing

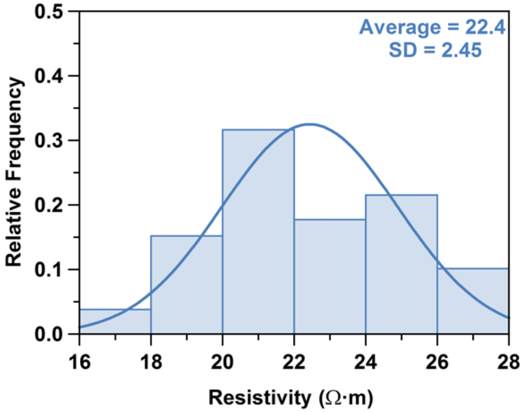
Opening Strength

Strength Acceptance

Joint Sealant

Detection

- Consider moving to a pay factor that is based on the formation factor (resistivity)
- Rewards process control that monitors water content in mixtures
- Impact – Med Risk due to learning, Contractors will need to become familiar with this test



Spragg et al. 2012

SPR 3093: (PI Weiss) Portland Cement Concrete Pavement Permeability Performance
SPR 3509: (PI Weiss) Variability Analysis of the Bulk Resistivity Measured Using Concrete Cylinders

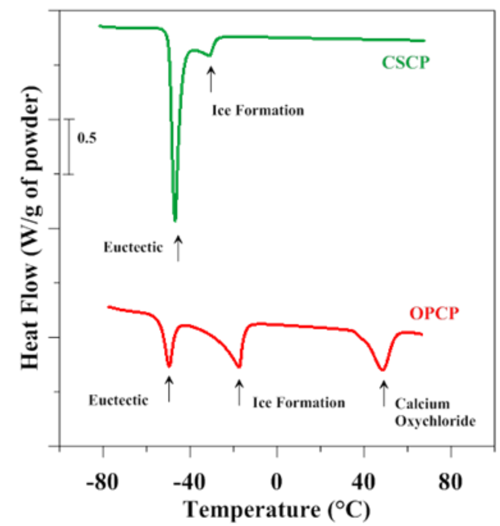
Concept: Chemical Salt Degradation

Volume of Air
SCM Use
Concrete Sealer
W/C
F. Factor
Backer Rod
Reduce Tie
Bar Size/Spacing
Opening Strength
Strength Acceptance
Joint Sealant
Detection

- CH plays a role in salt/joint durability (Ca-oxychloride)
- Recent research from Peterson et al. & Farnam et al.

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$$

- Phase change that results in a massive volume change (~ 30%)
- Can optimize the amount of SCM to reduce the potential for Ca-Oxy formation



PFS (co-PI Weiss) Joint Damage in Concrete Pavements
SPR 3864: (co-PI Weiss) Deicing Salts and Deicing Salt Cocktails

5. Mitigation of the Problem - SCM

Volume of Air

SCM Use

Concrete Sealer

W/C

F. Factor

Backer Rod

Reduce Tie

Bar Size/Spacing

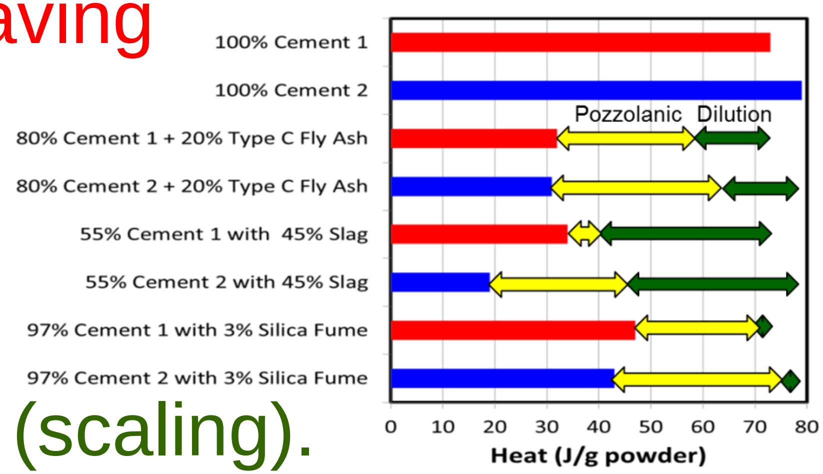
Opening Strength

Strength Acceptance

Joint Sealant

Detection

- Use SCM to mitigate Ca-Oxy
- Initial – Recommend Minimum SCM
- Long Term – LTDSC Test Qualification
- Remove current calendar limit on SCM use for slip form paving
- Examine SCM restriction limits
- Allow Ternary
- Impact – Low Risk (scaling). reduce risk in bidding potential lower cost



SPR 2475: (PI Olek and Weiss) Technical Issues Related to the Use of Fly Ash and Slag During the Late Fall (Low Temperature) Construction Systems

SPR 3864: (PI Weiss) Performance of Deicing Salts and Deicing Salt Cocktails

6. Mitigation of the Problem - Sealer

Volume of Air

SCM Use

Concrete Sealer

W/C

F. Factor

Backer Rod

Reduce Tie

Bar Size/Spacing

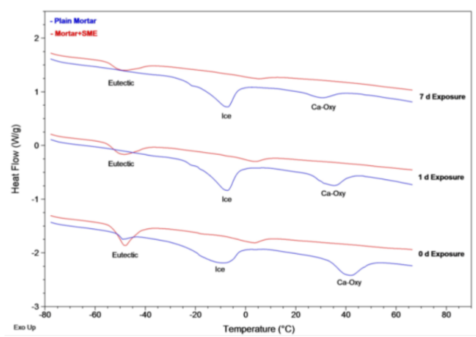
Opening Strength

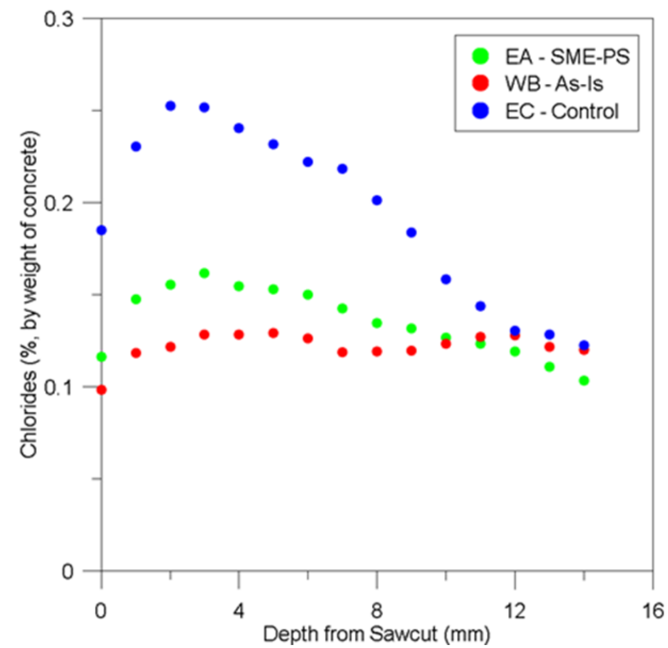
Strength Acceptance

Joint Sealant

Detection

- Use concrete sealant to reduce Ca-Oxy
- Use concrete sealer with open joints on new or existing joints
- Impact – Open Joints, Potential LCA saving



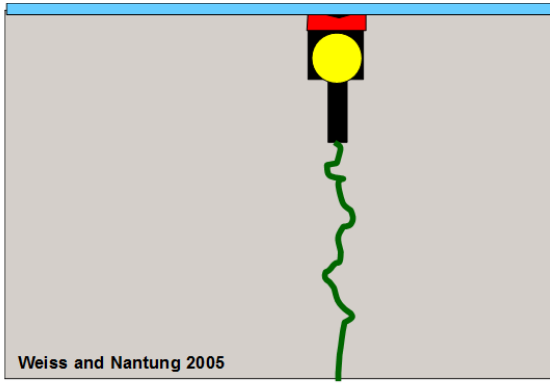


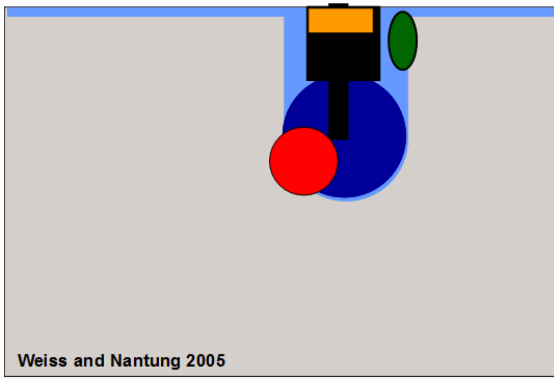
SPR 3200: (PI Weiss) Durability of Saw-Cut Joints in Plain Cement Concrete Pavements

SPR 3523: (PI Weiss) Evaluation of Sealers and Waterproofers for Extending the Life Cycle of Concrete

7. Reduce Tie Bar Size and Spacing

- Fluid entering joint is trapped as crack does not open and it does not drain
- As a result, fluid can not drain out easily to drainable subbase under the PCCP
- Already Implemented
- Impact – Low Risk

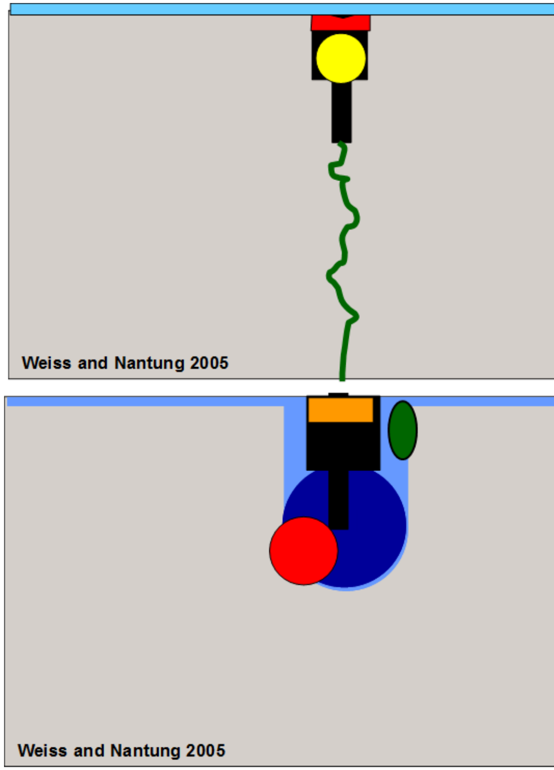




SPR 3200: (PI Weiss) Durability of Saw-Cut Joints in Plain Cement Concrete Pavements

8. Remove Backer Rod

- Fluid entering joint is trapped
- Fluid can not drain out easily to drainable subbase under the PCCP
- Silicone sealant & backer rod limit drying of trapped fluid which limits drying increase saturation & chemical rxn
- Remove backer rod, full filling (Iowa seeing issues) or remove completely
- Impact – Low Risk, Training and materials



SPR 3093: (PI Weiss) Portland Cement Concrete Pavement Permeability Performance

9. Removing Joint Sealant

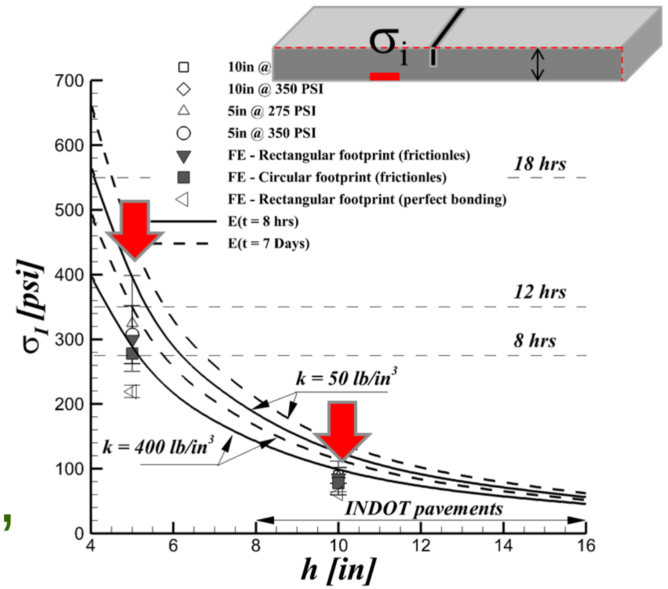
- A request was made to consider removing the joint sealant in 2008 led to SPR 3523 (to evaluate impact on concrete) and other projects (SPR 3506, 3510) to evaluate the impact on construction and subgrade
- From a concrete perspective remove the joint sealant and use concrete sealant
- Impact - Other factors, subgrade needs to be considered and this may require some understanding of the impact on the #53

SPR 3523: (PI Weiss and Tao) Evaluation of Sealers and Waterproofers for Extending the Life Cycle of Concrete

10. Reducing Opening Strength

- Volume of Air
- SCM Use
- Concrete Sealer
- W/C
- F. Factor
- Backer Rod
- Reduce Tie
- Bar Size/Spacing
- Opening Strength
- Strength Acceptance
- Joint Sealant
- Detection

- Stress due to traffic varies with pavement thickness as shown
- A one size fits all strength not needed
- Reduce strength of pavement to open
- Impact – random cracks, overloaded trucks, curl/warp considerations



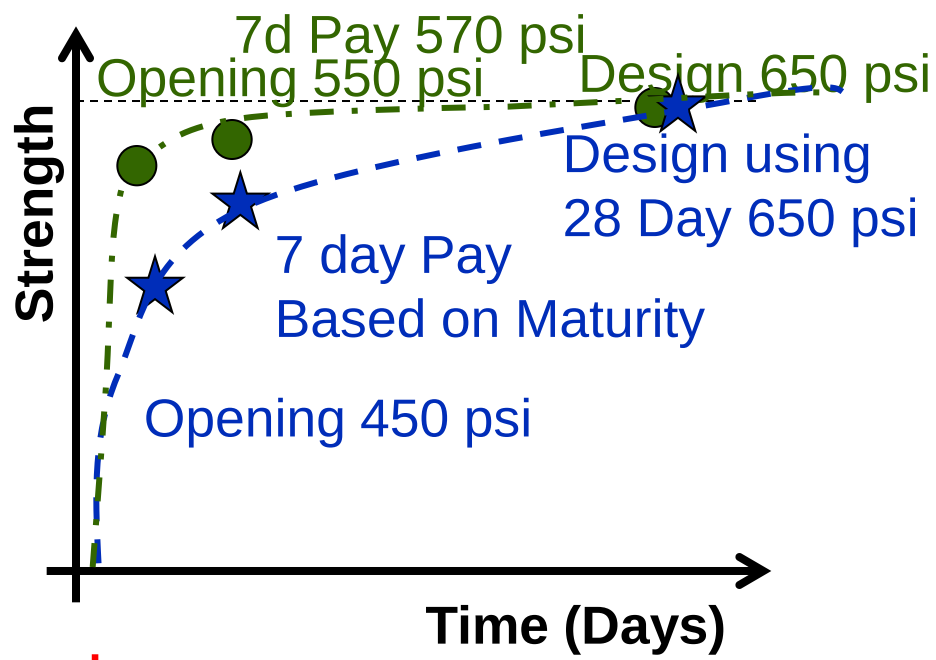
- Implications for patches (IC reduces curl)

SPR 3403: (PI Weiss) Removing Obstacles for Pavement Cost Reduction by Examining Early Age Opening Requirements – Material Properties

11. Altering Strength at the Time of Acceptance

Volume of Air
SCM Use
Concrete Sealer
W/C
F. Factor
Backer Rod
Reduce Tie
Bar Size/Spacing
Opening Strength
Strength Acceptance
Joint Sealant
Detection

- Encourage mixture designs that gain strength more slowly and to use maturity to determine the payment early for the contractor



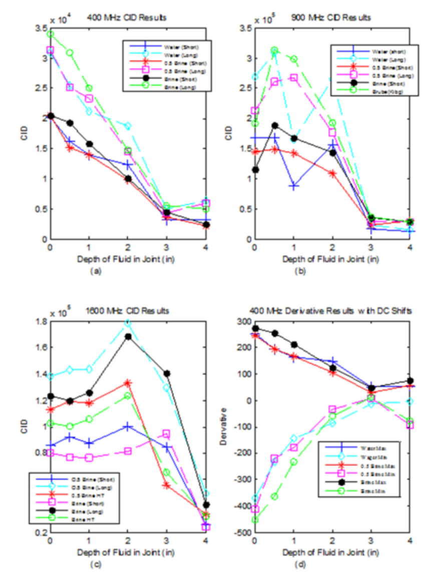
- Impact – Overloaded construction equipment can damage the concrete

SPR 7299-0599: (PI Weiss, Olek) Performance Related Specifications (PRS) for Concrete Pavements in Indiana

12. Detection of the Problem

Volume of Air
SCM Use
Concrete Sealer
W/C
F. Factor
Backer Rod
Reduce Tie
Bar Size/Spacing
Opening Strength
Strength Acceptance
Joint Sealant
Detection

- A procedure was developed using ground penetrating radar (CID) to detect standing water or salt solution in joints, with the goal of using this to identify when the joint may need to have the sealant stripped, dried and treated. (# 6 and 8)
- Electrical resistivity can be used but was time consuming and not well suited for a large number of joints
- D. Harris was integrally involved and has a very innovative solution that can be used and this is ready



SPR 3623: (PI Weiss) Early Detection of Joint Distress in Portland Cement Concrete Pavements

Summary of Recommendations

Volume of Air

SCM Use

Concrete Sealer

W/C

F. Factor

Backer Rod

Reduce Tie

Bar Size/Spacing

Opening Strength

Strength Acceptance

Joint Sealant

Detection

1. Volume of Air (lower bound move 5.0 to 5.5)
2. Volume of Cement (cementitious content)
3. Water to Cement (0.45 to 0.44)
4. Formation Factor (implement a pay factor)
5. Supplementary Cementitious Materials Use
6. Use Concrete Sealers (penetrating sealer)
7. Tie Bar and Spacing (already Implemented)
8. Remove Backer Rod
9. Remove Joint Sealant
10. Reduce Opening Strength
11. Reduce Strength At Time of Acceptance
12. Detection of the Problem (Use of GPR CID)

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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