

|   |  |  |  |   |           |
|---|--|--|--|---|-----------|
| 1. Report No.<br>FHWA/TX-05/0-4069-1  |  | 2. Government Accession No.                          |  | 3. Recipient's Catalog No.  |           |
| 4. Title and Subtitle<br><br>Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration: A Literature Review   |  |  |  | 5. Report Date<br>September 2004                                      |           |
|   |  |  |  | 6. Performing Organization Code                                       |           |
| 7. Author(s)<br><br>Amy E. Eskridge, Richard E. Klingner, Michael E. Kreger, and Timothy J. Fowler  |  |  |  | 8. Performing Organization Report No.<br>Research Report 0-4069-1     |           |
| 9. Performing Organization Name and Address<br><br>Center for Transportation Research<br>The University of Texas at Austin<br>3208 Red River, Suite 200<br>Austin, TX 78705-2650  |  |  |  | 10. Work Unit No. (TRAIS)   |           |
|   |  |  |  | 11. Contract or Grant No.<br>Research Project 0-4069                  |           |
| 12. Sponsoring Agency Name and Address<br><br>Texas Department of Transportation<br>Research and Technology Transfer Office<br>P.O. Box 5080<br>Austin, TX 78763-5080   |  |  |  | 13. Type of Report and Period Covered<br>Research Report (7/00-12/00) |           |
|   |  |  |  | 14. Sponsoring Agency Code  |           |
| 15. Supplementary Notes   |  |  |  |   |           |
| 16. Abstract<br><br>This report describes part of the work associated with Texas Department of Transportation Project 0-4069 ("Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration"). The Texas Department of Transportation is interested in developing techniques for mitigating or remediating premature concrete deterioration due to alkali silica reaction (ASR), delayed ettringite formation (DEF), or both, in order to extend the life of potentially affected structures. The parts of Project 0-4069 reported here consist of: a literature search for mitigation or remediation techniques; fabrication of concrete specimens intentionally susceptible to premature deterioration; and the application and monitoring of the mitigation techniques using laboratory testing and acoustic emission (AE) procedures. Specimens were exposed to three series of environmental conditions: an indoor series; an outdoor series; and a wet/dry series. Expansion and internal relative humidity were measured to determine the efficacy of the mitigation techniques at reducing expansion from premature concrete deterioration. Based on the test results, recommendations are made for choosing mitigation treatments now, and for additional research. |  |  |  |   |           |
| 17. Key Words<br>alkali-silica reaction, bridges, coating, concrete, crack sealer, delayed ettringite formation, high-molecular-weight methacrylate, lithium nitrate, maintenance, membrane, mitigation, remediation, penetrating sealer, polymer-modified cement mortar, repair, service life, silane, siloxane, urethane, water permeability, water-vapor permeability  |  |  | 18. Distribution Statement<br><br>No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161, www.ntis.gov. |   |           |
| 19. Security Classif. (of report)<br>Unclassified   |  | 20. Security Classif. (of this page)<br>Unclassified |  | 21. No. of pages<br>60  | 22. Price |

# Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration: A Literature Review

by

*Amy E. Eskridge, Richard E. Klingner,  
Michael E. Kreger, and Timothy J. Fowler*

Research Report 0-4069-1

*Research Project 0-4069*

*MITIGATION TECHNIQUES FOR IN-SERVICE STRUCTURES  
WITH PREMATURE CONCRETE DETERIORATION*

conducted for the  
**Texas Department of Transportation**

in cooperation with the  
**U.S. Department of Transportation  
Federal Highway Administration**

by the  
**CENTER FOR TRANSPORTATION RESEARCH  
BUREAU OF ENGINEERING RESEARCH  
THE UNIVERSITY OF TEXAS AT AUSTIN**

September 2004

*Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.*

## **ACKNOWLEDGEMENTS**

We greatly appreciate the financial support from the Texas Department of Transportation that made this project possible. The support of the project director, Brian Merrill (BRG) and program coordinator, Randy Cox (BRG) is also very much appreciated. We thank Project Monitoring Committee members, Moon Won (CST), John Vogel (HOU), Keith Ramsey (BRG), Thomas Rummell (BRG), and John Bassett (CST).

## **DISCLAIMER**

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the view of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

**NOT INTENDED FOR CONSTRUCTION,  
PERMIT, OR BIDDING PURPOSES**

R. E. Klingner, Texas P.E. #42483

M. E. Kreger, Texas P.E. #65541

T. J. Fowler

*Research Supervisors*

# TABLE OF CONTENTS

|   |          |
|---|----------|
| <b>CHAPTER 1: INTRODUCTION.....</b>   | <b>1</b> |
| 1.1 BACKGROUND OF TXDOT STUDY 4069 .....  | 1        |
| 1.2 SCOPE AND OBJECTIVES OF STUDY 4069.....   | 1        |
| 1.3 SCOPE OF REPORT .....   | 2        |
| 1.3.1 <i>Literature Review</i> .....  | 2        |
| 1.4 TEST PROGRAM.....   | 2        |
| 1.4.1 <i>Test Specimens</i> .....   | 2        |
| 1.4.2 <i>Expansion and Moisture Testing</i> .....   | 2        |
| 1.4.3 <i>Acoustic Emission Monitoring</i> .....   | 2        |
| 1.5 OBJECTIVES OF REPORT .....  | 2        |
| <b>CHAPTER 2: LITERATURE SEARCH.....</b>  | <b>3</b> |
| 2.1 INTRODUCTION .....  | 3        |
| 2.1.1 <i>Objectives</i> .....   | 3        |
| 2.1.2 <i>How this Literature Search was Conducted</i> .....   | 3        |
| 2.2 METHODS FOR MITIGATING OR REMEDIATING ASR.....  | 3        |
| 2.2.1 <i>Causes of ASR</i> .....  | 3        |
| 2.2.2 <i>The Goal of Mitigation or Remediation Methods for ASR</i> .....                                      | 4        |
| 2.2.3 <i>Published Information on Mitigation or Remediation of ASR</i> .....                                  | 4        |
| 2.2.3.1 ASR Mitigation Reference No. 1 (Abe et al. 1992).....   | 4        |
| 2.2.3.2 ASR Mitigation Reference No. 2 (Kamimoto et al. 1992).....  | 4        |
| 2.2.3.3 ASR Mitigation Reference No. 3 (Fujii et al. 1989).....   | 4        |
| 2.2.3.4 ASR Mitigation Reference No. 4 (Stokes 2000).....   | 5        |
| 2.2.3.5 ASR Mitigation Reference No. 5 (Whitmore et al. 2000).....  | 5        |
| 2.2.3.6 ASR Mitigation Reference No. 6 (Baillemont et al. 2000).....  | 5        |
| 2.3 METHODS FOR MITIGATING OR REMEDIATING DEF .....   | 6        |
| 2.3.1 <i>Causes of DEF</i> .....  | 6        |
| 2.3.2 <i>The Goal of Mitigation or Remediation Treatments for DEF</i> .....                                   | 6        |
| 2.3.3 <i>Published Information on Mitigation or Remediation of DEF</i> .....                                  | 6        |
| 2.4 OTHER TYPES OF DETERIORATION IN REINFORCED CONCRETE.....  | 6        |
| 2.4.1 <i>Damage to Concrete</i> .....   | 6        |
| 2.4.1.1 Sulfate Attack.....   | 6        |
| 2.4.1.2 Salt Crystallization.....   | 6        |
| 2.4.1.3 Freeze/Thaw Cycling.....  | 7        |
| 2.4.2 <i>Corrosion of Reinforcement</i> .....   | 7        |
| 2.4.2.1 Ingress of Chlorides .....  | 7        |
| 2.4.2.2 Carbonation.....  | 7        |
| 2.4.2.3 Lowered Resistivity .....   | 7        |
| 2.4.3 <i>Relation of Other Types of Deterioration to ASR/DEF Deterioration</i> .....                          | 7        |
| 2.5 SURFACE TREATMENTS FOR MITIGATING OR REMEDIATING OTHER TYPES OF DETERIORATION IN REINFORCED CONCRETE..... | 8        |
| 2.5.1 <i>Coatings and Membranes</i> .....   | 8        |
| 2.5.2 <i>Published Information on Coatings and Membranes</i> .....  | 8        |
| 2.5.2.1 Coating Reference No. 1 (ACI 515-1985).....   | 8        |
| 2.5.2.2 Coating Reference No. 2 (O'Donoghue et al. 1998).....   | 8        |

|   |   |           |
|---|---|-----------|
| 2.5.3   | <i>Penetrating Sealers</i> .....                                      | 9         |
| 2.5.4   | <i>Published Information on Penetrating Sealers</i> .....             | 9         |
| 2.5.4.1   | Penetrating Sealer Reference No. 1 (ACI 515-1985).....                | 9         |
| 2.5.4.2   | Penetrating Sealer Reference No. 2 (Wright et al. 1993).....          | 9         |
| 2.5.4.3   | Penetrating Sealer Reference No. 3 (Marks 1988).....                  | 9         |
| 2.5.4.4   | Penetrating Sealer Reference No. 4 (Basheer et al. 1998).....         | 10        |
| 2.5.4.5   | Penetrating Sealer Reference No. 5 (Rizzo et al. 1989).....           | 10        |
| 2.5.4.6   | Product Literature on Penetrating Sealers.....                        | 10        |
| 2.5.5   | <i>Crack Sealers</i> .....  | 10        |
| 2.5.6   | <i>Published Information on Crack Sealers</i> .....                   | 11        |
| 2.5.6.1   | Crack Sealer Reference No. 1 (Sprinkel et al. 1995).....              | 11        |
| 2.5.6.2   | Crack Sealer Reference No. 2 (Fowler 1989).....                       | 11        |
| 2.6   | ELECTROCHEMICAL TREATMENTS.....                                       | 11        |
| 2.7   | SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FROM LITERATURE SEARCH..... | 11        |
| 2.7.1   | <i>Summary and Conclusions</i> .....                                  | 11        |
| 2.7.2   | <i>Recommendations</i> .....  | 12        |
| 2.7.3   | <i>Recommendations for Specific Structures</i> .....                  | 13        |
| <b>CHAPTER 3: DEVELOPMENT OF TEST PROGRAM.....</b>  |   | <b>15</b> |
| 3.1   | OBJECTIVES.....   | 15        |
| 3.2   | TEST SPECIMENS.....   | 15        |
| 3.2.1   | <i>Specimen Fabrication</i> .....                                     | 15        |
| 3.2.2   | <i>Specimen Nomenclature</i> .....                                    | 16        |
| 3.2.3   | <i>Mitigation Techniques</i> .....                                    | 16        |
| 3.3   | EXPANSION AND MOISTURE TEST SETUP.....                                | 17        |
| 3.3.1   | <i>Indoor Series</i> .....  | 17        |
| 3.3.2   | <i>Outdoor Series</i> .....   | 18        |
| 3.3.3   | <i>Wet/Dry Series</i> .....   | 19        |
| 3.4   | ACOUSTIC EMISSION TEST SETUP.....                                     | 20        |
| <b>CHAPTER 4: TEST RESULTS.....</b>                 |   | <b>23</b> |
| 4.1   | RESULTS OF EXPANSION AND MOISTURE TESTING.....                        | 23        |
| 4.1.1   | <i>Indoor Series</i> .....  | 23        |
| 4.1.2   | <i>Outdoor Series</i> .....   | 23        |
| 4.1.2.1   | Expansion.....  | 23        |
| 4.1.2.2   | Moisture.....   | 25        |
| 4.1.3   | <i>Wet/Dry Series</i> .....   | 28        |
| 4.1.3.1   | Expansion.....  | 28        |
| 4.1.3.2   | Moisture.....   | 28        |
| 4.1.3.3   | Damage Indices.....   | 28        |
| 4.2   | RESULTS OF ACOUSTIC EMISSION MONITORING.....                          | 31        |
| 4.2.1   | <i>Indoor Series</i> .....  | 31        |
| 4.2.2   | <i>Wet/Dry Series</i> .....   | 35        |
| <b>CHAPTER 5: SIGNIFICANCE OF TEST RESULTS.....</b> |   | <b>37</b> |
| 5.1   | SIGNIFICANCE OF EXPANSION AND MOISTURE TESTING.....                   | 37        |
| 5.1.1   | <i>Indoor Series</i> .....  | 37        |
| 5.1.2   | <i>Outdoor Series</i> .....   | 38        |
| 5.1.3   | <i>Wet/Dry Series</i> .....   | 39        |
| 5.1.4   | <i>Damage Indices</i> .....   | 40        |
| 5.2   | SIGNIFICANCE OF ACOUSTIC EMISSION MONITORING.....                     | 41        |

|  |   |           |
|--|---|-----------|
| 5.2.1  | <i>Indoor Series</i> .....                  | 41        |
| 5.2.2  | <i>Wet/Dry Series</i> .....                 | 41        |
| <b>CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS.....</b> |   | <b>43</b> |
| 6.1  | SUMMARY .....                               | 43        |
| 6.1.1  | <i>Literature Search</i> .....              | 43        |
| 6.1.2  | <i>Expansion and Moisture Testing</i> ..... | 43        |
| 6.1.3  | <i>Acoustic Emission Monitoring</i> .....   | 44        |
| 6.2  | CONCLUSIONS .....                           | 44        |
| 6.3  | RECOMMENDATIONS.....                        | 44        |
| <b>REFERENCES.....</b>   |   | <b>47</b> |

## List of Figures

|             |   |    |
|-------------|---|----|
| Figure 3-1  | Specimens in molds .....  | 16 |
| Figure 3-2  | Length reading taken with length comparator.....                                  | 18 |
| Figure 3-3  | Specimens of outdoor series behind FSEL .....                                     | 19 |
| Figure 3-4  | Test frame and ram with specimen .....  | 20 |
| Figure 3-5  | MISTRAS 2001 instrument .....   | 21 |
| Figure 4-1  | Average Expansion, Indoor Series, Jobe Specimens .....                            | 23 |
| Figure 4-2  | Average Expansion, Indoor Series, Fordyce Specimens.....                          | 24 |
| Figure 4-3  | Average Expansion, Outdoor Series, Jobe Specimens.....                            | 24 |
| Figure 4-4  | Average Expansion, Outdoor Series, Fordyce Specimens .....                        | 25 |
| Figure 4-5  | Moisture at 0.5 in. Depth, Outdoor Series, Jobe Specimens .....                   | 26 |
| Figure 4-6  | Moisture at 1.5 in. Depth, Outdoor Series, Jobe Specimens .....                   | 26 |
| Figure 4-7  | Moisture at 0.5 in. Depth, Outdoor Series, Fordyce Specimens .....                | 27 |
| Figure 4-8  | Moisture at 1.5 in. Depth, Outdoor Series, Fordyce Specimens .....                | 27 |
| Figure 4-9  | Average Expansion, Wet/Dry Series.....  | 28 |
| Figure 4-10 | Moisture at 0.5 in. Depth, Wet/Dry Series .....                                   | 29 |
| Figure 4-11 | Moisture at 1.5 in. Depth, Wet/Dry Series .....                                   | 29 |
| Figure 4-12 | Damage Index " $\Sigma w_l$ ", Wet/Dry Series.....                                | 30 |
| Figure 4-13 | Damage Index " $\Sigma w^2l$ ", Wet/Dry Series .....                              | 30 |
| Figure 5-1  | Moisture in specimens plotted against rainfall and ambient relative humidity..... | 38 |
| Figure 5-2  | Sketches of cracks on specimens of wet/dry series.....                            | 41 |

## List of Tables

|           |  |    |
|-----------|--|----|
| Table 3-1 | Mitigation Techniques.....                         | 17 |
| Table 4-1 | AE results for Indoor Series Specimen CF a.....    | 32 |
| Table 4-2 | AE results for Indoor Series Specimen M7F b.....   | 33 |
| Table 4-3 | AE results for Indoor Series Specimen CJ b .....   | 33 |
| Table 4-4 | AE results for Indoor Series Specimen M7J b .....  | 34 |
| Table 4-5 | AE results for Wet/Dry Series Specimen CJ g.....   | 35 |
| Table 4-6 | AE results for Wet/Dry Series Specimen M17J g..... | 36 |





## **SUMMARY**

This report describes part of the work associated with Texas Department of Transportation Study 4069 (“Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration”). The Texas Department of Transportation is interested in developing techniques for mitigating or remediating premature concrete deterioration due to alkali silica reaction (ASR), delayed ettringite formation (DEF), or both, in order to extend the life of potentially affected structures. The parts of Study 4069 reported here consist of: a literature search for mitigation or remediation techniques; fabrication of concrete specimens intentionally susceptible to premature deterioration; and the application and monitoring of the mitigation techniques using laboratory testing and acoustic emission (AE) procedures. Specimens were exposed to three series of environmental conditions: an indoor series; an outdoor series; and a wet/dry series. Expansion and internal relative humidity were measured to determine the efficacy of the mitigation techniques at reducing expansion from premature concrete deterioration. Based on the test results, recommendations are made for choosing mitigation treatments now, and for additional research.

# CHAPTER 1: INTRODUCTION

## 1.1 BACKGROUND OF TXDOT STUDY 4069

In 1995, the Texas Department of Transportation (TxDOT) began identifying in-service structures with premature concrete deterioration. Damage was found across the state to prestressed beams, abutments, columns and bents, often requiring repair of the structure or removal from service after only several years. The damage was manifested as external and internal cracking, and as “map cracking.” The mechanisms of damage were identified as Alkali-Silica Reaction (ASR), Delayed Ettringite Formation (DEF), or both (Boenig 2000). Consequences of ASR/DEF damage are progressive loss of member function and increased susceptibility to corrosion and other forms of environmental attack<sup>1</sup>.

TxDOT Study 1857 (“Structural Assessment of In-Service Bridges with Premature Concrete Deterioration”) was conducted to develop methods to predict the capacity of damaged structural elements. Field observations and laboratory tests were used to develop damage indices and finite element models and nondestructive testing methods for identifying deterioration in the field (Boenig 2000).

TxDOT Study 4069 (“Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration”) is a follow-up to Study 1857. TxDOT is interested in developing techniques for mitigating or remediating premature concrete deterioration due to ASR, DEF, or both, in order to extend the life of potentially affected structures.

## 1.2 SCOPE AND OBJECTIVES OF STUDY 4069<sup>2</sup>

TxDOT Study 4069 is divided into six tasks:

- 1) Conduct an extensive literature search to identify treatments being used or tested worldwide to mitigate or remediate deterioration from ASR, DEF, or both. Compile the results as a bibliography and report of various mitigation or remediation techniques. Evaluate the published results and select the mitigation or remediation techniques to be used in Tasks 2 and 3.
- 2) Fabricate a large number of concrete specimens with a combination of aggregates and cement with a high susceptibility to ASR, DEF, or both. Induce premature deterioration by exposing the specimens to cycles of wetting and drying and to heat.
- 3) Use non-destructive evaluation (NDE) procedures and physical testing to evaluate the effectiveness of the mitigation or remediation techniques chosen in Task 1 on the concrete specimens with premature deterioration.
- 4) Prepare a report on the results of Tasks 2 and 3, with a recommendation for mitigation or remediation techniques to be evaluated in the field.
- 5) After acceptance by TxDOT of the proposal from Task 4, apply the recommended techniques to field structures with documented ASR/DEF deterioration. The effectiveness of the treatments will be evaluated with the NDE procedures developed in Study 1857 and used in Task 3.

---

<sup>1</sup> Klingner, R.E., T.J. Fowler, and M.E. Kreger, “Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration,” proposal to Texas Department of Transportation, 2000.

<sup>2</sup> Klingner, R.E., T.J. Fowler, and M.E. Kreger, “Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration,” proposal to Texas Department of Transportation, 2000.

- 6) Prepare a comprehensive report summarizing the results of the entire project.

### **1.3 SCOPE OF REPORT**

The parts of Study 4069 reported here cover Tasks 1 through 4. The work consisted of: a literature search for mitigation or remediation techniques for premature concrete deterioration; fabrication of concrete prisms with deterioration; and application and monitoring of the mitigation techniques using laboratory testing and NDE procedures.

#### ***1.3.1 Literature Review***

A literature search was conducted to identify treatments being used or tested worldwide to mitigate or remediate deterioration from ASR, DEF, or both. The initial focus of this literature search was treatments specific to the mitigation or remediation of ASR, DEF, or both. The next step in this literature search was to examine the known causes of ASR/DEF, and to investigate actions that have shown some success in addressing those causes. The second focus of the search was treatments specific to the mitigation or remediation of other forms of concrete deterioration, such as sulfate attack, chloride ingress, and carbonation. The fundamental mechanisms of these forms of deterioration were studied, and literature was gathered on available methods of mitigation and remediation for them, including coatings, membranes, sealers, and electrochemical processes. The literature review is presented as Chapter 2.

### **1.4 TEST PROGRAM**

#### ***1.4.1 Test Specimens***

A large number of concrete prisms were fabricated with a combination of aggregates and cement with a high susceptibility to ASR, DEF, or both. The reactivity of the fine aggregate and cement was evaluated as part of TxDOT Study 4085 (“Preventing Premature Concrete Deterioration due to ASR/DEF in New Concrete”). The specimens were subject to three exposure conditions to promote premature deterioration: accelerated indoor ASTM C 1293, outdoor, and wet/dry. Each set of specimens was then coated with one or a combination of the selected mitigation treatments.

#### ***1.4.2 Expansion and Moisture Testing***

The length change of the prisms was measured at intervals according to the procedure of ASTM C 1293 to determine if expansion was occurring due to ASR/DEF. The internal moisture was measured at the same intervals to determine the vapor permeability of the treatments.

#### ***1.4.3 Acoustic Emission Monitoring***

The NDE procedure of acoustic emission (AE) monitoring advanced in Study 1857 was used to quantify the internal cracking due to ASR/DEF deterioration. Monitoring was conducted at intervals reflecting those of the expansion testing, to follow the progression of cracking over time.

### **1.5 OBJECTIVES OF REPORT**

The results of expansion and internal moisture testing and the AE monitoring will be used to determine which treatments were most effective at mitigating or remediating premature deterioration from ASR/DEF for different exposure conditions representing field exposure.

## CHAPTER 2: LITERATURE SEARCH

### 2.1 INTRODUCTION

#### 2.1.1 Objectives

This literature search was conducted to identify treatments being used or tested worldwide to mitigate or remediate deterioration from alkali-silica reaction (ASR), delayed ettringite formation (DEF), or both. The proposed treatments are evaluated, according to published results, for use on Texas Department of Transportation structures displaying this damage. In addition, treatments used to mitigate other types of concrete deterioration are explored for their potential benefit against ASR/DEF deterioration.

#### 2.1.2 How this Literature Search was Conducted

The initial focus of this literature search was treatments specific to the mitigation or remediation of ASR, DEF, or both. In this report, “mitigation” refers to actions that reduce the rate at which deterioration occurs, while “remediation” refers to actions that completely arrest deterioration and restore all or part of the structure’s original strength, durability, and appearance. The ideal literature would describe the effects and efficacy of different treatments in mitigating or remediating ASR/DEF deterioration. Studies on treatment of ASR, though, are not extensive, and literature on treatment of DEF is very limited. The next step in this literature search, therefore, was to examine the known causes of ASR/DEF, and to investigate actions that have shown some success in addressing those causes.

The second focus of the search was treatments specific to the mitigation or remediation of other forms of concrete deterioration, such as sulfate attack, chloride ingress, and carbonation. The fundamental mechanisms of these forms of deterioration were studied, and literature was gathered on available methods of mitigation and remediation for them, including coatings, membranes, sealers, and electrochemical processes.

### 2.2 METHODS FOR MITIGATING OR REMEDIATING ASR

#### 2.2.1 Causes of ASR<sup>1</sup>

ASR is a reaction between siliceous aggregate and high-alkali pore water in the surrounding cementitious matrix. A high alkali concentration in the pore water provides the hydroxyl ions that react with the silica to form a gel at the cementitious matrix and aggregate interface. This gel grows as it absorbs water from the environment, consequently generating expansive forces that can produce map cracking or surface pop-outs.

ASR deterioration requires the following conditions:

- high alkali concentration in the pore water;
- aggregate with reactive silica; and
- water.

---

<sup>1</sup>Klingner, R.E., T.J. Fowler, and M.E. Kreger, “Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration,” proposal to Texas Department of Transportation, 2000.

## **2.2.2 *The Goal of Mitigation or Remediation Methods for ASR***

The goal for treating existing ASR-affected structures is to prevent water infiltration, one prerequisite for the reaction. At the same time, the treatment should permit the escape of water already in the structure, so that it does not continue to promote the reaction. Accordingly, the treatment, whether a penetrating coating or an encapsulation, must be impermeable to liquid water and permeable to water vapor.

## **2.2.3 *Published Information on Mitigation or Remediation of ASR***

### **2.2.3.1 ASR Mitigation Reference No. 1 (Abe et al. 1992)**

This article addresses the comparative effectiveness of two coatings, one impermeable to water and the other permeable to water vapor, in reducing ASR-related expansion. The impermeable coating consisted of three layers of epoxy. The vapor-permeable coating consisted of silane followed by a flexible polymer-modified cement mortar (PCM). The control specimens were uncoated.

All specimens were placed outside for two years. Specimens with the vapor-permeable coating showed continuous negative expansion, whereas after six months the specimens with the impermeable coating had much greater expansion than the uncoated specimens. The investigators attribute this high expansion to the excess initial pore water that could not escape through the impermeable epoxy coating.

### **2.2.3.2 ASR Mitigation Reference No. 2 (Kamimoto et al. 1992)**

The study described in this article measured the performance of several concentrations of a PCM using the criteria of water permeability, water-vapor permeability, elongation, adhesion, and expansion of a concrete specimen in the field. Water permeability and water-vapor permeability decreased with increasing polymer ratio, with the lowest permeability corresponding to the greatest tested polymer ratio, 0.75. Elongation of the PCM increased as the polymer ratio increased. Adhesion was greatest for a polymer ratio of 0.525.

For the field expansion tests, small, rectangular specimens were coated with either PCM or epoxy, while other specimens were left uncoated. Expansion was measured by change in length, and vapor permeability was measured by change in weight. The PCM-coated specimens had consistently low expansion, while the uncoated and epoxy-coated specimens had much higher overall expansion and greater rates of expansion. As the water-vapor permeability of the PCM increased, the specimens' expansion decreased.

### **2.2.3.3 ASR Mitigation Reference No. 3 (Fujii et al. 1989)**

The specimens in this study were subject to outdoor conditions and cycles of wetting and drying, considered the most severe environmental conditions for Japan. The coatings were applied to newly constructed specimens when their moisture content had reduced to 10%. In the outdoor series, silane- and urethane-coated specimens had expansion equivalent to that of a non-reactive specimen, actually showing negative expansion. Epoxy-coated and methyl-methacrylate-coated specimens expanded severely and the coatings cracked. Sodium silicate-coated specimens showed expansion equivalent to that of the uncoated reactive specimens. All specimens had very high expansion under cycles of wetting and drying.

Expansion was found to be related to ratios of surface area to volume and treated surface area to total surface area. As those ratios increase, expansion decreases. It was concluded that structures with large ratios of surface area to volume would especially benefit from surface treatment.

The final series of tests was a comparison of the performance of silane, silane with a PCM cover, and silane with a methyl-methacrylate cover under cycles of wetting and drying. Silane/PCM-coated specimens had four times the expansion of specimens with the other two coatings after 32 weeks of exposure, but still less than all specimens from the first series of tests.

#### **2.2.3.4 ASR Mitigation Reference No. 4 (Stokes 2000)**

In this article the use of a lithium-based solution to treat ASR was described. Tests were conducted to compare the penetration ability of various lithium solutions, to assess the efficacy of the best solution, and to study how the timing of the treatment influenced this efficacy.

Penetration ability was assessed by placing various lithium salt solutions at several concentrations in cavities in cylinders, and then recording the volume of solution entering the cylinder. The greatest penetration was achieved with a 30% lithium nitrate solution with a blend of surfactants, surpassing the penetration of lithium hydroxide, formate, and acetate.

Reactive mortar bars and concrete prisms were then used to study efficacy and application timing. In reactive mortar bars, one-half the amount of lithium required as an admixture to control ASR reduced expansion to as little as 55% of that of uncoated control specimens. Also, lithium nitrate reduced expansion twice as much as lithium hydroxide. The lithium nitrate was used on concrete prisms, applied in one and five coats. The one-coat specimens exhibited 0.1% expansion and the 5-coat specimens exhibited 0.05% expansion. The investigators concluded from the timing tests on both mortar bars and concrete prisms that some prior expansion aided penetration, and thus effectiveness, by inducing cracking. Existing cracks provided a path for the coating to penetrate.

#### **2.2.3.5 ASR Mitigation Reference No. 5 (Whitmore et al. 2000)**

Electrochemical chloride extraction, used to drive chloride ions out of salt-contaminated structures, can easily be adapted to drive lithium ions into a structure. The potential benefits are shortened treatment time and an increase in the effective amount of lithium in the structure.

The anode for the process is a titanium-coated metallic mesh, the same as is often used for cathodic protection and chloride extraction. Reinforcement in the structure is the cathode. The impressed current comes from AC/DC rectifiers, which convert high-voltage AC to low-voltage DC. Lithium solutions supply the lithium ions and act as the electrolyte providing electrical continuity between the anode and cathode. An electric field is created between the mesh and reinforcement. Lithium, being a positive ion, is driven away from the mesh and toward the reinforcement, and is thus distributed in the concrete.

Field application to bridge decks in Virginia and Delaware, carried out by the investigating companies, showed rapid migration of the ion into the concrete in the first week of treatment. Each treatment period lasted eight weeks. No samples were taken to determine the total lithium content at the end of treatment.

#### **2.2.3.6 ASR Mitigation Reference No. 6 (Baillemont et al. 2000)**

This article describes the diagnosis, treatment and monitoring of an ASR-affected bridge in northeastern France. Considerable map cracking was found on all the piles and one deck. Measurements on several cracks from 1982 through 1995 indicated continuing opening.

A treatment of silane followed by a thin polymer-cement coating was applied to the piles and deck. This combination was chosen for its flexibility, good adhesion to concrete, and resistance to de-icing salts. Sensors were installed over six cracks to record opening. Temperature was also recorded. After one year of measurement, the width of the cracks was seen to vary only with temperature, indicating that the reaction had been slowed. Measurements will be continued for several years.

## **2.3 METHODS FOR MITIGATING OR REMEDIATING DEF**

### **2.3.1 Causes of DEF<sup>2</sup>**

Ettringite, a normal hydration product, is a reaction between sulfates, calcium aluminates and water. Primary ettringite, which forms before the concrete sets, is not deleterious. Damage is caused by DEF in the hardened concrete. Delayed ettringite forms from a reaction between decomposed primary ettringite and water, creating nests of ettringite in the paste. Research indicates that high amounts of sulfur, contributed by the clinker, may be another source of the reaction. In both cases, exposure to water over time causes the ettringite to reform, producing expansive forces. Hime (1996) claims that the reaction requires substantial water exposure over months or years, but other sources say ambient temperature and moisture are sufficient for the reaction (G.M. Idorn 2001). DEF, like ASR, shows as map cracking.

DEF deterioration requires the following conditions:

- decomposed ettringite or high amounts of sulfur; and
- water.

### **2.3.2 The Goal of Mitigation or Remediation Treatments for DEF**

The goal of treating existing DEF-affected structures is the same as for ASR-affected structures -- prevent water infiltration and allow water vapor release.

### **2.3.3 Published Information on Mitigation or Remediation of DEF**

No references were found for mitigation or remediation of existing DEF deterioration.

## **2.4 OTHER TYPES OF DETERIORATION IN REINFORCED CONCRETE**

### **2.4.1 Damage to Concrete**

In addition to ASR/DEF deterioration, concrete is susceptible to damage from sulfate attack, salt crystallization, and freeze/thaw cycling. These mechanisms involve direct damage to the cementitious matrix. They are discussed here because some techniques to mitigate or remediate them may be relevant to ASR/DEF.

#### **2.4.1.1 Sulfate Attack**

Sulfate attack is caused by water-soluble sulfates entering the concrete. The sulfates react either chemically or physically with calcium aluminate hydrates in the paste, causing the cementitious matrix to weaken and disintegrate (Mehta *et al* 1993).

#### **2.4.1.2 Salt Crystallization**

Salt crystallization is the physical action of salts crystallizing out of solution in the pores of concrete. The pressure of the salts in the pores can be great enough to cause cracking and scaling (local delamination) of the concrete surface (Mehta *et al* 1993).

---

<sup>2</sup> Merrill, Brian D., *Premature Concrete Deterioration*, internal report, Texas Department of Transportation, 1997.



### **2.4.1.3 Freeze/Thaw Cycling**

Freeze/thaw damage occurs by mechanisms similar to those of salt crystallization. Water freezing in the pores generates large hydraulic pressures, causing scaling and cracking. The use of de-icing salt magnifies freeze/thaw damage. Salt is hygroscopic, absorbing and retaining water in the pores, and thereby promoting a higher degree of saturation. Also, salt-concentration gradients in the concrete promote partial or differential freezing, generating osmotic pressures (Mehta *et al* 1993).

## **2.4.2 Corrosion of Reinforcement**

Reinforced concrete elements can also deteriorate because of corrosion of their reinforcement. Corrosion of reinforcement deteriorates the concrete by filling it with a volume of corrosion products exceeding that of the original reinforcement, thereby inducing tensile stress in the surrounding concrete. Corrosion also reduces the cross-sectional area of the reinforcement and the bond between the concrete and reinforcement, thereby reducing the strength of the member.

Corrosion itself is an electrochemical process, requiring an anode, a cathode, an electrical conductor, and an electrolyte. The reinforcement acts as anode, cathode, and conductor, while any water in the concrete is the electrolyte. Normally, a passive layer of oxide film, maintained by the alkaline concrete, protects the steel. Corrosion of reinforcement is accelerated when the passivating layer is disrupted, which can occur by ingress of chlorides, carbonation, or electrolytic solutions (ACI 222 1996).

### **2.4.2.1 Ingress of Chlorides**

The ingress of chlorides reduces the passive protective layer around the reinforcement. Pitting-type corrosion is produced on the steel surface where the passive layer is diminished by chlorides in the presence of oxygen and moisture. Chlorides diffuse into the concrete in solution, and can come from de-icing salts, fog, mist, or marine spray (Leeming 1990).

### **2.4.2.2 Carbonation**

Concrete is generally very alkaline, providing an immune surrounding and maintaining the passivity. In the carbonation reaction, carbon dioxide from the air diffuses into the concrete and reacts with the cement to reduce this alkalinity. Below a pH of 9-10 the passive layer on the reinforcement breaks down and general corrosion begins. For carbonation to occur the concrete must be moist, but not saturated (Leeming 1990).

### **2.4.2.3 Lowered Resistivity**

The corrosion process requires a conducting electrolyte. Dry concrete is highly resistive and prevents corrosion of the reinforcement. Conversely, pore water with dissolved salt is an electrolyte providing very low resistance for corrosion current. Reinforcement in wet concrete corrodes at a much higher rate than in dry concrete (Leeming 1990).

## **2.4.3 Relation of Other Types of Deterioration to ASR/DEF Deterioration**

In all the types of concrete deterioration discussed above, water is the common factor.

- For freeze/thaw cycles and lowered resistivity, water is the root of the problem.
- Sulfate attack, salt scaling, and ingress of chloride all require water to transport the sulfate, salt, or chlorides that are the cause of the deterioration.
- Water is the agent that allows CO<sub>2</sub> to create carbonation damage.

Similarly, an external source of water is required for ASR/DEF deterioration. Many of the mitigating or remediating treatments for sulfate attack, salt scaling, freeze/thaw cycling, ingress of chlorides, carbonation, and lowered resistivity seek to prevent water infiltration, and therefore may be applicable as treatments for ASR/DEF deterioration. These treatments are discussed in Section 2.5.

## **2.5 SURFACE TREATMENTS FOR MITIGATING OR REMEDIATING OTHER TYPES OF DETERIORATION IN REINFORCED CONCRETE**

A large body of literature has been accumulated over many years related to surface treatments, penetrating sealers, epoxies, and crack sealers for the purpose of keeping water out of concrete and thereby mitigating or remediating concrete deterioration. These surface treatments are discussed here for their potential benefit in mitigating or remediating ASR/DEF deterioration.

### **2.5.1 *Coatings and Membranes***

Coatings and membranes include epoxies, polymer cements, and urethanes. All of these provide a layer on the surface of the concrete. Membranes are impermeable to water, while coatings may or may not be impermeable.

### **2.5.2 *Published Information on Coatings and Membranes***

#### **2.5.2.1 Coating Reference No. 1 (ACI 515-1985)**

Chapter 4 of ACI 515 deals with waterproofing barrier systems, which are coatings intended to completely prevent the movement of moisture into concrete. Traditional systems use hot-applied, bituminous-saturated felt. Today many cold-applied systems are also used, including bituminous materials, elastomeric membranes, cementitious membranes, and metallic oxides.

Both cold and hot bituminous systems use fabrics for strength. They are not as adaptable to irregular shapes as cold liquid systems.

Chapter 4 of ACI 515 lists neoprene, neoprene-bituminous blends, polyurethane, polyurethane-bituminous blends, and epoxy-bituminous blends as elastomeric membranes. All have good elongation characteristics. Some need fiberglass cloth for reinforcement or to bridge cracks and joints larger than 1.5 mm (0.06 in.). All are liquid-applied systems, requiring multiple coats for complete coverage.

Cementitious membranes can be applied to damp, smooth, rough, or irregular surfaces, usually by trowel. Because cementitious membranes are rigid, they should have the same thermal coefficient as the substrate on which they are applied to minimize differential thermal expansion and resultant cracking. Also, cementitious membranes should not be used to span moving joints.

Metallic oxides are another type of rigid barrier. Fine metallic filings, sand, cement, water, and a catalyst oxidize to fill the pores of the concrete, decreasing permeability. Metallic oxides require 3 to 5 coats, constant moist curing for a proper finish, and good quality control.

#### **2.5.2.2 Coating Reference No. 2 (O'Donoghue et al. 1998)**

Moisture-cured urethanes react with ambient moisture to create polymers. For this reason they are inherently beneficial in applications where moisture is present. Their curing temperature is as low as 20°F (-7°C). Moisture-cured urethanes can cure very rapidly, however, preventing penetration into the concrete surface. In such cases, the urethane acts more like a coating than a penetrating sealer.

### **2.5.3 Penetrating Sealers**

Penetrating sealers are solutions or suspensions that diffuse into the concrete near the surface. These include silane, siloxane, oils, high-molecular-weight methacrylate (HMWM), and penetrating epoxies. While not impermeable to liquid water, they create a hydrophobic layer, sometimes (as in the case of silane and siloxane) by chemical reaction with the concrete. Because they are clear, penetrating sealers offer the advantage of permitting continued observation of the concrete surface.

### **2.5.4 Published Information on Penetrating Sealers**

#### **2.5.4.1 Penetrating Sealer Reference No. 1 (ACI 515-1985)**

Chapter 5 of ACI 515 deals with dampproofing barrier systems, which are coatings capable of reducing the rate of transmission of water into the concrete, but are not impermeable to liquid water. Dampproofing is suitable for areas not subjected to hydraulic pressure, while waterproofing is necessary if hydraulic pressure is present. Chapter 5 claims that dampproofing systems are not capable of bridging cracks. Advantages are low application cost and minimal surface preparation. Multiple coats are needed for complete coverage. Above-grade systems are listed as: water-based portland cement paste; portland cement with stearic acid, water repellants, or latex emulsions; latex paint; two-component epoxy paint; solvent-based, chlorinated rubber paint; two-component or moisture-cured polyurethane paints; and fish oil-based materials with mica and asbestos fillers.

Chapter 6 of ACI 515 deals with protective barrier systems, which provide resistance to degradation by chemicals, prevent staining, and prevent liquids from being contaminated by the concrete. These systems are more durable than waterproofing or dampproofing barriers. Chapter 6 categorizes protective barrier systems as providing protection against mild, intermediate, and severe exposures. The category most related to mitigation and remediation of ASR/DEF deterioration is “mild,” which addresses damage from de-icing salts, freeze/thaw cycling, and acidic solutions. Applicable systems are a mixture of moisture-permeable and impermeable sealers, including: polyvinyl butyral; polyurethane; methyl-methacrylate; alkyl-alkoxysilane; epoxy resins; acrylic resins; chlorinated rubber; styrene-acrylic copolymer; asphalt; coal tar; vinyl; and neoprene.

#### **2.5.4.2 Penetrating Sealer Reference No. 2 (Wright et al. 1993)**

In this investigation boiled linseed oil was compared to silane and siloxane for penetration ability, salt-water absorption, vapor permeability and other characteristics. Each sealer was applied to three concrete pavement sites for the field investigation. Cores were taken from each site to determine the penetration depth, salt-water absorption, and chloride intrusion. Laboratory specimens were cubes, prisms, and slabs, used for tests of sealer penetration, salt-water absorption, vapor permeability, abrasion, chloride intrusion, and freeze/thaw resistance.

Penetration of the linseed oil was comparable to that of the other sealers in the field tests, and two or more times greater in the laboratory tests. Linseed oil performed best at reducing salt-water absorption in the field, although absorption results in the laboratory were comparable to silane and worse than siloxane. The investigators also found that in the field, the volume of silane and siloxane in the pore structure of the concrete diminished over time, allowing more absorption. In contrast, the linseed oil maintained consistently low absorption. Chloride-ion content was lower for the linseed-oil cores both two and three years after application. Finally, linseed oil was less permeable to water vapor than the other sealers.

#### **2.5.4.3 Penetrating Sealer Reference No. 3 (Marks 1988)**

This article reports on the Iowa Department of Transportation’s use of HMWM to seal the entire deck of a bridge that had full-depth cracks that were observed to leak. The cracks were found to lie above the transverse reinforcement, and the Department decided that sealing of the deck was needed to protect the

steel. According to Marks, HMWM was chosen because the California Department of Transportation had successfully used it as a sealer.

One coat of HMWM was applied and cores were taken one week later. The HMWM penetrated the full 2 in. (51 mm) of every core. Continued leakage, though at a lower rate, was observed along the entire deck during a steady rain and under standing water. The Department applied a second coat, but observations had not been made at the time of the article. The initial application was made when the temperature ranged between 45F and 55F (7C and 13C); the HMWM manufacturer suggested that the application temperature should be 50F (10C) or above. The second application was made at 60F (16C).

#### **2.5.4.4 Penetrating Sealer Reference No. 4 (Basheer et al. 1998)**

The article studied the effect of moisture in the concrete at the time of surface treatment application on the chloride intrusion and subsequent reinforcement corrosion. The surface treatments used were a 40% silane solution, a 100% silane solution, a silane-siloxane two-coat system, and a silane-acrylic two-coat system. Three moisture conditions were used: one very wet with little drying time; one very wet with considerably longer drying time; and one very dry. The specimens were repeatedly subjected to 7-day cycles of ponding with a sodium-chloride solution, followed by drying.

The depth of penetration of the treatments was greatest for the specimens that were driest. Very few specimens had corrosion of reinforcement, but those that did were from the group with the highest pre-application moisture condition. The investigators concluded that while all treatments reduced chloride infiltration, no one treatment was outstanding in this regard.

#### **2.5.4.5 Penetrating Sealer Reference No. 5 (Rizzo et al. 1989)**

This article investigated many penetrating sealers, including acrylic, polyurethane, gum resin, silicone, silane, and an acrylic topcoat for their permeability to water vapor and their resistance to absorption of water, ingress of chloride ions, and ingress of carbon dioxide. The silane sealers showed the lowest water absorption and chloride-ion ingress, although carbon-dioxide ingress was comparable to that of the other sealers.

A system of silane with an acrylic topcoat was then tested. It showed the positive benefits of the silane – reduced water absorption and chloride-ion ingress – while also reducing the ingress of carbon dioxide and remaining breathable. The silane-acrylic system was subjected to additional sulfate exposure, accelerated weathering, and freeze-thaw testing, and showed good results over the uncoated specimen. Cores from field applications on a tunnel in the United Kingdom exposed to frequent applications of de-icing salts confirmed that the silane-acrylic system substantially reduced the ingress of chloride ions.

#### **2.5.4.6 Product Literature on Penetrating Sealers**

In contrast to experimental findings reported here, some product literature does advertise epoxy-based penetrating sealers that are supposedly impermeable to liquid water and permeable to water vapor.<sup>3</sup>

#### **2.5.5 Crack Sealers**

Crack sealers are low-viscosity, flexible polymers applied specifically to cracks in reinforced concrete. Ideally, they penetrate the crack completely, thus eliminating an easy path for water entrance, and also restore structural strength to the member. Crack sealers include HMWM, epoxies, and urethanes.

---

<sup>3</sup> Epoxy Systems™ Product #850

## **2.5.6 Published Information on Crack Sealers**

### **2.5.6.1 Crack Sealer Reference No. 1 (Sprinkel et al. 1995)**

In this article three epoxies, one HMWM, and one polyurethane were tested for penetration depth and flexural strength. Unreinforced beams measuring 3 x 4 x 11 in. (76 x 102 x 279 mm) were tested in flexure to failure and then repaired by applying one of the five crack sealers to the top surface of the beam while the sections were held together in a jig. Sealer was ponded on the top surface until the crack was entirely filled. After curing, the beams were again tested to failure in flexure and then split to measure penetration depth of the polymer. Additional penetration tests were conducted at varying temperatures, between 7°C and 35°C (45°F and 95°F), by pouring the polymers over sand. Under ideal temperatures, all five sealers filled cracks as narrow as 0.2 mm. Each of the five sealers reacted uniquely to high and low temperatures, with the HMWM performing consistently well over the entire range. All polymers restored 100% of original strength in laboratory flexural tests. Most test beams re-cracked in the concrete, rather than in the sealer. The investigators rated HMWM first for tested results, and third for overall results, ease of use, odor, safety, and cost.

The investigators found that while the polyurethane was easy to use and almost odor-free, it easily leaked and was not practical for overhead surfaces. The three epoxies ranged from low to very strong in odor, and from easy to difficult mixing ratios. The HMWM had very high odor, easily leaked because of low viscosity, was difficult to mix, and was potentially explosive if mixed incorrectly.

### **2.5.6.2 Crack Sealer Reference No. 2 (Fowler 1989)**

The results of this investigation agree with those of Marks (1988). For this investigation, 4 x 6 x 12 in. (102 x 152 x 305 mm) slabs were cracked and then treated with three different HMWM. Slabs were treated under three conditions: dry, room temperature; dry, hot temperature; and wet, room temperature. HMWM restored 75-85% of the flexural strength under all conditions. HMWM filled 60-80% of the crack volume for the laboratory tests and in the cores taken from the treated field site. Cracks as small as 0.1 mm (0.004 in.) were filled. The investigators recommend 3 days drying time under normal conditions to achieve the best crack filling and strength gain.

## **2.6 ELECTROCHEMICAL TREATMENTS**

The purpose of electrochemical treatment is to reverse corrosion damage of the reinforcement, with no direct benefit to the surrounding concrete and no attempt to prevent water infiltration. While these treatments do not remediate ASR/DEF deterioration, one finding in particular is worth noting.

Cathodic protection is the most common electrochemical method of arresting or reducing the corrosion of steel reinforcement. Cathodic protection produces hydroxyl ions, which can combine with reactive aggregates to cause ASR. The use of cathodic protection can therefore easily worsen an existing ASR problem (Thompson 1990).

## **2.7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FROM LITERATURE SEARCH**

### **2.7.1 Summary and Conclusions**

While the articles referenced in this search do not comprise a complete list of mitigation and remediation treatments for ASR/DEF or other forms of concrete deterioration, they cover the range of methods currently researched and tested, and also contain important concepts. Many articles that corroborate the information given above or provide background are listed in Appendix G.

Polymer-modified cement mortar (PCM), silane, urethane, and lithium nitrate were found to be effective in reducing expansion from ASR. In some tests, the products were used as two-coat systems, such as

silane with a PCM topcoat, with good results. Several references, however, report that epoxy promotes expansion. Methyl-methacrylate and sodium silicate are also not effective at reducing expansion.

Lithium can be used either in an applied solution or in an electrochemical process. Lithium nitrate is more effective and safer to use than lithium hydroxide. In the electrochemical process, lithium ions are driven into the concrete toward the reinforcement. The benefit of this process is an increase in the amount of useful lithium deposited in the concrete. Lithium is successful at reducing ASR expansion, but because it is not a hydrophobic sealer, it does not have the added benefit of protecting against other forms of deterioration.

Membranes and impermeable coatings promote expansion in existing concrete structures. They are therefore not appropriate for mitigation or remediation of ASR/DEF. The treatments described in Chapter 4 of ACI 515 are waterproofing membranes.

The treatments described in Chapters 5 and 6 of ACI 515 can be permeable or impermeable to liquid water. Many of the systems listed are discussed in other references in this report, including modified Portland cement, epoxy, polyurethane, methyl-methacrylate, silane, and acrylic resins.

Penetrating hydrophobic sealers have the greatest potential for controlling expansion from ASR/DEF. While not completely impermeable to water, they are permeable to water vapor. Silane, already mentioned as a specific ASR treatment, has been found to reduce chloride-ion content. Silane was especially effective at reducing chloride- and sulfate-ion ingress, carbon-dioxide intrusion, and weathering when applied with an acrylic topcoat. Silane systems remain breathable.

Boiled linseed oil performed as well or better than silane and siloxane in tests for salt-water and chloride intrusion. Linseed oil is inexpensive, but may need more frequent reapplication than other penetrating sealers.

Moisture-cured urethanes have promise for treating existing structures because of their need for moisture. Controlling the rate of cure so that moisture-cured urethanes can penetrate the concrete surface may improve their effectiveness at reducing expansion from ASR/DEF.

High-molecular-weight methacrylate (HMWM) has been reported as both a penetrating sealer and crack sealer. In Marks (1988), HMWM could not prevent leakage through the bridge deck. The poor results of the first application can possibly be attributed to the cool application temperature. As a crack sealer, the HMWM penetrated very small cracks and restored structural strength. Only sealing cracks in ASR/DEF-affected structures is not beneficial, however, because new cracks will inevitably form. Also, Stokes (2000) suggests that some cracking aids the penetration of the sealer.

### **2.7.2 Recommendations**

To mitigate deterioration from ASR, DEF, or both, it is recommended to use the following treatments:

- Silane, PCM, urethane, and lithium nitrate solution, which reduce the expansion of ASR-affected specimens.
- Siloxane, which is similar in chemical makeup to silane, and performs like it in chloride-intrusion tests.
- Linseed oil, which performs as well as silane and siloxane in salt-water and chloride intrusion tests, and is much cheaper.
- HMWM, which has good penetration ability, but needs more research on its effectiveness as a penetrating sealer.

- Epoxy, which has shown negative results as a coating, but may be worth investigating as a penetrating sealer. It is safe to use and requires little or no re-application. It can also be used as a topcoat following treatment with lithium nitrate, silane, etc.

It is recommended to use these treatments, separately or in combination, on specimens made with aggregates and cement known to produce ASR/DEF deterioration, and to evaluate their effectiveness by measuring specimen expansion and internal moisture content, and by monitoring specimens with acoustic emission techniques.

### ***2.7.3 Recommendations for Specific Structures***

The mitigation options presented here apply to structures in general. Characteristics of specific studies may favor particular options or sets of options. One example of this, the Lake Ivie structure on FM 1929 is discussed in theses and reports for Study 1857. Such specific applications are not discussed further here.





## **CHAPTER 3: DEVELOPMENT OF TEST PROGRAM**

### **3.1 OBJECTIVES**

The objective of the test program is to fabricate specimens with high potential for expansion due to ASR/DEF, and to monitor their deterioration with laboratory testing and AE. Cement with high alkalinity and aggregates with high silica content are used to achieve expansion. Specimens are coated with treatments chosen from those evaluated in the literature search of Chapter 2.

### **3.2 TEST SPECIMENS**

#### **3.2.1 Specimen Fabrication**

All test specimens were fabricated according to ASTM C 1293-95 (“Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction”). Specimens have a square cross-section of 3 in. (75 mm). Gage studs were cast into the ends with a nominal gage length between studs of 10 in. (250 mm). The specimens were cured in the molds for 24 hours at 23°C and 95% relative humidity per ASTM C 157. After removal from the molds, the specimens were placed in storage containers and aged for seven days at 60°C in the storage environment. The storage containers consist of 5-gallon (22 liter) polyethylene pails with airtight lids, lined with felt wicking material around the wall, and PVC racks capable of holding four prisms vertically.

The specimens were lightly cleaned by sandblast, water-blast, or sandpaper, to remove laitance prior to application of the mitigation treatments. Treatments were applied by brush according to manufacturer’s instructions and allowed to cure for 24 hours. If a second treatment was required for a particular mitigation technique, the treatment was applied and allowed to cure for 24 hours. Specimens were then returned to the storage containers in the storage environment or placed outside, according to the exposure series described in Section 3.3.

Two plastic sleeves for moisture measurement were either cast or drilled into each specimen. Sleeves were placed at depths of 0.5 in. (12 mm) and 1.5 in. (40 mm) from the surface. The sleeves were plugged with rubber stoppers to prevent drying of the specimen interior. The specimens in the molds, with sleeves inserted during casting, are shown in Figure 3-1.

Concrete mixes were proportioned by the volume method. Quantities of cement, aggregate, and water and results of slump, yield, air content, and unit weight for each mix are presented in Appendix A.

Coarse aggregate was acquired from a local source, and was not evaluated for reactivity. The aggregate was mechanically crushed and sieved to meet the gradation requirements of ASTM C 1293.

TxDOT Study 4085 evaluated various sources of fine aggregate in the state of Texas for reactivity using ASTM C 1260. Two of the fine aggregates evaluated in that study were chosen for use in this project. The first fine aggregate had a 14-day expansion of 0.675%, the largest of those tested. The second had a 14-day expansion of 0.248%, in the middle range of those tested (Bauer 2001).

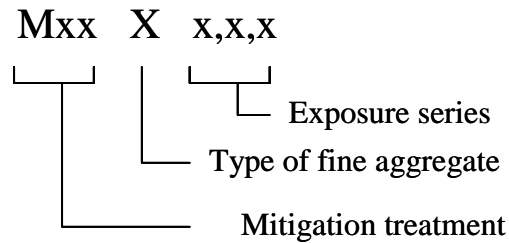
TxDOT Study 4085 tested various cement sources from around the country for total alkali content. The cement chosen for this project is the same one used for ASTM C 1293 prisms in Study 4085. This cement met the requirement of ASTM C 1293 to have a total alkali content of  $0.9 \pm 0.1\%$   $\text{Na}_2\text{O}_{\text{eq}}$  (Figurski 2001).



**Figure 3-1 Specimens in molds**

### 3.2.2 Specimen Nomenclature

The specimens are designated as follows:



- Mitigation treatment – The treatments selected based on the literature search are designated M1 through M23; control specimens are designated with “C” instead of “M.”
- Type of fine aggregate – “J” for Jobe fine aggregate; “F” for Fordyce fine aggregate.
- Exposure series – “a,b,c” for indoor series; “d,e,f” for outdoor series; and “g,h,j,k” for wet/dry series.

### 3.2.3 Mitigation Techniques

The mitigation techniques used were determined after the initial literature search was conducted. Table 3-1 shows the selected treatments.

Unless noted as a TxDOT specified product, mitigation treatments are commercially available. TxDOT-specified products were obtained from approved suppliers.

**Table 3-1 Mitigation Techniques**

| Designation | Mitigation Technique   | Abbreviation             |
|-------------|--|--------------------------|
| M1          | Moist-cure Urethane  | Ureth                    |
| M2          | Linseed Oil  | Linsd Oil                |
| M3          | Polymer-Modified Cement Mortar   | PCM                      |
| M4          | Polyurethane   | Poly                     |
| M5          | Silane 20% solids  | Silane 20                |
| M6          | Silane 40% solids  | Silane 40                |
| M7          | Siloxane 20% solids  | Silox 20                 |
| M8          | Siloxane 40% solids  | Silox 40                 |
| M9          | Lithium Nitrate  | LiNO <sub>3</sub>        |
| M10         | Lithium Nitrate, followed by Silane 20%  | LiNO <sub>3</sub> +Sil   |
| M11         | Lithium Nitrate, followed by Siloxane 20%  | LiNO <sub>3</sub> +Silox |
| M12         | Lithium Nitrate, followed by Linseed Oil   | LiNO <sub>3</sub> +Linsd |
| M13         | Lithium Nitrate, followed by Polyurethane  | LiNO <sub>3</sub> +Poly  |
| M14         | High-Molecular-Weight Methacrylate   | HMWM                     |
| M15         | Penetrating Epoxy  | Epoxy                    |
| M16         | TxDOT Penetrating Concrete Surface Treatment Type I-Silane, followed by TxDOT Type 742h Appearance Coat paint          | Sil+742                  |
| M17         | TxDOT Penetrating Concrete Surface Treatment Type I-Silane, followed by TxDOT Type 742 Appearance Coat paint (thinned) | Sil+742th                |
| M18         | TxDOT Penetrating Concrete Surface Treatment Type I-Silane, followed by Class B Type II Latex paint                    | Sil+latex                |
| M19         | TxDOT Penetrating Concrete Surface Treatment Type I-Silane, followed by Polymer-Modified Cement Mortar                 | Sil+PCM                  |
| M20         | TxDOT Type IV Epoxy  | IV Epoxy                 |
| M21         | Polyurethane   | Poly                     |
| M22         | Lithium Nitrate  | LiNO <sub>3</sub>        |
| M23         | Lithium Nitrate, followed by TxDOT Type 742h Appearance Coat paint   | LiNO <sub>3</sub> +742   |

### 3.3 EXPANSION AND MOISTURE TEST SETUP

Three series of tests were conducted, all using specimens fabricated as described in Section 3.2.1.

#### 3.3.1 Indoor Series

An accelerated ASTM C 1293 procedure, developed at The University of Texas at Austin, was used to shorten the length of testing time. The accelerated procedure follows ASTM C 1293 for specimen

fabrication and storage containers, but increases the temperature of the storage environment from 38°C to 60°C. The testing time is reduced from twelve months to thirteen weeks by increasing the temperature (Touma 2000).

Length readings for each specimen were taken using a length comparator (Figure 3-2) at 1 week, 2 weeks, 4 weeks, 8 weeks, and 13 weeks after fabrication. Readings were taken immediately after removing the specimens from the storage containers. Specimens were promptly returned to the storage containers and placed in the storage environment after completing the length readings.

Moisture readings were not taken for this series because the specimens were kept at constant humidity in the storage containers.



**Figure 3-2 Length reading taken with length comparator**

### **3.3.2 Outdoor Series**

After coating, the specimens of the outdoor series were placed on racks outside Ferguson Structural Engineering Laboratory (FSEL), as shown in Figure 3-3. The purpose of the outdoor series is to subject the specimens to conditions as similar as possible to actual field conditions. For this series, mitigation treatments were applied outside, during midday of the summer, and the specimens remained outside for curing.

Length readings for each specimen were taken using a length comparator at 1 week, 2 weeks, 4 weeks, 8 weeks, 13 weeks, 17 weeks, 21 weeks, and 25 weeks after fabrication. Moisture readings were taken concurrently with length readings.



**Figure 3-3 Specimens of outdoor series behind FSEL**

### **3.3.3 Wet/Dry Series**

The purpose of the wet/dry series is to examine the comparative performance of specimens under an environmental condition consisting of drastic changes in humidity, intended to promote the movement of moisture in and out of the specimens. By imposing a moisture gradient on the specimens, the effectiveness of each mitigation treatment for water impermeability and water vapor permeability can be evaluated.

The wet cycle was achieved by placing the specimens in the storage containers in the storage environment, therefore aging the specimens at 100% humidity. The dry cycle was achieved by placing the specimens in the storage environment without the buckets; the storage environment was maintained at a relative humidity less than 10%. The specimens were subjected to one week of wet aging prior to application of the mitigation treatment, then one week of dry aging, then to alternating two-week periods of wet and dry aging. The storage environment was maintained at 60°C, as specified in the accelerated ASTM C 1293 procedure.

Specimens “g” and “h” were cleaned prior to application of treatment with sandblasting in a blast cabinet. Specimens “j” and “k” were cleaned with a water-blast, using four passes from 18 in. (0.5 m) with a high-pressure water sprayer.

Length readings for each specimen were taken using a length comparator at 1 week, 2 weeks, 4 weeks, 6 weeks, 8 weeks, 10 weeks, 12 weeks, and 13 weeks after fabrication. Moisture readings were taken concurrently with length readings.

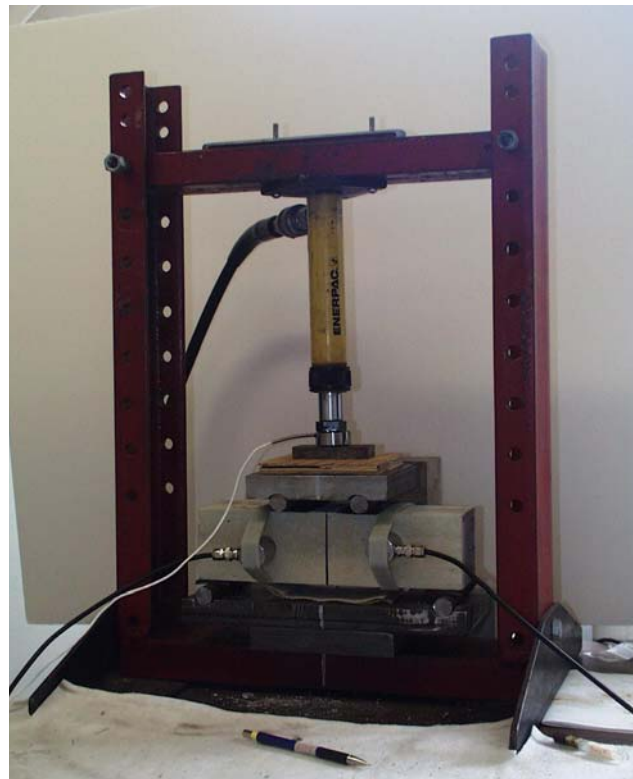
Damage indices (DI) were calculated at 7 weeks, 8 weeks, 10 weeks, 12 weeks, and 13 weeks after fabrication for specimens “h” and “k”. One face of the prism was chosen to measure the cracks at each interval. Cracks visible through the coating were measured for width and length using a crack comparator card. The index was calculated as  $DI = \sum_i w_i l_i$  and as  $DI = \sum_i w_i^2 l_i$ , where  $w$  is the crack width in thousandths of an inch, and  $l$  is the crack length in inches (Boenig 2000).

### 3.4 ACOUSTIC EMISSION TEST SETUP

The AE monitoring advanced in Study 1857 was used to quantify the internal cracking due to ASR/DEF deterioration for the indoor series and the wet/dry series. Monitoring was conducted at intervals reflecting those of the expansion testing, to follow the progression of cracking over time. The important data collected from AE testing include amount of emission during loading, amplitude of hits, historic index, and Felicity ratio.

The instrumentation for the AE testing included a six-channel MISTRAS 2001 instrument manufactured by Physical Acoustic Corporation (PAC). Two PAC R6I resonant sensors were mounted with a couplant material to the prisms at 2.5 in. (6 cm) from the ends. The R6I sensor has a resonant frequency of 60 kHz and incorporates an integral 40 dB preamplifier (Chotickai 2001). The electric signal from a 5 kip (22 kN) load cell was used to record the applied load as part of the MISTRAS data file.

The prisms were loaded under third-point bending, per ASTM C 78. Load was applied with a hand-operated hydraulic ram. The testing frame, ram, and instrumentation are shown in Figure 3-4 and Figure 3-5.



**Figure 3-4 Test frame and ram with specimen**

Before each test, the sensors were checked for proper function and contact with the prism using pencil lead breaks. Three 0.3 mm Pentel 2H leads were broken 1 in. (2.5 cm) from each sensor. The leads were extended approximately 2.5 mm for each break and held at 30° from the surface. The average amplitude recorded by a sensor was not allowed to vary more than 4 dB from the average of all sensors. A sensor not recording an amplitude or failing to meet the average criteria was replaced, until both sensors were working correctly (Chotickai 2000)

To determine the Felicity ratio, the following stepped loading schedule was used: 300-pound (1.3 kN) increase in load; hold; 150-pound (0.7 kN) unload; and hold. The Felicity ratio, defined as the load at the



onset of significant acoustic emission divided by the maximum previous load, is the most useful AE measure of structural deterioration for concrete (Tinkey 2000). Load was held until acoustic emission ceased. The loading sequence was continued to 1,200 pounds (5.3 kN) for Fordyce specimens and 600 pounds (2.7 kN) for Jobe specimens; the reduced load for Jobe specimens is a result of failure of several specimens above 600 pounds (2.7 kN).



**Figure 3-5 MISTRAS 2001 instrument**





# CHAPTER 4: TEST RESULTS

This chapter presents the data and observations from the tests described in Chapter 3. Results are discussed in Chapter 5.

## 4.1 RESULTS OF EXPANSION AND MOISTURE TESTING

### 4.1.1 Indoor Series

Figure 4-1 and Figure 4-2 show the average expansion of the indoor series, comprising the control specimens and specimens treated with seven different mitigation techniques. Plots for the eight other techniques are presented in Appendix B.

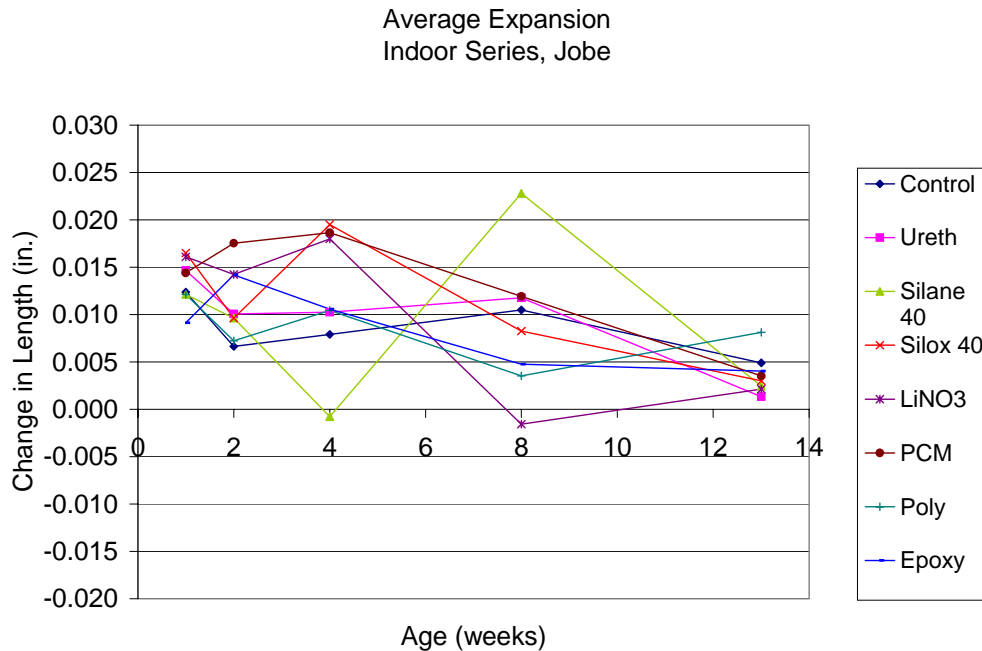
Expansion is defined as the change in length between successive measurements. Positive changes in length denote lengthening; negative changes denote shortening. The change in length is plotted versus the age of the specimens, in weeks, after fabrication.

For the remainder of this thesis, specimens fabricated with Jobe fine aggregate are referred to as Jobe specimens; likewise for Fordyce fine aggregate.

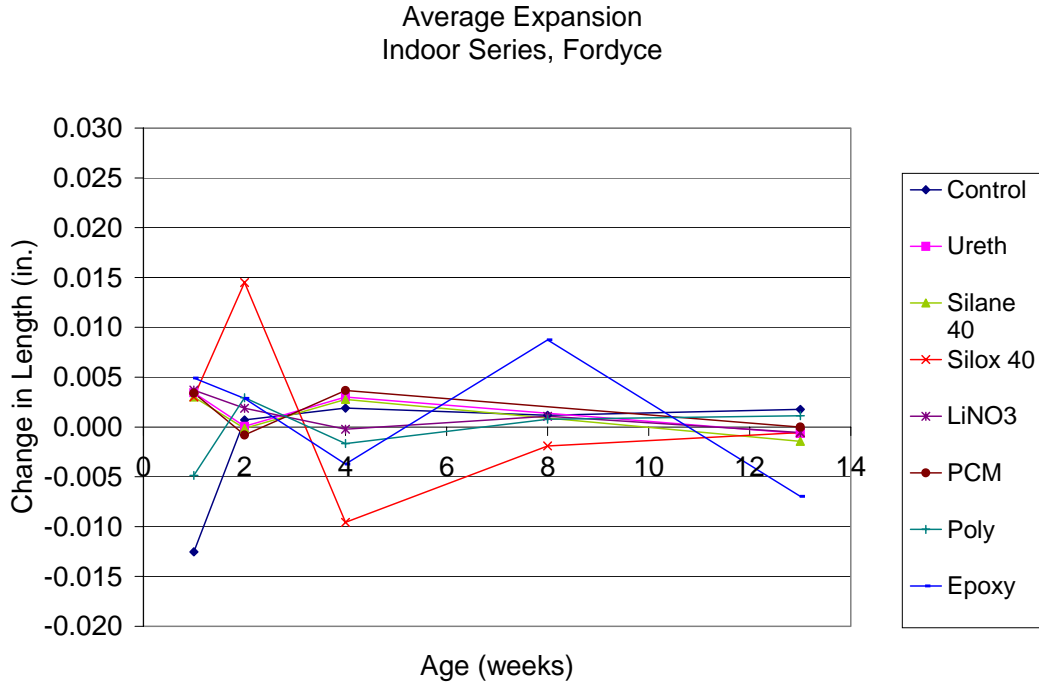
### 4.1.2 Outdoor Series

#### 4.1.2.1 Expansion

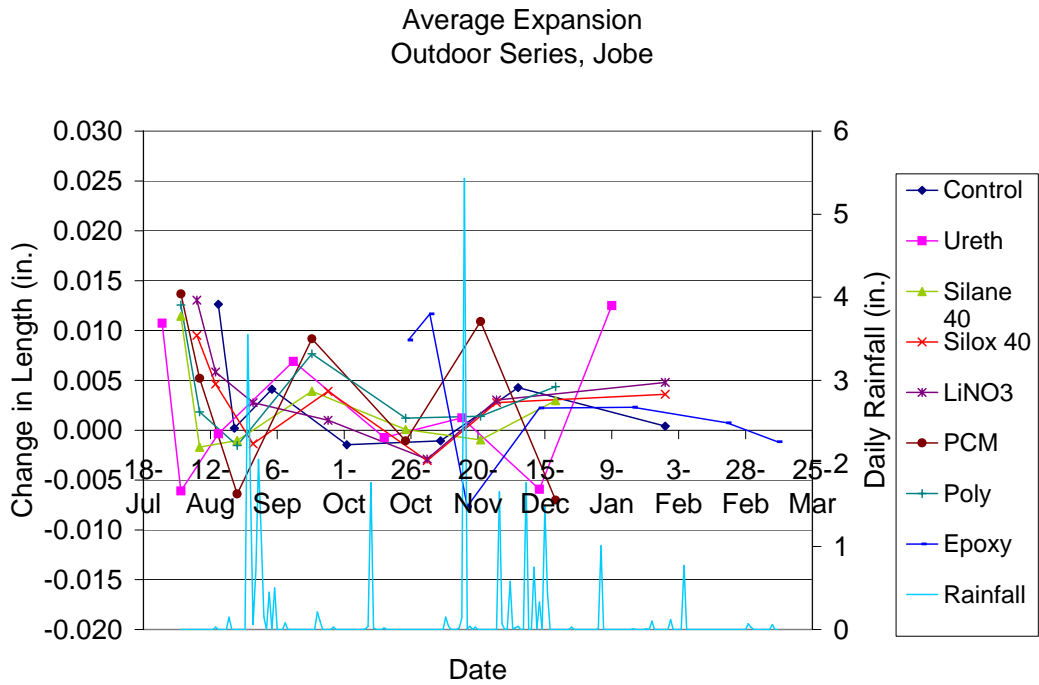
Figure 4-3 and Figure 4-4 show the average expansion of the prisms for the outdoor series, comprising the control specimens and specimens treated with seven different mitigation techniques. Plots for the eight other techniques are presented in Appendix B.



**Figure 4-1 Average Expansion, Indoor Series, Jobe Specimens**

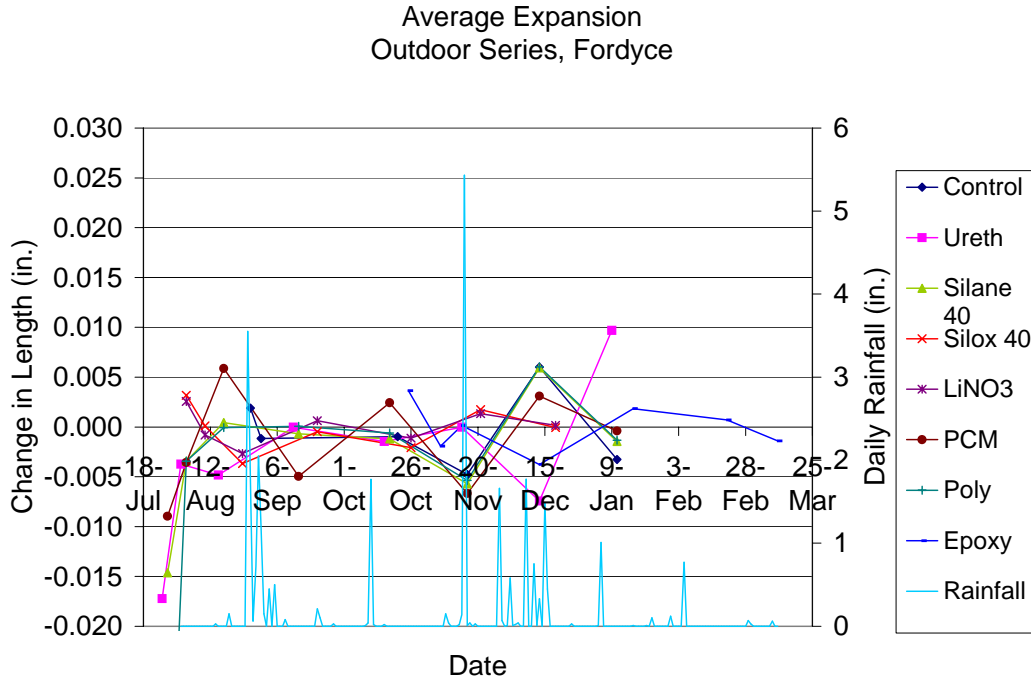


**Figure 4-2 Average Expansion, Indoor Series, Fordyce Specimens**



**Figure 4-3 Average Expansion, Outdoor Series, Jobe Specimens**

The horizontal axis of these figures shows dates that specimens were placed outside; each specimen, therefore, has a different starting point. Also plotted is the daily rainfall, so that the expansion and effectiveness of the mitigation technique can be correlated with the amount of moisture present.



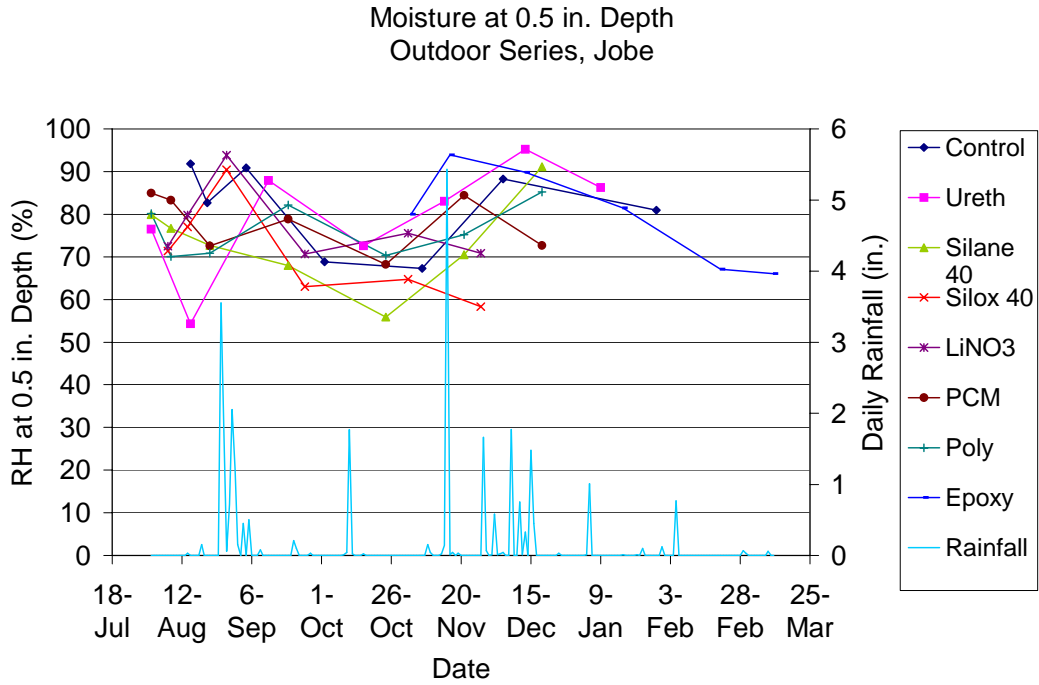
**Figure 4-4 Average Expansion, Outdoor Series, Fordyce Specimens**

#### 4.1.2.2 Moisture

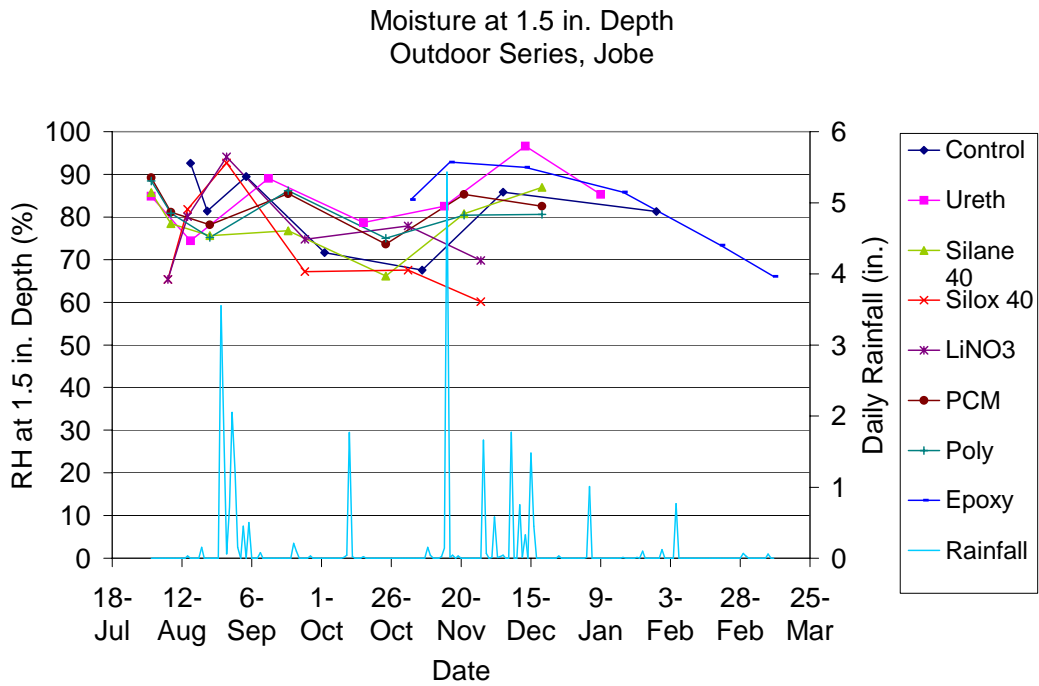
Figure 4-5 and Figure 4-6 show the relative humidity of the Jobe specimens at depth of 0.5 in. (12mm) and 1.5 in. (40 mm) from the surface, comprising the control specimens and specimens treated with seven different mitigation techniques. Figure 4-7 and Figure 4-8 show the relative humidity of the Fordyce specimens at depth of 0.5 in. (12 mm) and 1.5 in. (40 mm) from the surface, comprising the control specimens and specimens treated with seven different mitigation techniques. Plots for the eight other techniques are presented in Appendix B.

The internal relative humidity of the concrete is used to determine the impermeability of the mitigation techniques to liquid water and the permeability to water vapor. The relative humidity can be correlated with the daily rainfall, which is also plotted versus time.

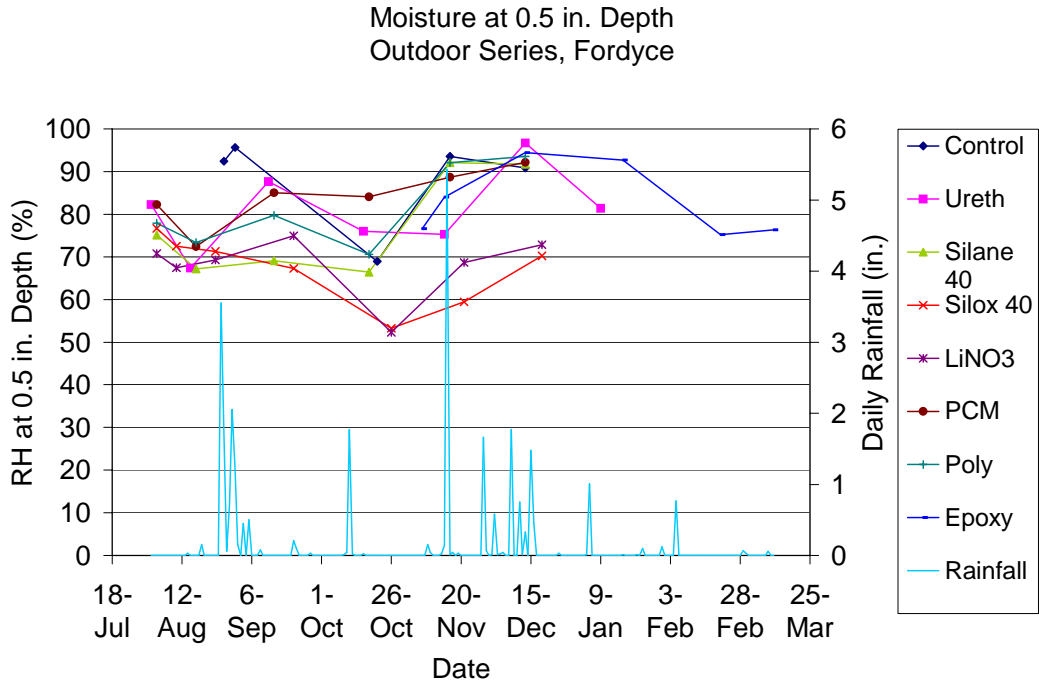
Plots of the change in relative humidity versus time were considered, but disregarded because they provided no more insight than that already gained from Figure 4-5 through Figure 4-8.



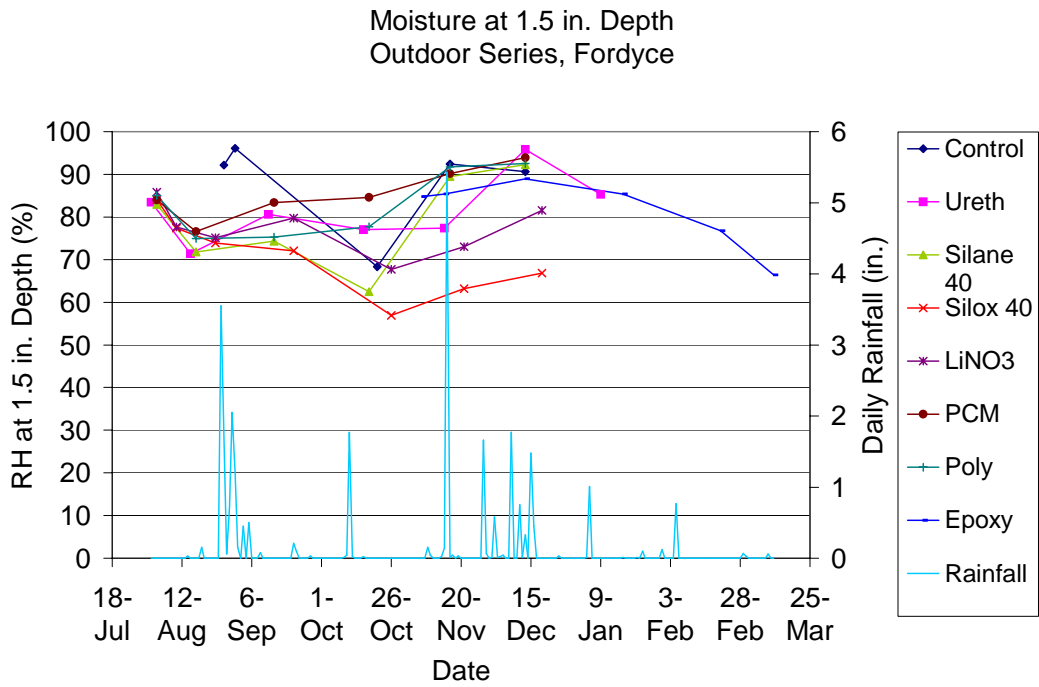
**Figure 4-5 Moisture at 0.5 in. Depth, Outdoor Series, Jobe Specimens**



**Figure 4-6 Moisture at 1.5 in. Depth, Outdoor Series, Jobe Specimens**



**Figure 4-7 Moisture at 0.5 in. Depth, Outdoor Series, Fordyce Specimens**



**Figure 4-8 Moisture at 1.5 in. Depth, Outdoor Series, Fordyce Specimens**

### 4.1.3 Wet/Dry Series

#### 4.1.3.1 Expansion

Figure 4-9 shows the average expansion of the specimens for the wet/dry series, including the control specimens and all mitigation techniques used in this series.

In that figure the change in length is plotted versus age of the specimens, in weeks, after fabrication. The wet/dry cycles imposed on the specimens during each interval are shown along the horizontal axis.

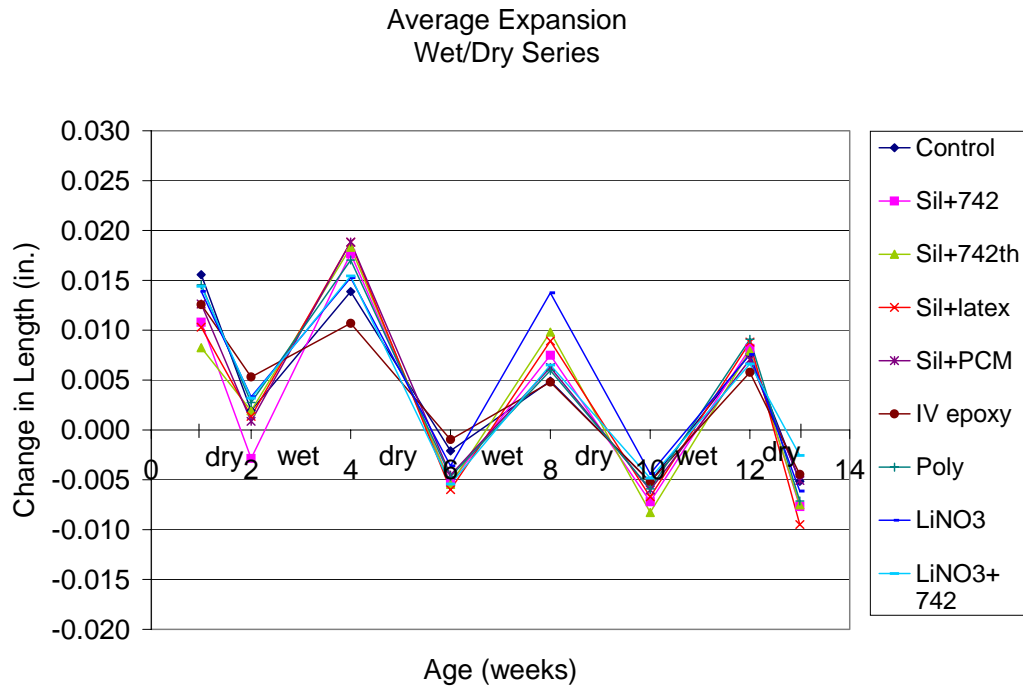


Figure 4-9 Average Expansion, Wet/Dry Series

#### 4.1.3.2 Moisture

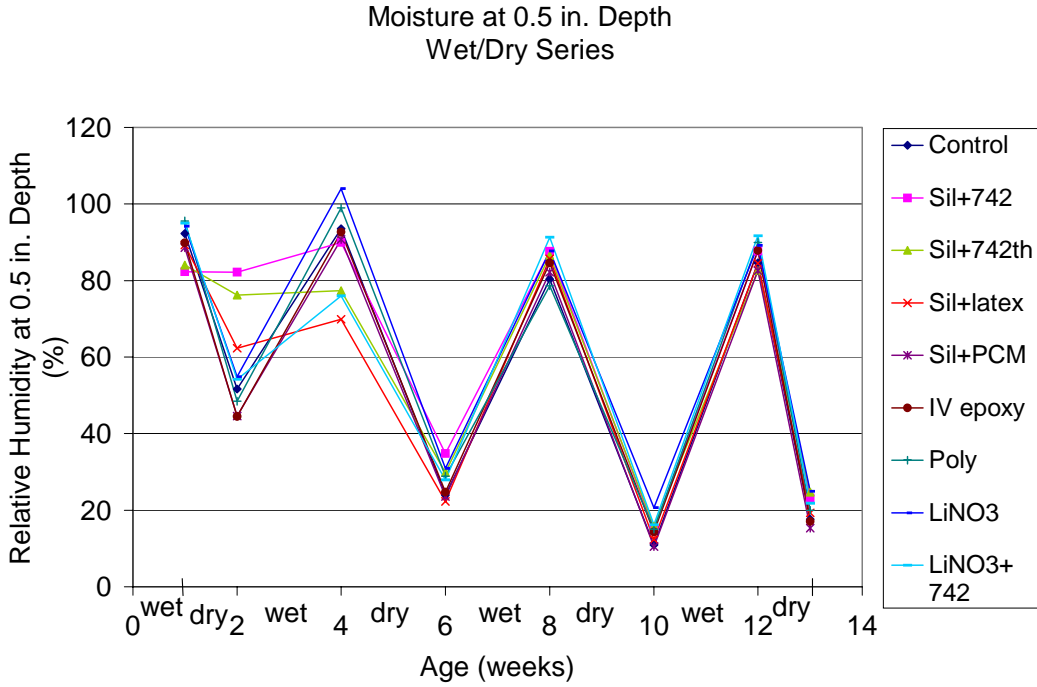
Figure 4-10 and Figure 4-11 show the relative humidity of the specimens at depth of 0.5 in. (12 mm) and 1.5 in. (40 mm) from the surface, including the control specimens and all mitigation techniques used in this series.

The relative humidity is plotted versus the age of the prisms, in weeks, after fabrication. The wet/dry cycles imposed on the specimens during each interval are shown along the horizontal axis.

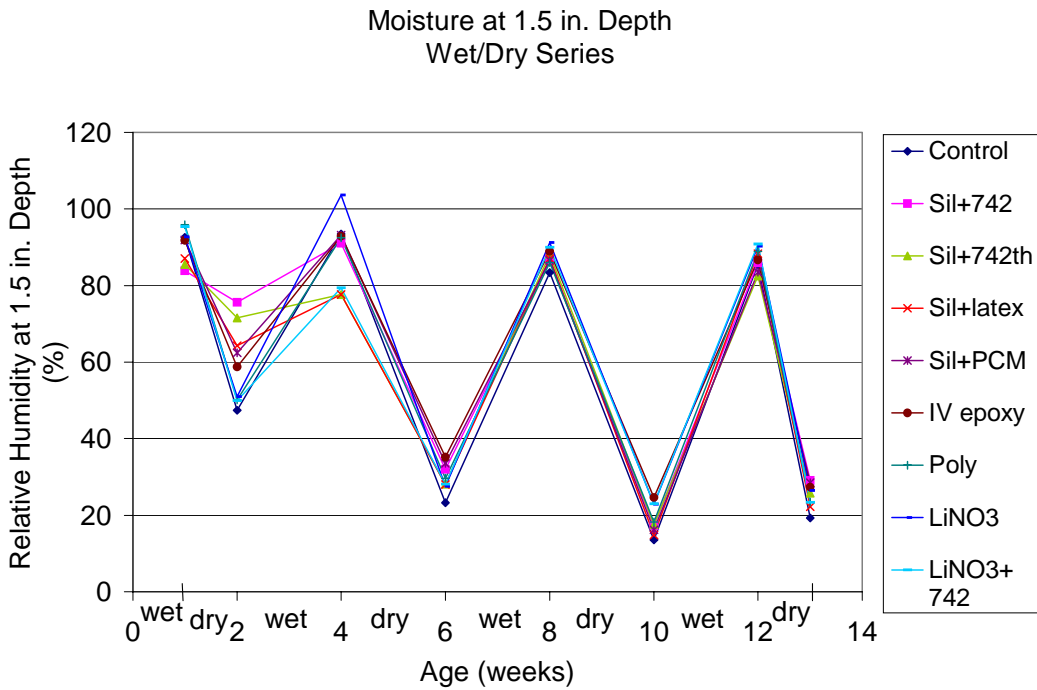
#### 4.1.3.3 Damage Indices

The average damage indices for Specimens “h” and “k” are plotted versus the age of the specimens, in weeks, after fabrication. Figure 4-12 shows the index calculated as  $DI = \sum_i w_i l_i$ . Figure 4-13 shows

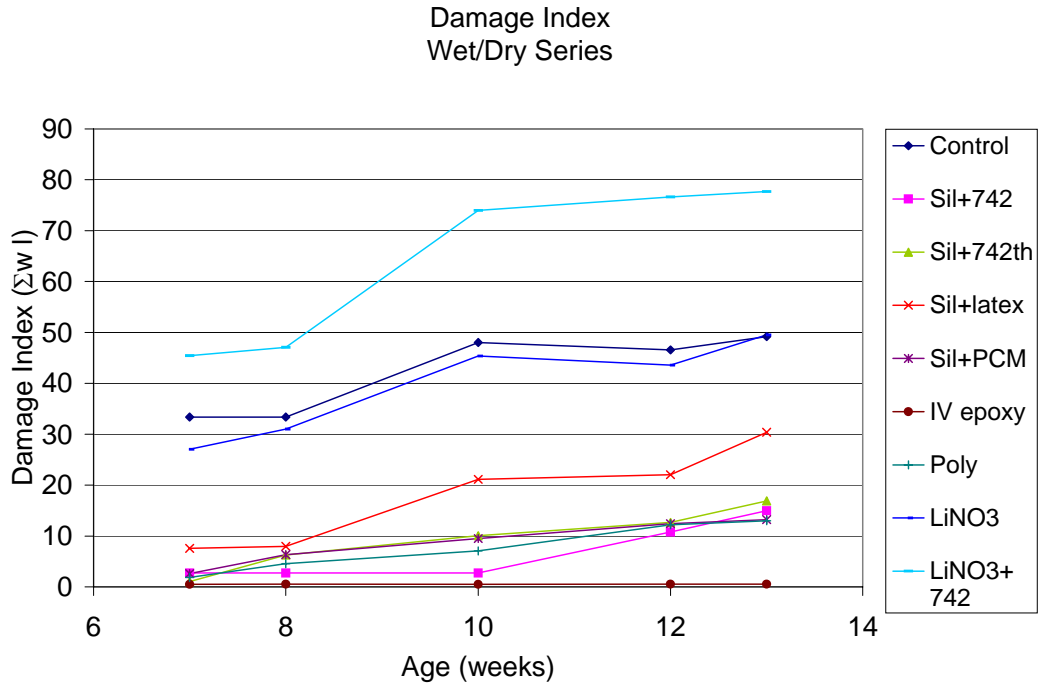
the index calculated as  $DI = \sum_i w_i^2 l_i$ . Damage indices are a rapid, visual method to quantify the amount of cracking in the specimens.



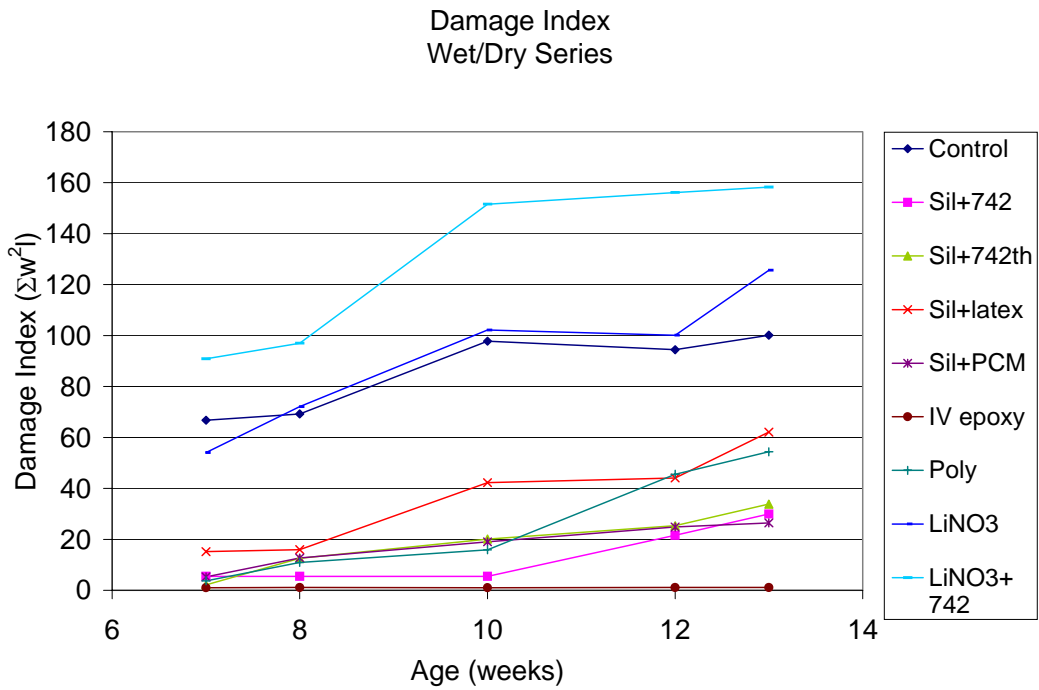
**Figure 4-10 Moisture at 0.5 in. Depth, Wet/Dry Series**



**Figure 4-11 Moisture at 1.5 in. Depth, Wet/Dry Series**



**Figure 4-12 Damage Index “Σ w l”, Wet/Dry Series**



**Figure 4-13 Damage Index “Σ w² l”, Wet/Dry Series**



## 4.2 RESULTS OF ACOUSTIC EMISSION MONITORING

Data collected from AE monitoring were used to calculate the Felicity ratio, defined as the load at the onset of significant acoustic emission divided by the maximum previous load. To do this, emission that signifies deterioration must be identified. The criteria for significant emission proposed in Study 1857 were used to analyze this data. These criteria were developed from tests on prestressed concrete girders with premature concrete deterioration (Chotickai 2001).

The criteria for significant emission are:

|                |      |
|----------------|------|
| Curvature      | >12  |
| Historic Index | >1.5 |

Curvature is the rate of change of the slope of the cumulative signal strength curve. Historic index is a comparison of the signal strength of recent hits to the signal strength of all hits. Large increases in either of these measures indicated damage. Curvature and historic index were used here because both are independent of the rate of loading. A criteria for slope of the cumulative signal strength curve was also proposed by Study 1857, but not employed here because of the dependence of slope on the rate of loading (Chotickai 2001).

Table 4-1 through Table 4-6 present the results for the indoor and wet/dry series. In the first column of each table was recorded the maximum load after each 300-pound (1.3 kN) load increase. When significant emission was identified, the load at which the emission occurred was recorded in the table for the corresponding previous maximum load, and the Felicity ratio was calculated. For maximum loads where no significant emission was identified, "NSE" is recorded in the table. The tables also provide the number of hits recorded during unloading of the specimen, which is another indication of deterioration. The same procedure was carried out for the indoor series and the wet/dry series.

### 4.2.1 Indoor Series

Table 4-1 shows the results for a Fordyce control specimen and Table 4-2 for a Fordyce specimen with a mitigation technique. Table 4-3 and Table 4-4 show corresponding results for a Jobe specimen. These results are typical for all mitigation techniques evaluated.

**Table 4-1 AE results for Indoor Series Specimen CF a**

**Specimen C F a**

pour date 18-Sep  
 test date 23-Oct  
 age 35

| previous max load (lb) | curvature |    | historic index |    | emission during unloading, hits |
|------------------------|-----------|----|----------------|----|---------------------------------|
|                        | load (lb) | FR | load (lb)      | FR |                                 |
| 255                    | NSE       | -  | NSE            | -  | 3                               |
| 451                    | NSE       | -  | NSE            | -  | 2                               |
| 609                    | NSE       | -  | NSE            | -  | 0                               |
| 754                    | NSE       | -  | NSE            | -  | 0                               |
| 907                    | NSE       | -  | NSE            | -  | 3                               |
| 1073                   | NSE       | -  | NSE            | -  | 3                               |
| 1208                   | NSE       | -  | NSE            | -  | -                               |

pour date 18-Sep  
 test date 14-Nov  
 age 57

| previous max load (lb) | curvature |    | historic index |      | emission during unloading, hits |
|------------------------|-----------|----|----------------|------|---------------------------------|
|                        | load (lb) | FR | load (lb)      | FR   |                                 |
| 309                    | NSE       | -  | NSE            | -    | 2                               |
| 450                    | NSE       | -  | NSE            | -    | 0                               |
| 602                    | NSE       | -  | 584            | 0.97 | 2                               |
| 750                    | NSE       | -  | NSE            | -    | 0                               |
| 898                    | NSE       | -  | NSE            | -    | 4                               |
| 1058                   | NSE       | -  | NSE            | -    | 0                               |
| 1201                   | NSE       | -  | NSE            | -    | -                               |

pour date 18-Sep  
 test date 19-Dec  
 age 92

| previous max load (lb) | curvature |      | historic index |    | emission during unloading, hits |
|------------------------|-----------|------|----------------|----|---------------------------------|
|                        | load (lb) | FR   | load (lb)      | FR |                                 |
| 315                    | NSE       | -    | NSE            | -  | 21                              |
| 469                    | NSE       | -    | NSE            | -  | 10                              |
| 617                    | 597       | 0.97 | NSE            | -  | 8                               |
| 761                    | NSE       | -    | NSE            | -  | 6                               |
| 934                    | NSE       | -    | NSE            | -  | 9                               |
| 1062                   | NSE       | -    | NSE            | -  | 12                              |
| 1273                   | NSE       | -    | NSE            | -  | -                               |

**Table 4-2 AE results for Indoor Series Specimen M7F b**

**Specimen M 7F b**

| pour date              | 2-Oct               |    |                          |    |                                 |
|------------------------|---------------------|----|--------------------------|----|---------------------------------|
| test date              | 6-Nov               |    |                          |    |                                 |
| age                    | 35                  |    |                          |    |                                 |
| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR | emission during unloading, hits |
| 302                    | NSE                 | -  | NSE                      | -  | 9                               |
| 477                    | NSE                 | -  | NSE                      | -  | 1                               |
| 597                    | NSE                 | -  | NSE                      | -  | 0                               |
| 751                    | NSE                 | -  | NSE                      | -  | 0                               |
| 901                    | NSE                 | -  | NSE                      | -  | 6                               |
| 1053                   | NSE                 | -  | NSE                      | -  | 9                               |
| 1205                   | NSE                 | -  | NSE                      | -  | -                               |

**Table 4-3 AE results for Indoor Series Specimen CJ b**

**Specimen C J b**

| pour date              | 20-Sep              |      |                          |    |                                 |
|------------------------|---------------------|------|--------------------------|----|---------------------------------|
| test date              | 1-Nov               |      |                          |    |                                 |
| age                    | 42                  |      |                          |    |                                 |
| previous max load (lb) | curvature load (lb) | FR   | historic index load (lb) | FR | emission during unloading, hits |
| 307.35                 | NSE                 | -    | NSE                      | -  | 3                               |
| 461.26                 | NSE                 | -    | NSE                      | -  | 3                               |
| 620.24                 | 583                 | 0.94 | NSE                      | -  | 6                               |
| 750.18                 | -                   | -    | -                        | -  | -                               |

**Table 4-4 AE results for Indoor Series Specimen M7J b**

**Specimen M7 J b**

pour date 11-Oct  
 test date 9-Nov  
 age 29

| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR | emission during unloading, hits |
|------------------------|---------------------|----|--------------------------|----|---------------------------------|
| 295                    | NSE                 | -  | NSE                      | -  | 21                              |
| 451                    | NSE                 | -  | NSE                      | -  | 13                              |
| 600                    | NSE                 | -  | NSE                      | -  | -                               |

pour date 11-Oct  
 test date 5-Dec  
 age 55

| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR | emission during unloading, hits |
|------------------------|---------------------|----|--------------------------|----|---------------------------------|
| 325                    | NSE                 | -  | NSE                      | -  | 15                              |
| 477                    | NSE                 | -  | NSE                      | -  | 9                               |
| 606                    | NSE                 | -  | NSE                      | -  | -                               |

pour date 11-Oct  
 test date 15-Jan  
 age 96

| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR | emission during unloading, hits |
|------------------------|---------------------|----|--------------------------|----|---------------------------------|
| 330                    | NSE                 | -  | NSE                      | -  | 0                               |
| 475                    | NSE                 | -  | NSE                      | -  | 3                               |
| 613                    | NSE                 | -  | NSE                      | -  | 4                               |
| 760                    | NSE                 | -  | NSE                      | -  | 7                               |
| 901                    | NSE                 | -  | NSE                      | -  | 58                              |
| broken                 |                     |    |                          |    |                                 |

#### 4.2.2 Wet/Dry Series

Table 4-5 shows the results for a control specimen, and Table 4-6 for a specimen with a mitigation technique. These results are typical for all mitigation techniques evaluated.

**Table 4-5 AE results for Wet/Dry Series Specimen CJ g**

##### Specimen C J g

pour date 1-Jan  
 test date 14-Feb  
 age 44

| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR | emission during unloading, hits |
|------------------------|---------------------|----|--------------------------|----|---------------------------------|
| 321                    | NSE                 | -  | NSE                      | -  | 0                               |
| 469                    | NSE                 | -  | NSE                      | -  | 1                               |
| 607                    | NSE                 | -  | NSE                      | -  | 1                               |
| 788                    | NSE                 | -  | NSE                      | -  | -                               |

pour date 1-Jan  
 test date 14-Mar  
 age 72

| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR | emission during unloading, hits |
|------------------------|---------------------|----|--------------------------|----|---------------------------------|
| 374                    | NSE                 | -  | NSE                      | -  | 0                               |
| 461                    | NSE                 | -  | NSE                      | -  | 2                               |
| 633                    | NSE                 | -  | NSE                      | -  | 2                               |
| 782                    | NSE                 | -  | NSE                      | -  | -                               |

**Table 4-6 AE results for Wet/Dry Series Specimen M17J g**

**Specimen M17 J g**

pour date 30-Dec  
 test date 12-Feb  
 age 44

| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR   | emission during unloading, hits |
|------------------------|---------------------|----|--------------------------|------|---------------------------------|
| 397                    | NSE                 | -  | NSE                      | -    | 0                               |
| 570                    | NSE                 | -  | NSE                      | -    | 0                               |
| 770                    | NSE                 | -  | NSE                      | -    | 0                               |
| 792                    | NSE                 | -  | 783                      | 0.99 | -                               |

pour date 30-Dec  
 test date 12-Mar  
 age 72

| previous max load (lb) | curvature load (lb) | FR | historic index load (lb) | FR | emission during unloading, hits |
|------------------------|---------------------|----|--------------------------|----|---------------------------------|
| 302                    | NSE                 | -  | NSE                      | -  | 0                               |
| 509                    | NSE                 | -  | NSE                      | -  | 1                               |
| 643                    | NSE                 | -  | NSE                      | -  | 0                               |
| 811                    | NSE                 | -  | NSE                      | -  | -                               |

## **CHAPTER 5: SIGNIFICANCE OF TEST RESULTS**

This chapter discusses the significance of the test results presented in Chapter 4. Results of the three exposure series are evaluated based on water impermeability and water-vapor permeability, and on shrinkage. Damage indices and AE monitoring are used to quantify the amount of cracking.

### **5.1 SIGNIFICANCE OF EXPANSION AND MOISTURE TESTING**

When evaluating the test data, two concepts appeared to be most useful for understanding the expansion observed. The first concept is the impermeability to liquid water and the permeability to water vapor of the mitigation techniques. Water impermeability and water-vapor permeability were identified in the literature search as essential prerequisites for mitigation technique to be effective at treating ASR, DEF, or both.

The second concept is shrinkage. In hardened concrete, shrinkage occurs by three dominant mechanisms: drying shrinkage; carbonation shrinkage; and autogenous shrinkage. Others shrinkage mechanisms have been identified by various authors. Different mechanisms are often lumped together because of the difficulty in distinguishing among them (Wittmann 1982, Neville 1981). The most important of these is drying shrinkage, the volume change that occurs by the loss of water from the pores of the cement paste. Drying produces shrinkage in the range of  $350\text{-}650 \times 10^{-6} \mu\epsilon$  (Somayaji 2001). Carbonation shrinkage occurs by the chemical reaction of calcium hydroxide in the cement with carbon dioxide in the air. A product of the reaction is water, which evaporates and causes a decrease in volume at the surface (Wittmann 1982). Carbonation shrinkage is a long-term effect (Neville 1981). Autogenous shrinkage is the volume change that occurs because of hydration of the cement with no movement of water to or from the paste (Neville 1981). Autogenous shrinkage is mostly a concern for mixes with low water to cement (w:c) ratios because less water is available for hydration. The average w:c ratio of the test specimens is 0.42, although several mixes dropped to 0.33; as a consequence, autogenous shrinkage should not be significant in this study.

#### **5.1.1 Indoor Series**

For the indoor series, the specimens were aged for the entire test duration in the storage containers at 100% relative humidity. Because the specimens were never in contact with liquid water, the test cannot be used to evaluate the mitigating effect of impermeability to liquid water. All test results are considered due to the effects of the water-vapor permeability of the different mitigation techniques.

Although relative humidity readings were not taken for this series, it can be assumed that the relative humidity of the specimens was very high when the mitigation techniques were applied, because the specimens had been aged for one week in 100% relative humidity. Under these conditions, if a mitigation technique is water-vapor permeable, the relative humidity of the specimen would be kept high, and ASR/DEF expansion would be expected to continue at a constant or increasing rate. Such expansion would cease only when the reactive material had been consumed. If the mitigation technique is not water-vapor permeable, the moisture contained inside would be consumed by hydration and ASR/DEF expansion, and such expansion will decrease over time. The total expansion would be less than in the previous case.

Concrete maintained in a moist environment from the time of casting will swell from absorption of water into the cement paste, to about  $100\text{-}150 \times 10^{-6} \mu\epsilon$  (Neville 1981). This expansion occurs over several days and then levels off. For this series, drying or carbonation shrinkage is not possible because the specimens were aged for the entire test duration at 100% relative humidity.

Most of the Jobe specimens showed positive expansion for the duration of the test, and a decrease in expansion over time. At 13 weeks, the expansion of most of the specimens treated with mitigating techniques is slightly less than the expansion for the control specimens, and there is little difference between the behaviors of the individual techniques. Judging by this, either all the mitigation techniques are water-vapor impermeable and mitigate the deterioration, or a moist environment alone does not provide enough water to maintain the expansive reaction.

In the Fordyce specimens, expansion is very small for the entire test duration. The Fordyce fine aggregate has a 14-day ASTM C 1260 expansion less than half of that for the Jobe fine aggregate (Bauer 2001). Several Fordyce specimens experienced negative expansion at different points during the test. Autogenous shrinkage is a likely explanation for negative expansion at 1 week; apparent negative expansion at later ages is most likely a result of scatter in data.

### 5.1.2 Outdoor Series

In the outdoor series, the specimens were exposed both to liquid water in the form of rain, and to water vapor in the air. Because of this exposure, the outdoor series theoretically can be used to evaluate both water impermeability and water-vapor permeability.

Figure 5-1 shows the relative humidity of the Jobe specimens for the outdoor series, and also the total daily rainfall and average daily ambient relative humidity. Clearly, the relative humidity of the specimens increases when there is rainfall, and decreases when there is not. On the other hand, a correlation between ambient relative humidity and relative humidity of the specimens is not so apparent. The ambient relative humidity fluctuates considerably, even within a single day. The relative humidity of a specimen cannot respond as quickly, and the ambient relative humidity can be expected to change before any appreciable difference can be seen in the relative humidity of the specimen. The outdoor series, therefore, is considered an evaluation of water impermeability only.

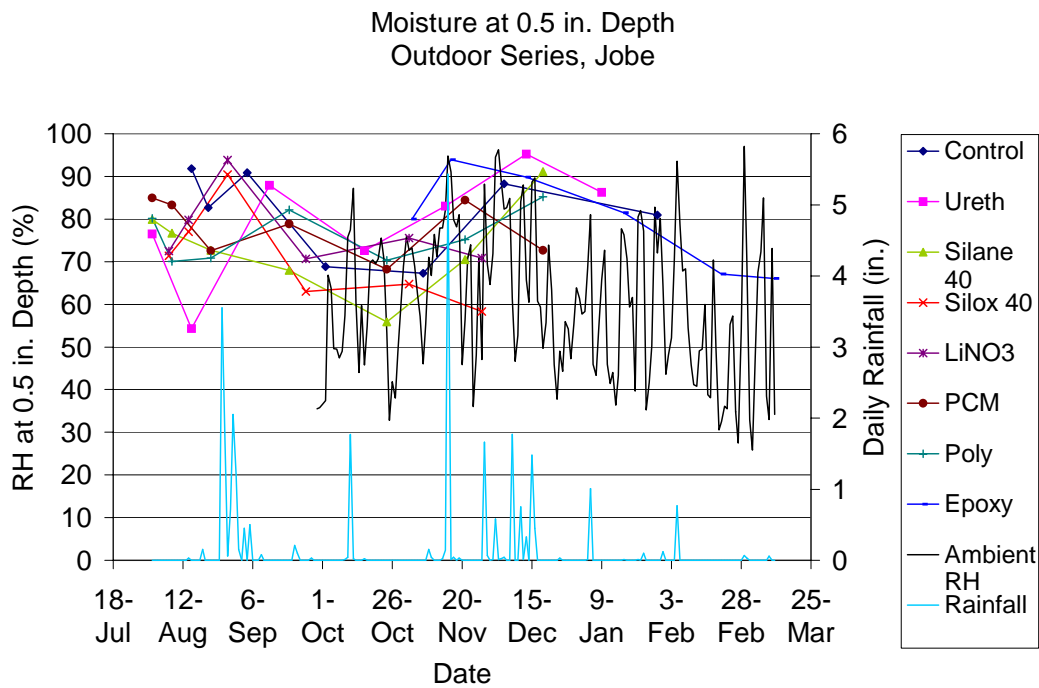


Figure 5-1 Moisture in specimens plotted against rainfall and ambient relative humidity



The outdoor series also provides evidence that the indoor series is not a useful test for differentiating among treatments. The indoor series is a measure of water-vapor permeability only, but it is seen that relative humidity alone appears to have considerably less influence on the expansion due to ASR/DEF deterioration than exposure to liquid water. Field observations also show that portions of girders directly in contact with liquid water, such as under joints or scuppers, have considerably worse deterioration than the interior girders, which are covered by the deck (Boenig 2000). The mitigation techniques in the indoor series, therefore, behave similarly because not enough water was provided to promote the deterioration reaction.

For both Jobe and Fordyce specimens, expansion and relative humidity clearly increase during rainy periods and decrease over dry periods.

Jobe specimens treated with silane, siloxane, or  $\text{LiNO}_3$  behave similarly to the control specimens. Jobe specimens treated with PCM, moist-cured urethane, and polyurethane have expansion slightly greater than the control specimens. Toward the end of the readings, specimens treated with PCM and moist-cured urethane diverge from the readings for the other techniques.

Similar to the indoor series, the Fordyce specimens exhibit less expansion than the Jobe specimens. Toward the end of the readings, specimens treated with PCM, moist-cured urethane, linseed oil, or  $\text{LiNO}_3$  plus siloxane diverge from the readings for the other techniques. The remaining specimens behaved like the control specimens.

From readings at Week 1, the relative humidity of the specimens at time of coating was between upper 70% and lower 90%, and was mostly about 80%. If the mitigation technique is water-impermeable, the initial moisture will be consumed by hydration and ASR/DEF expansion; over time, the expansion will decrease. Because the relative humidity of the specimens increases with rain, there is some degree of water permeability.

Both drying shrinkage and wetting expansion can affect this series. The former is governed by water-vapor permeability, and the latter by water impermeability.

Because none of the mitigated specimens varies distinctly from the control specimens, it is difficult to determine which techniques have the greatest water impermeability. The lack of differentiation can be attributed to the exposure condition itself. The total amount of rain is low, and the duration of exposure to rain is very short. It is possible that not enough water was available for ASR/DEF deterioration to proceed.

During application of the PCM to the specimens in all series, the researcher observed that it was unlike any of the other mitigation techniques. While the other treatments provided a smooth, sleek coating, the PCM was granular and slightly porous. From appearance, the PCM did not seem to be water-impermeable.

### **5.1.3 Wet/Dry Series**

Like the indoor series, the prisms of the wet/dry series were never in contact with liquid water; therefore, the test cannot be used to evaluate the water impermeability of the mitigation techniques. All test results are considered on the basis of water-vapor permeability.

All specimens show negative expansion and decrease in relative humidity over dry cycles, and positive expansion and increase in relative humidity over wet cycles. After six weeks, there is little difference between the relative humidity readings for different techniques at both 0.5 in. (12 mm) and 1.5 in. (40 mm) depths. Because the relative humidity of the specimens is easily correlated with the exposure cycle, all the mitigation techniques appear to be water vapor-permeable.

It is possible that prolonged exposure to very high temperature altered the water-vapor permeability of the treatments. Although all treatments were allowed to cure for the manufacturers' specified time before placement in the storage environment, a few treatments were observed to be sticky for the first several weeks in the high temperature.

As explained with the indoor series, concrete expands when maintained in a moist environment. The expansion seen at one week is due to this, and possibly also to expansion from ASR/DEF. Assuming no ASR/DEF deterioration, successive dry cycles are expected to promote drying shrinkage and wet cycles to promote wetting expansion. While 30% to 60% of the initial drying shrinkage is permanent, concrete experiences reversible shrinkage and expansion when exposed to alternating dry and wet cycles (Murdock 1979). In these tests, the magnitude of negative expansion after a dry cycle is consistent for all techniques at 6, 10, and 13 weeks, suggesting that the dominant mechanism is drying shrinkage. At 2 weeks, most specimens continue to show expansion, although much less than before. The change in relative humidity from Week 1 to Week 2 is less than for subsequent dry cycles. This is probably because more water is retained in the specimens, allowing for deterioration to occur along with or prior to the effect of drying shrinkage.

The magnitude of positive expansion after wet cycles at 4 and 8 weeks varies, however, indicating that deterioration may be occurring during the wet cycles along with wetting expansion. By Week 12, the expansion is similar for all but one specimen, and the corresponding increase in relative humidity is the same as the decrease over the previous period. At this point, any deterioration can be assumed to have ceased, and the only mechanism occurring is wetting expansion.

In comparison to the outdoor series, the wet/dry series is a very severe exposure, and is not an accurate or useful indication of the expansion caused by ASR, DEF, or both. The internal relative humidity of the outdoor specimens does not fall below 50%, whereas the wet/dry series specimens are dried to a relative humidity of 10%. The ambient relative humidity in Austin, recorded by Project 4085 between September 2001 to April 2002, ranges from upper 10% to upper 90%, with an average value of 60%. The relative humidity of the storage environment during dry cycles is less than 10%. By Week 6, the expansion and shortening are controlled primarily by reversible wetting and drying deformations. Any potential for expansion from ASR/DEF deterioration appears to be precluded by the extreme drying cycle.

#### 5.1.4 Damage Indices

Damage indices were recorded only for the wet/dry series. The plots of  $DI = \sum_i w_i l_i$  and

$DI = \sum_i w_i^2 l_i$  both show the trend of increase in damage index with time. Over the period of

observation, none of the specimens developed cracks any wider than 0.003 inches (0.08 mm). Because the cracks remain narrow and of comparable width for all mitigation techniques, squaring the width term in the second formulation of the damage index does not affect the result.

Figure 5-2 shows sketches of the cracks used to calculate damage indices for a control specimen, a Type IV epoxy (M20) specimen, and a silane+742 (M16) specimen. Very little surface cracking is observed on the silane+742 and Type IV epoxy specimens, as seen in Figure 5-2. Silane+742th, silane+PCM, and polyurethane also exhibit small damage indices, while silane+latex is slightly greater than the previous five mitigation techniques. These six mitigation techniques prevent or retard surface cracking by preventing rapid moisture loss from the surface. Also, cracks were observed under the surface of the painted specimens, but were not included in the damage indices because the paint itself had not cracked.

Both the  $\text{LiNO}_3$  and  $\text{LiNO}_3+742$  specimens exhibited cracking equivalent to or greater than the control specimens. The lithium nitrate, which may only penetrate slightly into the surface by brush application, increases surface cracking.



Figure 5-2 Sketches of cracks on specimens of wet/dry series

## 5.2 SIGNIFICANCE OF ACOUSTIC EMISSION MONITORING

### 5.2.1 Indoor Series

For all the specimens, very little significant emission was recorded. When significant emission was identified, the Felicity ratio was 0.94 or greater. A Felicity ratio this large does not represent deterioration (Chotickai 2001). While the specimens do exhibit cracking under load, the cracks are not sufficiently large to be of structural concern. Specimens tested after a year of aging would most likely have developed structural cracking and exhibit significant emission.

As observed during testing, the Jobe specimens produced many more AE hits than the Fordyce specimens. Although the testing procedure prescribes holding the load until quieting (cessation of emission), the Jobe specimens rarely quieted. Load was held on these for two minutes. The greater number of hits recorded for the Jobe specimens indicates that these specimens had more internal cracks than the Fordyce specimens.

### 5.2.2 Wet/Dry Series

As with the indoor series, very little significant AE emission was recorded. The emission during unloading of these specimens is less than for the indoor series. The same conclusion can be reached: deterioration had not proceeded far enough to create structurally significant cracking.



## **CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS**

### **6.1 SUMMARY**

This thesis describes part of the work associated with TxDOT Study 4069 (“Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration”). TxDOT is interested in developing techniques for mitigating or remediating premature concrete deterioration due to alkali silica reaction (ASR), delayed ettringite formation (DEF), or both, in order to extend the life of potentially affected structures. The parts of Study 4069 reported here consist of: a literature search for mitigation or remediation techniques; fabrication of concrete specimens intentionally susceptible to premature deterioration; and the application and monitoring of the mitigation techniques using laboratory testing and acoustic emission (AE) procedures.

#### **6.1.1 Literature Search**

The literature search was conducted to identify treatments being used or tested worldwide to mitigate or remediate deterioration from ASR, DEF, or both. The proposed treatments were evaluated, according to published results, for use on Texas Department of Transportation structures displaying this damage. In addition, treatments used to mitigate other types of concrete deterioration were explored for their potential use to mitigate or remediate ASR/DEF deterioration.

The search identified treatments that were effective at reducing expansion of ASR-affected specimens or preventing other types of concrete deterioration. These treatments are: silane; siloxane; linseed oil; high-molecular-weight methacrylate (HMWM), epoxy, polymer-modified cement mortar (PCM); urethane; and lithium nitrate.

It was recommended to use these treatments, separately or in combination, on specimens made with aggregates and cement known to produce ASR/DEF deterioration, and to evaluate their effectiveness by measuring specimens’ expansion and internal moisture content, and by monitoring them with acoustic emission techniques. Applications of these techniques to specific structures, such as FM 1929 at Lake Ivie, are discussed in theses and reports for Study 1857. It is not discussed further here.

#### **6.1.2 Expansion and Moisture Testing**

Specimens were fabricated according to ASTM C 1293-95 with fine aggregates known to be reactive, and high-alkali cement. The specimens had a square cross-section of 3 in. (75 mm) and a nominal length of 10 in. (250 mm). Plastic sleeves were cast into the specimens at depths of 1.5 in. (40 mm) and 0.5 in. (12 mm) in order to measure internal relative humidity.

Expansion (defined as the change in length between successive measurements) and internal relative humidity were measured for specimens exposed to three series of environmental conditions: an indoor series; an outdoor series; and a wet/dry series.

The indoor series used an accelerated ASTM C 1293 procedure of high-temperature storage, reducing the required testing time from 2 years to 13 weeks. The temperature of the storage environment is increased from 38°C to 60°C. The length of each specimen was recorded at 1 week, 2 weeks, 4 weeks, 8 weeks, and 13 weeks. Moisture readings were not taken for this series because the specimens were kept at constant humidity in the storage containers.

The specimens in the outdoor series were coated and aged outside in order to subject them to conditions as similar as possible to actual field conditions. Length and moisture readings were taken at 1 week, 2 weeks, 4 weeks, 8 weeks, 13 weeks, 17 weeks, 21 weeks, and 25 weeks after fabrication.

For the wet/dry series, drastic changes in humidity were imposed on the specimens in order to evaluate the effectiveness of each mitigation treatment for water impermeability and water-vapor permeability. Length and moisture readings were taken at 1 week, 2 weeks, 4 weeks, 6 weeks, 8 weeks, 10 weeks, 12 weeks, and 13 weeks after fabrication. To provide a rapid visual measure of cracking, damage indices were calculated at 7 weeks, 8 weeks, 10 weeks, 12 weeks, and 13 weeks after fabrication.

### **6.1.3 Acoustic Emission Monitoring**

Acoustic emission monitoring was used to evaluate the deterioration in the specimens from the indoor series and wet/dry series. The procedures and criteria developed in Project 1857 were used (Chotickai 2001). The important data collected from testing includes amount of emission during loading, amplitude of hits, historic index, and Felicity ratio.

The prisms were loaded under third-point bending, per ASTM C 78. To determine the Felicity ratio, a stepped loading schedule was used. The Felicity ratio, defined as the load at the onset of significant acoustic emission divided by the maximum previous load, is the most useful AE measure of structural deterioration (Tinkey 2000).

## **6.2 CONCLUSIONS**

- From the indoor series, most of the Jobe specimens (those specimens made with Jobe fine aggregate) show positive expansion for the duration of the test, and a decrease in expansion over time. There is little difference between the behaviors of the individual techniques. Judging by this, a moist environment alone does not provide enough water to maintain the expansive reaction. The Fordyce specimens (those specimens made with Fordyce fine aggregate) show very small expansion for the entire test duration. The test procedure used for the indoor series is not useful for differentiating among treatments.
- From the outdoor series, expansion and relative humidity of both Jobe and Fordyce specimens increase during rainy periods and decrease over dry periods. A correlation between ambient relative humidity and relative humidity of the specimens is not so apparent.
- The lack of differentiation between performance of the mitigation techniques for the outdoor series can be attributed to the lack of sufficient water for ASR/DEF deterioration to proceed.
- The wet/dry series is a very severe exposure, and is not a realistic predictor of the expansion caused by ASR, DEF, or both.
- Silane+742, silane+742th, silane+latex, silane+PCM, Type IV epoxy, and polyurethane prevent or retard surface cracking by preventing rapid moisture loss from the surface. Lithium nitrate increases surface cracking.
- Acoustic emission monitoring was successfully used on small specimens, although the cracking in these specimens was not great enough for the AE to identify structural deterioration.

## **6.3 RECOMMENDATIONS**

In this study, no particular mitigation technique was determined to be effective at reducing expansion from premature concrete deterioration under the three exposure series used. From the results of the indoor and the outdoor series, ambient relative humidity appears to have considerably less influence on the expansion due to ASR/DEF deterioration than exposure to liquid water. Because the outdoor series,

which did provide exposure to rain, did not differentiate between performance of the mitigation techniques, a test series should be conducted that exposes the specimens to a large, measurable quantity of liquid water at regular intervals. Increasing the amount of water available for the expansive reaction should provide a greater opportunity to distinguish the efficacy of the different mitigation techniques. In Appendix H, one possible test procedure is proposed. It involves ASTM C 1293 specimens treated with mitigation techniques and exposed to cycles of immersion in water, storage at high temperature and 100% relative humidity, and drying in ambient temperature and relative humidity. The different mitigation techniques identified in this study should be further compared using the proposed test procedure.

At this time, it is recommended that current structures with premature concrete deterioration need not be treated with a mitigation technique. Study 1857 found that field girders with the largest crack widths were less damaged than the wetted laboratory-tested box girders. The flexural capacity of the damaged box girders was determined not to be significantly lower than for undamaged girders (Boenig 2000). Results from the first 4 weeks of the wet/dry series suggest that painted specimens do not behave significantly better or worse than control specimens. Therefore, paint may be applied to exterior girders for visual appearance, but need not be applied to interior girders, which have little exposure to rain.





## References

1. Abe, Michihiko, Mikio Wakasugi, Masashi Tanaka, and Hideki Kamimoto, "The Effect of Surface Coating on Inhibition of Alkali-Silica Reaction," Rehabilitation of Concrete Structures, International RILEM/CSIRO/ACRA Conference, Melbourne, Australia, 1992, pp. 409-414.
2. ACI Committee 222 "Corrosion of Metals in Concrete," (ACI 222R-96), American Concrete Institute, Farmington Hills, Michigan, 1996.
3. ACI Committee 515 "A Guide for Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete," (ACI 515.1R-79), American Concrete Institute, Farmington Hills, Michigan, 1985.
4. ASTM C 78-00, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)," American Society for Testing and Materials, 2000.
5. ASTM C 157-99 "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," American Society for Testing and Materials, 1999.
6. ASTM C 1293-95 "Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction," American Society for Testing and Materials, 1995.
7. Baillemont, Ghislaine, Jean-Baptiste Delaby, Marc Brouxel, and Pascal Rémy. "Diagnosis, Treatment and Monitoring of a Bridge Damaged by AAR," Proceedings, 11<sup>th</sup> International Conference on Alkali-Aggregate Reaction, Quebec, Canada, 2000, pp. 1099-1108.
8. Basheer, L., D.J. Cleland, and A.E. Long, "Protection Provided by Surface Treatments Against Chloride Induced Corrosion," Materials and Structures/Materiaux et Constructions, vol. 31 n. 211, Aug-Sep 1998, pp. 459-464.
9. Bauer, S.C., "Laboratory Investigations of Alkali-Silica Reaction using the Accelerated Mortar Bar Test and its Modifications," Master's Thesis prepared for the Graduate School of The University of Texas at Austin, December 2001.
10. Boenig, A., "Bridges with Premature Concrete Deterioration: Field Observations and Large-Scale Testing," Master's Thesis prepared for the Graduate School of The University of Texas at Austin, May 2000.
11. Chotickai, P., "Acoustic Emission Monitoring of Prestressed Bridge Girders with Premature Concrete Deterioration," Master's Thesis prepared for the Graduate School of The University of Texas at Austin, May 2001.
12. Figurski, D.G., "Laboratory and Field Investigations of Alkali-Silica Reaction in Portland Cement Concrete," Master's Thesis prepared for the Graduate School of The University of Texas at Austin, December 2001.

13. Fowler, David W., "High Molecular Weight Methacrylate for Sealing Cracked Concrete," Proceedings, Sessions Related to Structural Materials, ASCE Structures Congress '89, American Society of Civil Engineers, May 1-5 1989, pp. 313-322.
14. Fujii, Manabu, Kasuo Kobayashi, Toyooki Miyagawa, and Makoto Hisada, "Surface Treatment for Concrete Structures Damaged By Alkali-Aggregate Expansion," Proceedings, 8<sup>th</sup> International Conference on Alkali-Aggregate Reaction, Kyoto, Japan, 1989, pp. 875-880.
15. G.M. Idorn Consultants, website, <http://www.gmic.dk>.
16. Hime, W.G., "Delayed Ettringite Formation – A Concern for Precast Concrete?" PCI Journal, July-August 1996, p26-30.
17. Kamimoto, Hideki and Mikio Wakasugi, "Effect of Coating with Flexible Polymer Modified Cement Mortar on Inhibition of Alkali Silica Reaction," ASTM Special Technical Publication n 1176. Proceedings, Symposium on Polymer-Modified Hydraulic-Cement Mixtures and Mortars, Jun 16 1992, pp. 34-43.
18. Leeming, M.B., "Keeping Water Out of Concrete – The Key to Durability," Bridge Management, Inspection, Maintenance, Assessment and Repair, Papers Presented at the First International Conference on Bridge Management, University of Surrey, Guildford, March 28-30, 1990, pp. 243-258.
19. Marks, Vernon J., "High Molecular Weight Methacrylate Sealing of a Bridge Deck," Transportation Research Record, n. 1204, 1988, pp. 983-988.
20. Mehta, P. Kumar, and Paulo J.M. Monteiro, Concrete - Microstructure, Properties, and Materials, New York: McGraw-Hill, 1993, pp.126-131, 138
21. Murdock, L.J. and Brook, K.M., Concrete Materials and Practice, 5<sup>th</sup> ed. New York: John Wiley and Sons, Inc., 1979.
22. Neville, A.M., Properties of Concrete, 3<sup>rd</sup> ed. London: Pitman Publishing Limited, 1981.
23. O'Donoghue, Mike, Ron Garrett, V.J. Datta, and Leslie Peer, "Penetrating Sealers: A Comparison of Epoxy, Moisture-Cured Urethane, and Siloxane Technology on Concrete, Rust, and an Inorganic Zinc Coating," Journal of Protective Coatings and Linings, vol. 15 n. 12, Dec 1998, pp. 30-47.
24. Rizzo, Edward M., and Steven Bratchie, "Use of Penetrating Sealers for the Protection of Concrete Highways and Structures," Journal of Protective Coatings and Linings, vol. 6 n. 1, Jan 1989, pp. 62-70.
25. Somayaji, Shan, Civil Engineering Materials, 2<sup>nd</sup> ed. New Jersey: Prentice-Hall, Inc., 2001.
26. Sprinkel, Michael M, and Mary DeMars, "Gravity-fill Polymer Crack Sealers," Transportation Research Record, n. 1490, Jul 1995, p43-53.
27. Stokes, David B., "Development of a Lithium-based Material for Decreasing ASR-Induced Expansion in Hardened Concrete," Proceedings, 11<sup>th</sup> International Conference on Alkali-Aggregate Reaction, Quebec, Canada, 2000, pp. 1079-1087.

28. Thompson, D.M., "Repair of Corrosion Damaged Concrete," Highway Research: Sharing the Benefits. Proceedings of the Conference, The United States Strategic Highway Research Program, London, October 29-31, 1990, pp. 113-124.
29. Tinkey, B.V., "Nondestructive Testing of Prestressed Bridge Girders with Distributed Damage," Master's Thesis prepared for the Graduate School of The University of Texas at Austin, May 2000.
30. Touma, W.E., "Alkali-Silica Reaction in Portland Cement Concrete: Testing Methods and Mitigation Alternatives," Doctorate Dissertation prepared for the Graduate School of The University of Texas at Austin, August 2000.
31. Whitmore, David, and Sean Abbott, "Use of an Applied Electric Field to Drive Lithium Ions Into Alkali-Silica Reactive Structures," Proceedings, 11<sup>th</sup> International Conference on Alkali-Aggregate Reaction, Quebec, Canada, 2000, pp. 1089-1098.
32. Wittmann, F.H., "Creep and Shrinkage Mechanisms," Creep and Shrinkage in Concrete Structures, Bazant, Z.P. and Wittmann, F.H., ed., New York: John Wiley and Sons, Inc., 1982.
33. Wright, J., S. Rizkalla, and Z. Shen, "Three-Year Field and Laboratory Evaluation of Linseed Oil as a Concrete Sealer," Canadian Journal of Civil Engineering, vol. 20 n. 5, Oct. 1993, pp. 844-854.