
Investigation of Deterioration of Joints in Concrete Pavements

National Concrete Pavement
Technology Center



Final Report
August 2012

Sponsored through

Federal Highway Administration (DTFH61-06-H-00011 (Work Plan 26))
Pooled Fund Study TPF-5(224): Indiana, Iowa (lead state), Michigan,
Minnesota, New York, South Dakota, Wisconsin; American Concrete
Pavement Association (ACPA), Iowa Concrete Paving Association (ICPA),
Portland Cement Association (PCA)

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The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Iowa Department of Transportation or the U.S. Department of Transportation Federal Highway Administration.

Technical Report Documentation Page

1. Report No. DTFH61-06-H-00011 Work Plan 26		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Investigation of Deterioration of Joints in Concrete Pavements				5. Report Date July 2012	
				6. Performing Organization Code	
7. Author(s) Peter Taylor, Larry Sutter, and Jason Weiss				8. Performing Organization Report No. InTrans Project 09-361	
9. Performing Organization Name and Address National Concrete Pavement Technology Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No.	
12. Sponsoring Organization Name and Address Federal Highway Administration U.S. Department of Transportation 1200 New Jersey Avenue SE Washington, DC 20590				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code TPF-5(224)	
15. Supplementary Notes Visit www.cptechcenter.org for color PDF files of this and other research reports.					
16. Abstract <p>Premature deterioration of concrete at the joints in concrete pavements and parking lots has been reported across the northern states. The distress is first observed as shadowing when microcracking near the joints traps water, later exhibiting as significant loss of material. Not all roadways are distressed, but the problem is common enough to warrant attention.</p> <p>The aim of the work being conducted under this and parallel contracts was to improve understanding of the mechanisms behind premature joint deterioration and, based on this understanding, develop training materials and guidance documents to help practitioners reduce the risk of further distress and provide guidelines for repair techniques.</p> <p>While work is still needed to understand all of the details of the mechanisms behind premature deterioration and prevention of further distress, the work in this report has contributed to advancing the state of knowledge.</p>					
17. Key Words concrete pavement—deicing salts—pavement joints—portland cement concrete				18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.		20. Security Classification (of this page) Unclassified.		21. No. of Pages 208	22. Price NA

INVESTIGATION OF DETERIORATION OF JOINTS IN CONCRETE PAVEMENTS

**Final Report
July 2012**

Principal Investigator

Peter Taylor, Associate Director
National Concrete Pavement Technology Center, Iowa State University

Researchers

Larry Sutter, Professor and Director
Michigan Tech Transportation Institute

Jason Weiss, Professor and Director
Pankow Materials Laboratory, Purdue University

Authors

Peter Taylor, Larry Sutter, and Jason Weiss

Sponsored by

the Federal Highway Administration (FHWA)
DTFH61-06-H-00011 Work Plan 26

FHWA Pooled Fund Study TPF-5(224): Indiana, Iowa (lead state), Michigan, Minnesota,
New York, South Dakota, Wisconsin; American Concrete Pavement Association (ACPA), Iowa
Concrete Paving Association (ICPA), Portland Cement Association (PCA)

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation
(InTrans Project 09-361)

A report from

National Concrete Pavement Technology Center

Iowa State University

2711 South Loop Drive, Suite 4700

Ames, IA 50010-8664

Phone: 515-294-8103

Fax: 515-294-0467

www.cptechcenter.org

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ACKNOWLEDGMENTS

This research was conducted under Federal Highway Administration (FHWA) DTFH61-06-H-00011 Work Plan 26 and the FHWA Pooled Fund Study TPF-5(224), involving the following state departments of transportation:

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

The authors would like to express their gratitude to the National Concrete Pavement Technology (CP Tech) Center, the FHWA, the Iowa Department of Transportation (DOT), and the other pooled fund state partners for their financial support and technical assistance.

The authors would also like to thank the following industry sponsors on this research:

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

EXECUTIVE SUMMARY

Premature deterioration of concrete at the joints in concrete pavements and parking lots has been reported across the northern states. The distress is first observed as shadowing when microcracking near the joints traps water, later exhibiting as significant loss of material. Not all roadways are distressed, but the problem is common enough to warrant attention.

Based on the findings of this work, the following points are noted:

- Different forms of failure are observed in different locations. Failure appears to be related to the details of the system including the type and permeability of the base, the effectiveness of the seal in the joint, and the type of aggregate in the mixture, among many others.
- Distress is almost always a combination of marginal factors rather than a single bad parameter. These factors include the following:
 - Locally saturated concrete
 - Air content below 5%
 - Water to cement ratio (w/cm) above 0.4
 - Aggressive salting
 - Marginal or slowly D-cracking aggregates
- Shadowing and typical freeze-thaw damage are associated with saturated conditions and often marginal air void systems.
- There is a form of the distress in which wedges are broken off the joint face, which is likely associated with effects of the interfacial transition zone.
- Sealants are showing promise in being able to reduce the risk of damage occurring.
- It is not uncommon to see signs of distress in the joint face that is not observed on the top surface. This is likely related to a combination of ponding, salts collecting in the joints, and differential permeability between the faces.

INTRODUCTION

Joint deterioration has been reported in a number of locations in cold weather states. The pavements affected include state highways, city and county streets, and parking lots. The information available about these occurrences is limited and a systematic approach is needed to investigate the commonalities that may provide clues to the causes. Added to this situation is the need for a carefully-designed research program that can reproduce the distress in the laboratory, so it can then be investigated in detail, leading to guidelines on how distress can be prevented and repaired.

The work described in this report discusses the tasks conducted under this research contract.

Project Goals

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

The approach taken was as follows:

- Conduct interviews of stakeholders in locations having the problem
- Develop a database of parameters from sites where distress is observed
- Test samples taken from selected sites
- Investigate techniques to treat locations where the problem is occurring
- Attempt to reproduce and mitigate distress in laboratory samples
- Identify failure mechanisms
- Provide guidance for practitioners about prevention and mitigation methods

Background

Premature deterioration of concrete at the joints in concrete pavements and parking lots has been reported across the northern states. The distress is first observed as shadowing, when microcracking near the joints traps water, later exhibiting as significant loss of material.

Not all roadways are distressed, but the problem is common enough to cause some local authorities to reconsider the use of concrete in their pavements. A number of potential causes have been suggested and it is likely that different design details and construction systems are leading to differences in the observed distress.

The work described in this report describes work conducted to investigate some of the most likely mechanisms. The work overlaps with other projects being conducted at the same institutions under other funding sources.

OVERVIEW

A number of tasks have been conducted to address the goals of the project under this contract. Each task has been written up as an individual report, each of which is included as an Appendix.

The body of this report comprises a summary of the findings of the separate reports. Some of the work, primarily the field reviews and petrography, was conducted through Michigan Technological University.

The full petrographic reports are included in the appendices. The work related to wetting and drying was conducted at Purdue University. Their findings were published as technical papers.

The following tasks were planned:

- Field sampling
- Base permeability measurement
- Freeze-thaw tests
- Wetting and drying effects

FIELD SAMPLING

The researchers conducted visits to multiple sites in Iowa, Michigan, Minnesota, and Wisconsin to observe and investigate the various forms of distress being reported.

Based on the observations, the researchers selected cores from five locations and submitted them to a petrographer for analysis. The motivation behind the selections and the findings are summarized below.

Wisconsin, Eau Claire

The site selected in Wisconsin was at the intersection of 1st Avenue and Grand Avenue in Eau Claire. The full report is included in Appendix A.

Both streets were built in 1997 by different contractors. One street is showing distress while the other is not. Sampling and analysis were conducted to investigate the differences between the systems to help understand why they are performing differently.

The findings may be summarized as follows:

- Both mid-panel cores appeared in good condition.
- Both joint cores taken from different portions of the same joint showed distress.

- There is evidence of chemical attack near the surface of the joints, likely due to use of deicing salts other than sodium chloride. The form and details of the chemical attack are unknown.
- Both joint cores show signs of air voids being filled with ettringite. It is notable that this has not occurred in the mid panel cores, indicating that the saw cuts are significantly more permeable than the top surfaces and/or the joints are acting as reservoirs.
- All of the concrete exhibited satisfactory air contents at the time of placing.

Work is continuing under another contract to address some questions, including the form of chemical attack and why a system that should be free-draining is showing evidence of saturation.

Iowa, Ames

This site is a two-lane city street, approximately a half mile long, in a research park. The full report is included in Appendix B. The road was paved in 1997 in reportedly one day using a full-width slipform paver on a drainable base. Some of the joints have been filled with hot-seal material.

In 2010, it was noted that deterioration was occurring. There does not appear to be a correlation between the presence of sealant and the joint deterioration.

Two cores taken from adjacent damaged and undamaged joints were sent for petrographic examination:

- The original air void systems of both the undamaged and damaged cores were satisfactory, but had been filled with ettringite.
- Some D-cracking was observed, particularly in the distressed sample.
- Despite the reportedly compromised air void system of the undamaged sample, it is still in reasonable condition.

The most significant difference between the samples was that the water to cement ratio (w/cm) of the undamaged sample was slightly lower than that of the damaged sample.

Iowa, Ankeny

This site is a two-lane arterial street in a suburban neighborhood. The full report is included in Appendix C.

The road was reportedly paved in 1982 and has appeared in reasonable condition until recently (within the last 5 years) when joint deterioration became evident. The distress is concentrated at intersections.

Two cores were extracted in to investigate the effects of deicing salts on the rate of deterioration. One core was taken at the intersection that is heavily salted. The other core was taken several panels to the south where salting is less aggressive, and distress appeared to be less marked at the surface.

The pavement was reportedly constructed without a base layer and on clay. It is, therefore, not surprising to find evidence of saturation in the concrete, particularly at the joints.

The petrographic findings may be summarized as follows:

- Both cores are damaged, although the degree of distress is lower in the sample from the lower salt load site.
- The original air void systems of both cores were satisfactory but had been filled with ettringite.
- Some D-cracking was observed.

The less-salted sample appears to be in slightly better condition, particularly at the surface, but failure is still likely, albeit slightly later. It would appear that the quality of the aggregate is a contributing factor where it is reaching the end of its life after nearly 30 years in service.

Minnesota, Meeker County

The Minnesota Department of Transportation (MnDOT) changed their specification in the 1990s to require that mixtures have a w/cm less than 0.40. In 2011, MnDOT extracted a large number of cores from highways around the state that represented both low and high w/cm mixtures.

Four cores were selected for examination under this project to assess why variations in joint performance were observed. The full report is included in Appendix D.

In reviewing other data provided by MnDOT, it appears that systems with the lower w/cm are performing considerably better than the one with the higher w/cm. Some distress is still observed, but the rates are lower, meaning that the time to failure is extended.

Two cores were taken from Route 12 west of Minneapolis in Meeker County. One represented a distressed joint while the other appeared to be in better condition.

The petrographic findings may be summarized as follows:

- The silicone sealant in both joints was de-bonded from the concrete.
- Cracking is typical of freeze-thaw distress.
- Both cores exhibited air voids filled with ettringite. The depth of ettringite-filled voids and of carbonation is greater in the distressed core, indicating greater permeability in this core.
- The air-void system of the distressed core was better than that of the sound core.

- w/cm of the distressed core was slightly higher than that of the sound core.
- Top surface of both cores was in good condition.

It is notable that distress is more closely correlated with w/cm and permeability than air void system.

Minnesota, Stearns County

Two cores were taken from Route 94 near Brainerd, Minnesota. One was selected as representing a distressed joint, including a so-called tunnel at the bottom of the joint, while the other appeared to be in better condition.

The petrographic findings may be summarized as follows:

- The silicone sealant was de-bonded from the concrete in the damaged core, but bonded in the other.
- The damage was typical of freeze-thaw distress.
- Both cores exhibit air voids filled with ettringite, but the extent is greater in the damaged core.
- Carbonation is slightly deeper in the sound core.
- The w/cm was similar in both cores.
- The air void system is better in the sound core.
- Top surface of both cores was in good condition.

In this case, the better performance appears to be tied to the very high air content, while both samples had similar, low, w/cm. The sample in good condition also is the only one that still had an effective sealant.

BASE PERMEABILITY

Based on the premise that damage is associated with saturated concrete systems, one of the questions to be addressed is the effect of the permeability of the base under the concrete. A permeable system would be presumed to indicate lower risk of distress than a closed system.

Under this project, a system was developed to measure base permeability through a core hole drilled through the concrete pavement. Several units were built and tested at one of the sites described above. The operation of the equipment and data gathered are discussed in the field report for the Iowa, Ames location (Appendix B).

The tests indicated that the device worked as intended and that repeatable data could be collected, even in a reasonable open foundation system.

For the location evaluated, there did not seem to be a correlation between joint deterioration and base permeability. Further tests are planned as the project continues under other funding sources. The researchers also plan to publish formal papers describing the system and the theories behind it.

FREEZE-THAW TESTS

A series of freeze-thaw tests were conducted on different matrices of variables to assess their significance. The variables addressed include the following:

- Effect of air entraining admixture type
- Effect of fly ash
- Effect of deicing salt
- Effect of saw cutting
- Effect of w/cm
- Effect of air content
- Factors that influence interfacial transition zone

The work was conducted in three phases and individual reports were developed to discuss each phase. These reports are included as Appendices. The work conducted and findings are summarized below.

Phase 1 – Air Entraining Admixture, Fly Ash, Deicing Salt and Saw Cutting

A limited set of concrete mixtures was prepared and samples were exposed to a freezing and thawing environment in accordance with ASTM C 666 Method A. The full report is in Appendix E. The base mixture was an Iowa DOT C-4 WRC mixture as used in some locations where the distress has been observed.

The following parameters were varied:

- Type of air entraining admixture: vinsol, tall-oil
- Class C fly ash content: 0% and 15%
- Half of the samples were cured in water for 14 days before drying was started, and half were sprayed with curing compound when de-molded and left in the laboratory environment
- Solutions in test cell: water, 3% NaCl

Samples prepared included 3 x 4 x 12 in. beams. A shallow saw cut was cut into the top face of each of the beams to model the sawing conducted in pavements in which distress is sometimes observed. Sawing was conducted 24 hrs after casting. The idea was to investigate whether exposing the aggregate surface may be contributing to the accelerated distress.

A visual rating was also determined for the formed, finished (top) and sawn faces of the beams after 300 cycles of freezing and thawing were completed. The rating was based on the approach used in ASTM C 672, where a 5 denotes extensive damage and a 1 denotes very little to no damage.

The greatest distress was observed in the samples that had been wet cured and tested in salt. While the effect of the salt is not surprising, the poor performance of the wet-cured samples is somewhat surprising. It is likely that, because the wet-cured samples were dried in air for 14 days before testing, they were more likely to absorb salt solution when testing was initiated than the samples coated with curing compound. This is supported by the distress occurring only in the salt-solution exposure.

Only one set tested in water showed any distress (Vinsol, wet cured, 0% fly ash) and the amount of distress was small. In general, the salt solution was more aggressive than water.

Little effect can be observed with respect to the effects of using fly ash or the type of admixture in the mixtures.

It is notable that the formed surface seemed to incur more damage than the other surfaces, while the sawn surface performed well.

Phase 2 – w/cm, Air Content, Solution Depth

The mechanisms evaluated with this phase include the following:

- Effect of w/cm
- Effect of air content
- Effect of exposure to salt solution

A set of concrete mixtures was prepared and samples were exposed to a freezing and thawing environment in accordance with ASTM C 666 Procedure A, except the beams were under 3% calcium chloride solution instead of fresh water. The full report is included in Appendix F.

The depth of solution was limited to half the depth of the beams to evaluate whether samples need to be fully immersed to display distress.

The following parameters were varied:

- w/cm: 0.4 and 0.6
- Target air content: 3% and 6%
- Half the depth of each beam was in salt solution and the other half in air

After cycling, a sample of the mixture with w/cm of 0.55 and air content of 5.5% was cut out and examined in a scanning electron microscope (SEM).

The mass change data show that the higher w/cm mixture gained about the same weight initially and this was somewhat higher than the low w/cm mixtures, as expected. Subsequently, the greatest distress occurred in the samples containing a low w/cm and low air content. Little difference was observed among the other mixtures at the end of the cycling. The poor performance of the low w/cm and low air content mixture is likely because the laboratory staff later reported difficulty in consolidating those samples.

The visual rating shows, as expected, that the wet portion of the sample has more distress than the dry portion of the samples and the bottom side of the samples has the most distress. What is interesting is that this indicates that the degree of saturation is not above critical levels more than a fraction of an inch above the water level. This is despite the extremely high capillary suction or wicking that may be expected in the size of pores in hydrated cement paste.

It was noted that material loss was primarily in the paste, leaving the coarse aggregate particles clean. This finding is consistent with field observations.

The aim of the SEM work was to assess whether the solution had penetrated the system through the bulk past or preferentially through the interfacial zone around coarse aggregate particles. This was achieved by elemental mapping and looking at chlorides that would have come from sources external to the sample. Both the chlorine and calcium maps show a lighted area around the aggregate, indicating that the salt solution is concentrated in the interfacial zone.

Phase 3 – Interfacial Transition Zone (ITZ)

A suite of tests was conducted to investigate the significance of the interfacial transition zone on the distress. The full report is included in Appendix G. The factors that influence the ITZ include the following:

- Silica fume
- w/c
- Aggregate type

The following parameters were varied:

- w/cm: 0.4 and 0.5
- Binder: 0, 3 and 5% silica fume
- Coarse aggregate: round gravel and crushed limestone

The following tests were conducted:

- ASTM C 666 Procedure A freeze-thaw resistance. 3% sodium chloride solution was applied to the beams with gravel aggregate at high w/cm without silica fume and limestone aggregate at low w/cm with high silica fume content
- Air permeability (University of Cape Town Method) on finished surface and sawn surface
- ASTM C1585 sorption tests on finished surface and sawn surface

A visual rating was also determined for the sawn and formed surface of the beams after 600 cycles of freezing and thawing were completed. The rating was based on the approach used in ASTM C 672, where a 5 denotes extensive damage and 1 denotes very little to no damage.

Slices were cut from samples after 600 cycles. These slices were vacuum-saturated in sodium chloride; then, 0.1 M silver nitrate was applied. The aim was to observe how solutions would penetrate the different mixtures.

Concrete mixtures with higher w/cm ratios exhibited higher absorption and higher air permeability. High w/cm samples also exhibited more salt accumulation around aggregate particles, greater distress, and greater tendency for cracks to go around the aggregate. Surprisingly, the higher w/cm mixtures performed slightly better in the freeze-thaw testing. It is possible that this is associated with consolidation difficulties associated with the dry mixtures.

Concrete mixtures with limestone aggregate showed significantly higher durability than the mixtures with gravel aggregate, but this is likely due mainly to a significant effect of popouts from porous materials in the gravel.

The effects of the silica fume were more significant in the mixtures containing gravel aggregate than those with limestone aggregate. Both absorption and air permeability were improved with increasing silica fume content in mixtures containing a high w/cm and gravel. No other trends were observed in effects on absorption and air permeability. No trend could be seen with respect to scaling as a function of the silica fume content.

Based on the visual ratings, the sawn faces of the samples exhibited more distress than the formed face of the samples.

The samples treated with silver nitrate showed a white ring around some of the aggregate particles. This finding seems to indicate that salt solution preferentially penetrated into the concrete through the interfacial zone.

The limestone aggregates show fewer rings than the sample made with gravel. The sample mixed with gravel also had a higher w/cm without any silica fume, with all factors likely leading to a more dominant interfacial zone.

A typical failure surface includes both cracks through and around aggregate particles. Failures around the aggregates are likely associated with the ITZ, because it is normally unusual to see

aggregates particles without paste adhering to them, unless the mechanism of stress is adjacent to the surface.

WETTING AND DRYING EFFECTS

It is clear that the movement/presence of moisture is a key factor in several of the distress mechanisms including those associated with freeze/thaw and/or physical salt attack. It has been hypothesized (Weiss and Nantung 2005) that deicing salts may increase the degree of saturation at joints over time. To fully understand the influence of fluid properties on the wetting and drying behavior of concrete a series of experiments were performed using aqueous solutions containing deicing salts. Specifically, fundamental wetting and drying properties were obtained for cementitious systems containing aqueous deicing salt solutions. The work compliments work that has shown that sealers may help to reduce the degree of saturation.

The main findings are as follows:

1. The presence of deicing salts alters the viscosity, water activity, surface tension and density of the solution. An experimental investigation was conducted to evaluate the change in these properties, analyzing salt solutions with different concentrations and compositions. Compared to the case of pure water, the presence of salt appears to increase surface tension, increase the viscosity, decrease the water activity (or equilibrium relative humidity) and increase the specific gravity.
2. A thermodynamic model was used to relate the equilibrium relative humidity (the humidity at which the system would start to dry) to the properties of the solution evaluated experimentally and to the pore structure. The equilibrium relative humidity resulted to be function of the concentration of the salt solution.
3. The properties of the liquid are known to influence the absorption process in concrete. Sorption tests and water re-absorption were performed using different aqueous solutions. The results showed that as the salt concentration increased, the rate of absorption and the total absorption were reduced proportionally with the square root of the ratio of surface tension and viscosity. The re-absorption tests conducted on samples previously wetted with different salt solution and then oven dried, revealed that pure water would enter in the system differently if salts was deposited in the pores. Therefore, the history of the samples plays a role on the fluid ingress mechanisms.
4. The influence of properties of the solution on drying processes was also studied. Desorption analysis were conducted on mortar samples submerged in calcium chloride, magnesium chloride and sodium chloride solutions with different concentrations. The results confirm a higher degree of saturation of the material in presence of salts. This effect was shown to be function of the salt composition and of the concentration of the solution.

It was also noticed that samples with salt concentrations do not show a reduction in sample mass until the RH decreases below an equilibrium relative humidity, RH_{eq} . In fact, samples may gain mass at high RH due to the hygroscopic nature of the salt. As a result, samples containing deicing salt solutions are likely to have a higher degree of saturation than samples without deicing salt solutions in practice. This is especially true when drying and wetting occur. The initial DOS of the sample was also proved to be important for fluid transport tests. Some sorption tests were conducted using samples conditioned differently (at 50% RH, 65% RH and 80% RH). The results showed that the higher the initial moisture content (or DOS), the lower the water absorbed and the rate of absorption.

5. The non-linear moisture diffusion coefficient was also evaluated from the desorption analysis data. The experimental data were able to be fitted using the model proposed by Xi et al. (1994) and they show a clear trend when adding deicing salt in the system, compared to the case of pure water. The diffusivity versus relative humidity curves tend to shift to lower RH values and to cover a narrower range of humidities starting from the equilibrium relative humidity.

The results of this study show the importance of considering the properties of solutions when describing fluid transport processes. This suggests also that particular care must be taken when performing field tests on concrete exposed to deicing salts. Furthermore, this illustrates the potential benefits of sealers that can keep deicing salts out of the pores in concrete.

These findings were published as technical papers referenced in Appendix H.

DISCUSSION

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

Based on the findings of this work, the following points are noted:

- Different forms of failure are observed in different locations. This appears to be related to the details of the system, including the type and permeability of the base, the effectiveness of the seal in the joint, and the type of aggregate in the mixture, among many others.
- Distress is almost always a combination of marginal factors rather than a single bad parameter. These include the following:
 - Locally saturated concrete
 - Air content below 5%
 - w/cm above 0.4
 - Aggressive salting
 - Marginal or slowly D-cracking aggregates
- Shadowing and typical freeze-thaw damage are associated with saturated conditions and often marginal air void systems.

- Deicing salts strongly affect the wetting and drying rates of concrete systems, leading to greater potential for saturation.
- There is a form of the distress in which wedges are broken off the joint face, which is likely associated with effects of the interfacial transition zone.
- It is not uncommon to see signs of distress in the joint face that is not observed on the top surface. This occurrence is likely related to a combination of ponding, salts collecting in the joints, and differential permeability between the faces.

The effects of deicing salts are likely the tipping point, explaining why this is perceived as a relatively new phenomenon. It is likely that this form of distress has been occurring for a long time, but the change in salting practices have made it more common and, therefore, more notable than before.

These recommendations can now be made regarding best practices that will reduce the risk of problems:

- Ensure an adequate air-void system behind the paver.
- Use a w/cm below 0.4.
- Consider applying topical sealants to the joint.
- Ensure that all of the design details prevent water or salt solution from ponding in the joint.
- Use only as much salt as needed for safety. Avoid non-NaCl salts unless dictated by safety or traffic needs.

FUTURE WORK

Additional work is still needed to address some outstanding questions:

- The ettringite debate needs to be settled:
 - Which came first – the ettringite or the damage?
 - Do ettringite deposits compromise effectiveness of the air voids?
- Do air voids fill with water under normal conditions?
- How do we measure saturation in situ?
- Is there a critical pore size as there is in D-cracking aggregates?
- Can we improve the IFZ cost effectively?
- When and how do we seal joints when distress starts?
- When and how do we initiate repairs?

In addition, there is a need to educate practitioners on the current state of knowledge. This would include the following:

- Collecting data on new pavements built using the guidelines above and monitoring them over time.

- Workshops, seminars, and webinars targeted at local and state paving engineers.
- Visits and individual meetings with local authorities observing distress.

OTHER IMPACTS

A Guidance document, aimed at practitioners, has been published that discusses the distress mechanisms and makes recommendations to prevent further problems. This guide is currently being revised based on new findings. Another document is also being prepared that discusses applications of using overlays as a repair approach.

A number of students at Purdue and Iowa State University have been engaged in this work leading to graduates with advanced degrees in concrete pavement technology. Papers related to this work are included in the Bibliography.

Presentations have been made on the subject to at least 13 workshops in eight states.

BIBLIOGRAPHY

- Arribas-Colón, M., Radliński, M., Olek, J., and Whiting, N., (2010) “Investigation of Premature Distress Around Joints in PCC Pavements - Phases I and II,” *JTRP* 3016.
- Castro, J. Bentz, D., and Weiss, W. J., (2011) “Effect of Sample Conditioning on the Water Absorption of Concrete,” *Cement & Concrete Composites*, 33, 805–813.
- Coates, K., Mohtar, S., Tao, B., and Weiss, W. J., (2009) “Can Soy Methyl Esters Reduce Fluid Transport and Improve the Durability of Concrete?” *Transportation Research Record: Journal of the Transportation Research Board*, No. 2113, pp. 22-30.
<http://trb.metapress.com/content/94080g3q6n60l60x/>
- Golias, M., Castro, J., Peled, A., Nantung, T. Tao, B., and Weiss, J. (2012). Can Soy Methyl Esters Improve Concrete Joint Durability? Transportation Research Board (TRB) 91st Annual Meeting, Washington, DC. Paper #12-1656.
<http://trid.trb.org/view.aspx?id=1129365>
- Li, W., Pour-Ghaz, M., Castro, J., and Weiss, W. J. (March 2012) “Water Absorption and the Critical Degree of Saturation as it relates to Freeze-Thaw Damage in Concrete Pavement Joints,” *ASCE Journal of Civil Engineering Materials*. Vol. 23, No. 3, pp. 299-307.
- Pour-Ghaz, M., Castro, J. E., Rajabipour, F., and Weiss, W. J., (2009). Measurement and Modeling Fluid Transport in Cracked Concrete. International RILEM Conference on Concrete Durability and Service Life Planning. Concrete Life '09, Haifa, Israel.
- Pour-Ghaz, M., Rajabipour, F., Couch, J. B, and Weiss, J., (2010) “Numerical and Experimental Assessment of Unsaturated Fluid Transport in Saw-Cut (Notched) Concrete Elements,” *ACI Special Publication*.
- Raoufi, K., Radlinska, A., Nantung, T., and Weiss, W. J., (2008) “Practical Considerations to Determine the Time and Depth of Saw-Cuts in Concrete Pavements,” *TRB*.
- Raoufi, K., Weiss, J., and Nantung, T., (2008) Numerical Assessment of Saw-Cutting: The Influence on Stress Development and Cracking. 6th RILEM International Conference on Cracking in Concrete Pavements, Chicago, IL.

- Raoufi, K., Nantung, T. E., and Weiss, W. J., (2010) “Numerical Analysis Of Saw-Cutting: The Influence Of Environmental Conditions,” *ACI Special Publication*.
- Raoufi, K., Their, T., Weiss, J., Olek, J. and Nantung, T. (2009), *Saw-Cutting Guidelines for Concrete Pavements: Examining the Requirements for Time and Depth of Saw-Cutting*, Final Report, FHWA/IN/JTRP-2007/5, Joint Transportation Research Program.
- Spragg, R., Castro, J., Li, W., Pour-Ghaz, M., Huang, P., and Weiss, W. J. (2011). “Wetting and Drying of Concrete in the Presence of Deicing Salt Solutions,” *Cement and Concrete Composites*, Volume 33, Issue 5, May, Pages 535-542.
- Spragg, R., Castro, J., Nantung, T., Paredes, M., and Weiss, J., (2011). *Variability Analysis of the Bulk Resistivity Measured Using Concrete Cylinders*. Internal Report.
- Taylor, P. C., Rasmussen, R. O., Torres, H., Fick, G., Harrington, D., Cackler, E. T., *Interim Guide for Optimum Joint Performance of Concrete Pavements*, Ames IA, National Concrete Pavement Technology Center, September 2011.
- Villani, C., Spragg, R., Pour-Ghaz, M. and Weiss, W. J., *The Role of Deicing Salts on the Non-Linear Moisture Diffusion Coefficient of Cementitious Materials During Drying*, 10th International RILEM Symposium on Brittle Matrix Composites, 15-17 October 2012, Warsaw, Poland
- Zhang, J., and Taylor, P. (2012). Investigation of the Effect of the Interfacial Zone on Joint Deterioration of Concrete Pavements. International Conference on Long-Life Concrete Pavements 2012, Seattle, WA.

APPENDICES

Appendices complete this report as follows:

- A Investigation of Localized Joint Deterioration in Eau Claire, Wisconsin
- B Investigation of Localized Joint Deterioration in Ames, Iowa
- C Investigation of Localized Joint Deterioration in Ankeny, Iowa
- D Investigation of Localized Joint Deterioration in Minnesota
- E Investigation of Effects of Admixture Type and Fly Ash on Freeze-Thaw Durability of Concrete
- F Investigation of Effects of Water/Cementitious Mixture Ratio, Air Content, and Tidal Zone on Freeze-Thaw Durability of Concrete
- G Investigation of Effects of Interfacial Zone on Freeze-Thaw Durability of Concrete
- H Wetting and Drying Effects

APPENDIX A. INVESTIGATION OF LOCALIZED JOINT DETERIORATION IN EAU CLAIRE, WISCONSIN

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INTRODUCTION

The aim of the work described in this report is to continue collecting information about potential causes of joint deterioration by looking at appropriate field examples.

Reports have been received from projects in several Midwest states that concrete, at joints, is deteriorating prematurely in various types of pavement from 5 to 30 years old.

It is likely that several mechanisms are contributing to the distress at the same time and possible that different deterioration locations are the result of different combinations of these mechanisms.

The work in this report covers an investigation of localized damage occurring on city streets in Eau Claire, Wisconsin.

BACKGROUND

The intersection of First Avenue and Grand Avenue is in a local commercial area. It is a lightly-trafficked T junction. Distress was easily observed in the joints (Figures 1 and 2) on Grand Avenue, but not as apparent on First Avenue.



Figure 1. Grand Avenue



Figure 2. Distress in transverse joint

Reportedly, both streets were built in 1997 and comprise 7 in. concrete on a selected fill base. Grand Avenue was built using a slipform paver, while First Avenue used a bridge-deck paver.

Four cores were extracted in 2011. Two cores were taken at or near a joint on Grand Avenue and another mid-panel from each street. The intent was to investigate why one street appeared to be performing well while the other was not.

PETROGRAPHIC DATA

The full petrographic report is included. The findings may be summarized as follows:

- Both mid-panel cores appeared in good condition.
- Both joint cores showed distress.
- FG2 shows distress at the top of the core while FG1 shows distress at the bottom. The latter is surprising, because it is presumed that the base would drain water away from the bottom of the slab. During coring, it was noted that the water in the hole at FG1 drained quickly while that in FG2 did not. This is contrary to the distress pattern.
- There is evidence of chemical attack near the surface of the joints, likely due to use of deicing salts other than sodium chloride. The form and details of the chemical attack are unknown.

- Both cores at joints show signs of air voids being filled with ettringite. It is notable that this has not occurred in the mid-panel cores, indicating that the saw cuts are significantly more permeable than the top surfaces and/or the joints are acting as reservoirs.
- All of the concrete exhibited satisfactory air content at the time of placing.
- There are signs of extensive carbonation pointing to inadequate curing.

DISCUSSION

This work raises some interesting questions:

- Why are there signs of water retention in a system that should drain?
- Why is one core distressed at the bottom and the other at the top?
- What is the form of the reported chemical attack?

Work is continuing to address these questions.

It is noted in one of the images, FG1 shows cracking propagating around the coarse aggregate (Figure 3).



Figure 3. Cracks concentrated adjacent to the coarse aggregate in FG1

This finding is consistent with the hypothesis that water/salt solutions are penetrating the interfacial zone around coarse aggregate particles and accelerating distress in local zones remote from the face of the joint. The concept is being investigated in the laboratory.

PETROGRAPHIC REPORT

The site report follows in this appendix.

REPORT OF CONCRETE ANALYSIS

PROJECT:

Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

ATTN: Larry Sutter, PhD

AET PROJECT NO: 24-00425

DATE: June 28, 2012

INTRODUCTION

This report presents the results of laboratory work performed by our firm on four concrete core samples submitted by Larry Sutter, PhD, of the MI Tech Transportation Institute on December 28, 2011. We understand three cores were obtained from distressed concrete pavement on Grand Avenue in Eau Claire, Wisconsin. A fourth core was obtained from a less distressed First Avenue as a comparison. Both pavements were reportedly placed in 1990. Deicer exposure reported includes sodium chloride rock salt pre-wetted with calcium chloride solution. The scope of our work was limited to performing petrographic analysis on the four core samples to document the general overall quality, composition, and condition of the concrete cores.

CONCLUSIONS

Based on our observations and testing, we believe:

1. The cause of the joint distress in cores FG1 and FG2 is a yet fully described chemical attack by deicers other than sodium chloride. The distress is characterized by an obvious chemical alteration of the concrete paste exposed within the likely saturated joint. Concentrated, anastomosing microcracking within this still-intact paste generally within 4mm of the spalled near-vertical joint surface, and unlike that typically associated with freeze-thaw action, is currently devoid of secondary minerals other than thin veneers of calcium carbonate. Calcium carbonate is an innocuous mineral. Both concretes were well consolidated and were purposefully air entrained. FG1 and FG2 contain a significantly fine and large volume air void system considered freeze-thaw resistant under severe exposure conditions. Secondary ettringite and portlandite fills most air voidspaces with several millimeters of the distress plane. Additional, more widespread microcracking, typical of freeze-thaw distress, intersects previously ettringite-filled and unfilled voidspaces to 25mm depth from the distress.

2. The semi-intact concrete paste within at most, 8mm of the joint distress, exhibits a lighter, tannish coloration. The paste is mostly carbonated and exhibits "bi-carbonation", a coarser mosaic of calcium carbonate-like material, within a few millimeters of the joint surface. Calcite spar occurs within air voids with ettringite or as a replacement of the now typically unstable calcium sulfo-aluminate in the lower pH carbonated paste. The portland cement is fully hydrated in this zone. Ferrite phase of the portland cement is lighter in coloration than the body of the concrete in this paste; exhibiting a "leached" appearance. Some occurrences of fractured masses of non-carbonated paste mostly devoid of portlandite were also present at the distress.
3. Core FG1 was centered and taken directly through a silicone sealed, sawcut control joint. The top surface of the core exhibited minor mortar erosion. The silicone sealant was intermittently de-bonded on both side of the joint and the sawcuts were in relatively pristine condition; apart from "rounding" and wear of the top surface edges. The distress in core FG1 is confined to mass lost, incipient vertical spalling, and altered paste generally below the depth of the greatest extent of the pilot sawcut of the jointing (53mm). The greatest mass loss of approximately 15mm of concrete occurs between approx. 105mm and 135mm depth in the core. The greatest extent of incipient distress (vertical spalling) occurs generally below 142mm depth in the joint and becomes more horizontal in orientation within 30mm of the bottom surface of the core.
4. Core FG2 was taken offset from the joint and no evidence of the resulting joint crack was intersected. The distress in the core was characterized by a loss of the top surface of the concrete at an approx. 45° to 50mm depth into the joint. Incipient damage, in a similar orientation, extends to 106mm depth into the core. No evidence of sawcutting or joint sealant remains with the sample.
5. In general, the coarse and fine aggregate was hard, sound, and durable and is not participating in any level of distress of the concrete joint. No evidence of alkali-silica reactivity (ASR) was observed.
6. The concrete represented by the cores was placed at a "moderate" w/cm; estimated to be between 0.44 and 0.50. Core FG4 contained flyash as a replacement of portland cement. The replacement was visually estimated at 10-15%. The estimated w/cm's were judged to be excessive for concrete paving. The superfluous porosity of the pastes, when compared to other lower w/cm pavements, allow greater ingress of water and brines and greater susceptibility to physical and chemical attack.

7. The mid-panel concrete cores FG3 and FG4 generally exhibit no distress other than surface traffic wear and aggregate exposure. The cores do exhibit significant "craze cracking" reflecting into a few sub-vertical drying shrinkage microcracks proceeding up to a 51mm (2") maximum depth. The cracking and significantly deep carbonation along it is a result of excessive early age drying due to inadequate curing and protection against evaporation. Weathering and traffic wear will expose and wear the edges of the microcracking and make them more obvious with age. There is no evidence of any other expansive reactions in the concrete other than at the joints.

SAMPLE IDENTIFICATION

Sample ID:	FG1 Grand Ave.	FG2 Grand Ave.	FG3 Grand Ave.	FG4 First Avenue.
Sample Type:	145mm (5 3/4") Diameter Hardened Concrete Cores			
Sample Lengths:	195mm (7 3/4")	195mm (7 3/4")	195mm (7 3/4")	165mm (6 1/2")

TEST RESULTS AND SUMMARY OF GENERAL CONCRETE PROPERTIES

Our complete petrographic analysis documentation appears on the attached sheets entitled 00 LAB 001 "Petrographic Examination of Hardened Concrete, ASTM:C856." A brief summary of these results is as follows:

1. The coarse aggregate in all four cores was comprised of 37mm (1 1/2") nominal sized natural glacial gravel that appeared generally well graded and exhibited fair to good overall distribution. The coarse aggregate is consistent with typical Lake Superior Lobe glacial deposits and is composed chiefly of rhyolite, granite, gneiss, basalt, quartzite, sandstone, chert, and graywacke. The fine aggregate was a natural glacial sand composed chiefly of quartz and feldspar with many lithic fragments consistent in composition with the coarse aggregate.
2. The paste color in cores FG1, FG2, and FG3 was generally light tannish gray. Core FG4 exhibits a slightly "grayer" coloration. The paste hardness in all four cores was judged to be "moderately hard" with the paste/aggregate bond generally considered fair to poor.
3. The original top surface condition of the four cores was generally roughly screeded and tined or deeply broomed. Mortar erosion and /or traffic wear has exposed fine aggregates, and in the case of core FG4, several coarse aggregate surfaces. Overall, the depth of carbonation ranged from negligible up to a 16mm maximum depth, intermittently, from the top surface of core FG4. Carbonation in all cores "spikes" significantly deep along sub-vertical drying shrinkage microcracking.

4. The w/cm of cores FG1, FG2, and FG3 was similar and estimated to be between 0.44 and 0.50 with approximately 6 to 9% residual portland cement clinker particles. Portland cement hydration was very advanced. The w/cm of core FG4 was estimated to be between 0.44 and 0.49 with approximately 6 to 8% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 – 15% replacement of portland cement.

Air Content Testing

Sample ID	FG1	FG2	FG3	FG4
Total Air Content (%)	8.3	9.3	9.4	6.0
“Entrained” Air (%) voids < 1mm (0.040”)	8.2	9.2	8.0	5.6
“Entrapped” Air (%) voids > 1mm (0.040”)	0.1	0.1	1.4	0.4
Spacing Factor, in.	0.002	0.002	0.002	0.003

TEST PROCEDURES

Laboratory testing was performed on December 28, 2012 and subsequent dates. Our procedures were as follows:

Petrographic Analysis

A petrographic analysis was performed in accordance with Standard Operating Procedure 00 LAB 001, “Petrographic Examination of Hardened Concrete,” ASTM:C856-latest revision. The petrographic analysis consisted of reviewing the cement paste and aggregate qualities on a whole basis on sawcut and lapped, and fractured sections. Reflected light microscopy was performed under an Olympus SZX-12 binocular stereozoom microscope at magnifications up to 160x. The depth of carbonation was documented using a phenolphthalein pH indicator solution applied on freshly sawcut and lapped surfaces of the concrete sample. The paste-coarse aggregate bond quality was determined by fracturing a sound section of the concrete in the laboratory with a rock hammer.

The water/cementitious of the concrete was estimated by viewing a thin section of each concrete core under an Olympus BX-51 polarizing light microscope at magnifications of up to 1000x. Thin section analysis was performed in accordance with Standard Operating Procedure 00 LAB 013, “Determining the Water/Cement of Portland Cement Concrete, APS Method.” An additional, smaller, sawcut subdivision of the concrete sample is epoxy impregnated, highly polished, and then attached to a glass slide using an optically clear epoxy. Excess sample is sawcut from the glass and the thin slice remaining on the slide is lapped and polished until the

concrete reaches 25 microns or less in thickness. Thin section analysis allows for the observation of portland cement morphology, including: phase identification, an estimate of the amount of residual material, and spatial relationships. Also, the presence and relative amounts of supplementary cementitious materials and pozzolans may be identified and estimated.

Air Content Testing

Air content testing was performed using Standard Operating Procedure 00 LAB 003, “Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete, ASTM:C457-latest revision.” The linear traverse method was used. The concrete core was sawcut perpendicular with respect to the horizontal plane of the concrete as placed and then lapped prior to testing.

REMARKS

The test samples will be retained for a period of at least sixty days from the date of this report. Unless further instructions are received by that time, the samples may be discarded. Test results relate only to the items tested. No warranty, express or implied, is made.

Report Prepared By:

Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: FG1

Date: June 28, 2012
Performed by: G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on both lapped sides of a 195mm (7 3/4") x 145mm (5 3/4") x 39mm (1 1/2") thick lapped section and a 76mm (3") x 52mm (2") thin section that were sawcut and prepared from the original 145mm (5 3/4") diameter x 195mm (7 3/4") long core.
2. Surface Conditions:
Top: Fairly rough screeded and tined surface with mortar erosion exposing fine aggregates.
Bottom: Rough, irregular formed surface; placed on sub-grade.
3. Reinforcement: None observed.
4. General Physical Conditions: The core was taken directly through a sawcut control joint. The sawcutting included an approx. 5mm wide pilot cut to 50mm depth and an 11mm wide by 28mm deep reservoir cut centered over the pilot cut. A white silicone sealant is intermittently de-bonded from both sides of the joint. The concrete exhibits fair overall condition. Significant vertical spalling and incipient spalling occurs along the joint crack from the depth of the sawcut to the subgrade with the greatest loss of concrete to 15mm width occurring between approx. 105mm and 135mm depth and below 165mm depth in the joint. Paste along the distressed joint below 70mm depth and generally within 4mm of the present joint face is characterized by a light tan coloration, and is significantly softer than the body of the concrete. The paste has a "leached" or chemically altered appearance. This zone contains highly concentrated, anastomosing microcracking, oriented sub-parallel to the joint plane. The paste is mostly carbonated and the cracking is thinly lined by apparent calcite. Most all fine air voids within 6mm of the present joint face are filled or partly filled with secondary ettringite. Calcite replaces ettringite in many voids within approx. 2mm of the joint. Several other microcracks were observed oriented sub-parallel to the joint crack and up to 25mm depth from it; below 100mm depth in the core. The cracking generally proceeds through the paste. However, a single microcrack bisects a coarse granit particle.

The concrete was very well consolidated, with an entrapped sized voidspace volume of 0.1%. No voids were observed in the core in excess of 3mm in diameter. The concrete was purposefully air entrained and contains a very fine air void system (0.002" spacing factor) considered freeze-thaw resistant under severe exposure conditions. Darker colored, denser paste containing less air entrainment, observed in many concave coarse aggregate notches, suggests the concrete was tempered after initial batching and mixing.

II. Aggregate

1. Coarse: 36mm (1 1/2") nominal sized naturally occurring glacial gravel composed chiefly of rhyolite, granite, gneiss, basalt, quartzite, sandstone, chert, and graywacke. The coarse aggregate appeared well graded and exhibited fair to good overall distribution.
2. Fine: Natural quartz, feldspar, and lithic glacial sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 8.3% total
2. Depth of carbonation: Ranges from 2mm up to 9mm depth from the mortar-eroded top surface. Ranges from negligible up to 10mm depth from the distressed joint plane generally below 50mm depth in the core.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Fair to poor.

5. Paste color: Very light tannish gray; becoming light tan in the up to 8mm of altered paste directly adjacent to the spalled joint crack plane.
6. Paste hardness: Overall, moderately-hard (Moh's 3). Soft in the up to 8mm of paste directly adjacent to the spalled joint crack plane.
7. Microcracking: Several, fine, sub-vertical shrinkage microcracks proceed up to a 9mm maximum depth from the top surface. Relatively wide, highly concentrated, anastomosing microcracking, oriented sub-parallel to the joint plane, generally occurring within approx. 4mm of the spalled joint crack plane. Several other microcracks were observed oriented sub-parallel to the joint crack and up to 25mm depth from it; below 100mm depth in the core. A single microcrack, intersecting these microcracks, is oriented sub-parallel to the bottom surface between approx. 157mm and 187mm depth in the core.
8. Secondary deposits: Needly ettringite thin lines, partly fills or fills many fine entrained sized voids with acicular clumps throughout the core; with concentrations of fillings in the approx. 8mm of paste directly adjacent to the spalled joint crack plane. Portlandite commonly fills or partly fills some of the finest entrained sized air voids scattered in the core also. Calcite crystals partly fill fine entrained-sized voidspaces within the altered, microcracked, and carbonated paste generally within a few millimeters of the spalled joint crack plane. Fine calcium carbonate lines microcracking in this altered paste also.
9. w/cm: Estimated at between 0.44 and 0.49 with approximately 7 to 9% residual portland cement clinker particles.
10. Cement hydration: Alites: Mostly fully.
Belites: Mostly fully.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: FG2

Date: June 28, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** Our analysis was performed on both lapped sides of a 195mm (7 3/4") x 145mm (5 3/4") x 45mm (1 3/4") thick lapped section and a 76mm (3") x 52mm (2") thin section that were sawcut and prepared from the original 145mm (5 3/4") diameter x 195mm (7 3/4") long core.
2. **Surface Conditions:**
Top: Fairly rough screeded and tined surface with traffic wear and minor mortar erosion exposing fine aggregates.
Bottom: Rough, irregular formed surface; placed on sub-grade.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core was apparently taken directly adjacent to a distressed joint. No sawcutting or joint crack was intersected by the core. However, the core exhibits moderately-angled (approx. 45°) spalling and incipient spalling (micro and macrocracking) to 106mm depth from the top surface of the core and generally within 25mm of the spalled surface. A loss of concrete extends to approx. 50mm (2") depth along the cored perimeter of the sample. Numerous microcracks, oriented sub-parallel to the joint plane, were observed in the past-only and within approx. 4mm of the spalled surface plane. Several other, less concentrated micro and macrocracks were observed oriented sub-parallel to the spalled surface and up to 25mm depth from it. Fractured, "bi-carbonated" concrete fragments up to 3mm in sized appear poorly cemented by calcite and reside in topographic lows in the spalled face of the core. Most all fine air voids within 6mm of the spalled face are filled or partly filled with secondary ettringite linings or acicular growths. The amount of ettringite within voids decrease with distance from the distress.

The concrete was very well consolidated, with an entrapped sized voidspace volume of 0.1%. No voids were observed in the core in excess of 6mm in diameter. The concrete was purposefully air entrained and contains a very fine air void system (0.002" spacing factor) considered freeze-thaw resistant under severe exposure conditions. Darker colored, denser paste containing no air entrainment, observed in many concave coarse aggregate notches, suggests the concrete underwent multiple stages of batching and mixing.

II. Aggregate

1. **Coarse:** 36mm (1 1/2") nominal sized naturally occurring glacial gravel composed chiefly of rhyolite, granite, gneiss, basalt, quartzite, sandstone, chert, and graywacke. The coarse aggregate appeared well graded and exhibited fair to good overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic glacial sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. **Air Content:** 9.3% total
2. **Depth of carbonation:** Ranges from <1mm up to 7mm depth from the mortar-eroded top surface. Ranged from 2mm up to 14mm, continuously, and up to 32mm depth, intermittently, along incipient spalling from the distressed plane.
3. **Pozzolan presence:** None observed.
4. **Paste/aggregate bond:** Fair to poor.
5. **Paste color:** Very light tannish gray (same as FG1); becoming light tan within the few mm of altered paste directly adjacent to the spalling.

6. Paste hardness: Overall, moderately-hard (Moh's 3). Soft (Moh's 2) in the up to 5mm of paste directly adjacent to the spalled joint crack plane.
7. Microcracking: Several, fine, sub-vertical shrinkage microcracks proceed up to a 7mm maximum depth from the top surface. Numerous microcracks, oriented sub-parallel to the joint plane, were observed in the past-only and within approx. 4mm of the spalled surface plane. Several other, less concentrated micro and macrocracks were observed oriented sub-parallel to the spalled surface and up to 25mm depth from it.
8. Secondary deposits: Needly ettringite thin lines, partly fills or fills many fine entrained sized voids with acicular clumps throughout the core; with concentrations of fillings in the approx. 6mm of paste directly adjacent to the spalled surface plane. Portlandite commonly fills or partly fills some of the finest entrained sized air voids scattered in the core; with a decrease in propensity with depth from the spalled surface.
9. w/cm: Estimated at between 0.45 and 0.50 with approximately 6 to 8% residual portland cement clinker particles.
10. Cement hydration: Alites: Mostly fully.
Belites: Mostly fully.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: FG3

Date: June 28, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** Our analysis was performed on both lapped sides of a 195mm (7 3/4") x 145mm (5 3/4") x 39mm (1 1/2") thick lapped section and a 76mm (3") x 52mm (2") thin section that were sawcut and prepared from the original 145mm (5 3/4") diameter x 195mm (7 3/4") long core.
2. **Surface Conditions:**
Top: Fairly rough screeded and tined or deeply broomed surface; with traffic wear and minor mortar erosion exposing fine aggregates.
Bottom: Rough, irregular formed surface; placed on sub-grade.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core was apparently taken at a mid-panel location. No sawcutting or joint crack was intersected by the core. The top surface of the core exhibits traffic wear; exposing and truncating fine aggregate particles. Carbonation ranges from a minimum of 1mm to a maximum of 8mm depth; "spiking" along sub-vertical drying shrinkage microcracking.

The concrete was well consolidated, with an entrapped sized voidspace volume of 1.4%. A few voids were observed in the core up to 12mm in diameter. The concrete was purposefully air entrained and contains a very fine air void system (0.002" spacing factor) considered freeze-thaw resistant under severe exposure conditions. Scattered fine voidspaces are filled or partly filled with secondary ettringite linings or acicular growths of ettringite. Darker colored, denser paste containing air entrainment and not containing air entrainment, observed in many concave coarse aggregate notches, suggests the concrete underwent multiple stages of batching and mixing.

II. Aggregate

1. **Coarse:** 36mm (1 1/2") nominal sized naturally occurring glacial gravel composed chiefly of rhyolite, granite, gneiss, basalt, quartzite, sandstone, chert, and graywacke. The coarse aggregate appeared well graded and exhibited fair to good overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic glacial sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. **Air Content:** 9.4% total
2. **Depth of carbonation:** Ranges from 1mm up to 8mm depth from the traffic-worn top surface; proceeding along sub-vertical shrinkage microcracking.
3. **Pozzolan presence:** None observed.
4. **Paste/aggregate bond:** Fair to poor.
5. **Paste color:** Very light tannish gray (same as FG1).
6. **Paste hardness:** Overall, moderately-hard (Moh's 3).
7. **Microcracking:** Several, fine, sub-vertical shrinkage microcracks proceed up to 5mm maximum depth from the top surface. One microcrack proceeds up to 51mm and another to 21mm depth from the top surface.
8. **Secondary deposits:** Needly ettringite thinly lines, partly fills or fills scattered, fine, entrained-sized voids with acicular clumps throughout the core.
9. **w/cm:** Estimated at between 0.45 and 0.50 with approximately 6 to 8% residual portland cement clinker particles.
10. **Cement hydration:** Alites: Well to fully.
Belites: Well to fully.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: FG4

Date: June 28, 2012
Performed by: G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on both lapped sides of a 165mm (6 1/2") x 145mm (5 3/4") x 39mm (1 1/2") thick lapped section and a 76mm (3") x 52mm (2") thin section that were sawcut and prepared from the original 145mm (5 3/4") diameter x 165mm (6 1/2") long core.
2. Surface Conditions:
Top: Fairly rough screeded and tined or deeply broomed surface; with traffic wear and mortar erosion exposing several coarse aggregates.
Bottom: Rough, irregular formed surface; placed on sub-grade.
3. Reinforcement: None observed.
4. General Physical Conditions: The core was apparently taken at a mid-panel location. No sawcutting or joint crack was intersected by the core. The top surface of the core exhibits traffic wear; exposing and truncating fine aggregate particles and several coarse aggregates. Carbonation ranges from negligible up to a maximum of 16mm depth, intermittently; "spiking" along sub-vertical drying shrinkage microcracking.

The concrete was very well consolidated, with an entrapped sized voidspace volume of 0.4%. No voidspaces >4mm in diameter were observed in the core. The concrete was purposefully air entrained and contains a very fine air void system (0.003" spacing factor) considered freeze-thaw resistant under severe exposure conditions. Scattered fine voidspaces are filled or partly filled with secondary ettringite linings or acicular growths of ettringite. Darker colored, denser paste not containing air entrainment, observed in several concave coarse aggregate notches, suggests the concrete underwent multiple stages of batching and mixing. An anomalous, sub-horizontally-oriented "swirl" of a couplet of lighter colored, softer, carbonated and excessive w/cm paste and darker colored, denser, lower w/cm paste (than the body of the core) occurs within 22mm of the top surface of the core. The anomaly was at least 41mm in diameter.

II. Aggregate

1. Coarse: 36mm (1 1/2") nominal sized naturally occurring glacial gravel composed chiefly of rhyolite, granite, gneiss, basalt, quartzite, sandstone, chert, and graywacke. The coarse aggregate appeared well graded and exhibited fair to good overall distribution.
2. Fine: Natural quartz, feldspar, and lithic glacial sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 6.0% total
2. Depth of carbonation: Ranged from negligible up to 16mm depth, intermittently, from the top surface; proceeding along sub-vertical shrinkage microcracking.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair to poor.
5. Paste color: Light tannish gray (slightly "grayer" than FG1, FG2, or FG3).
6. Paste hardness: Overall, moderately-hard (Moh's 3).
7. Microcracking: Several, fine, sub-vertical shrinkage microcracks proceed up to 4mm maximum depth from the top surface. One microcrack proceeds up to 42mm and another to 22mm depth from the top surface.
8. Secondary deposits: Needly ettringite thin lines, partly fills or fills scattered, fine, entrained-sized voids with acicular clumps throughout the core.
9. w/cm: Estimated at between 0.44 and 0.49 with approximately 6 to 8% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 to 15% replacement of portland cement.
10. Cement hydration: Alites: Well to fully.
Belites: Well.

AIR VOID ANALYSIS

PROJECT:

Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

AET PROJECT NO: 24-00425**ATTN:** Larry Sutter, PhD
DATE: June 28, 2012**Sample Number:**

FG1

Conformance:

The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

By ASTM C457

Description:

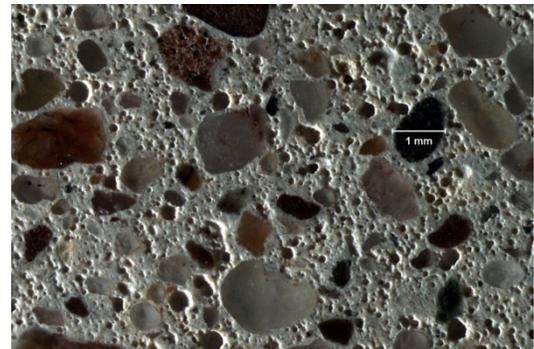
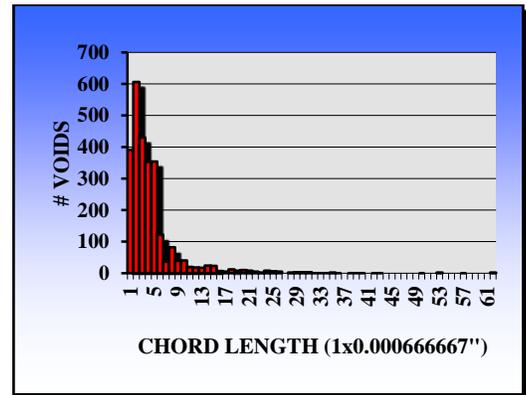
Hardened Concrete Core

Dimensions:

145mm (5 3/4") diameter by
195mm (7 3/4") long**Test Data:**

By ASTM C:457

Air Void Content %	8.3
Entrained, % < 0.040"(1mm)	8.2
Entrapped, % > 0.040"(1mm)	0.1
Air Voids/inch	26.6
Specific Surface, in ² /in ³	1280
Spacing Factor, inches	0.002
Paste Content, % estimated	18.1
Magnification	75x
Traverse Length, inches	100
Test Date	6/28/12



Magnification: 15x

Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:

Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

AET PROJECT NO: 24-00425**ATTN:** Larry Sutter, PhD**DATE:** June 28, 2012**Sample Number:**

FG2

Conformance:

The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

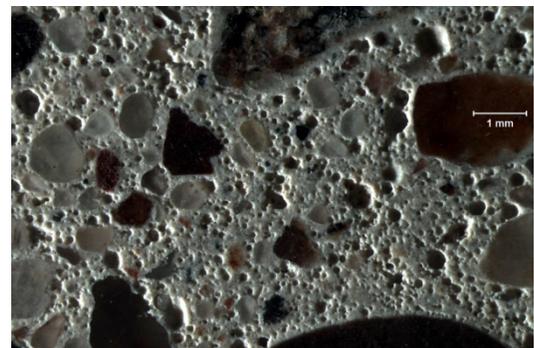
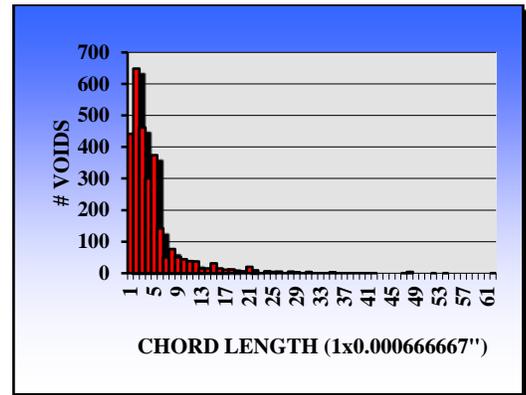
By ASTM C457

Description: Hardened Concrete Core

Dimensions: 145mm (5 3/4") diameter by
195mm (7 3/4") long**Test Data:**

By ASTM C:457

Air Void Content %	9.3
Entrained, % < 0.040"(1mm)	9.2
Entrapped, % > 0.040"(1mm)	0.1
Air Voids/inch	28.6
Specific Surface, in ² /in ³	1220
Spacing Factor, inches	0.002
Paste Content, % estimated	17.7
Magnification	75x
Traverse Length, inches	100
Test Date	6/28/12



Magnification: 15x

Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:

Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

AET PROJECT NO: 24-00425**ATTN:** Larry Sutter, PhD**DATE:** June 28, 2012**Sample Number:**

FG3

Conformance:

The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

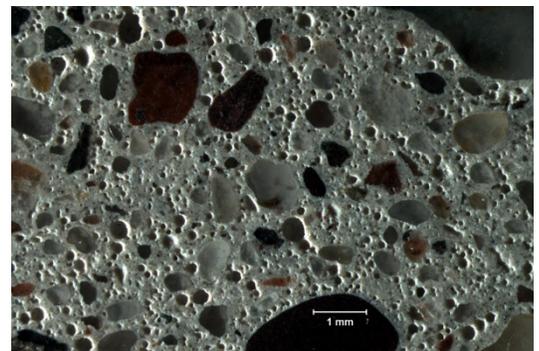
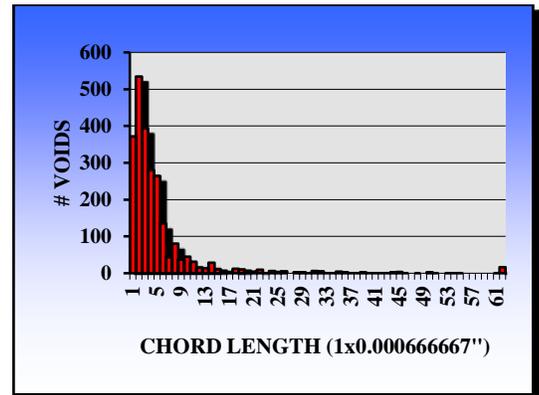
By ASTM C457

Description: Hardened Concrete Core

Dimensions: 145mm (5 3/4") diameter by
195mm (7 3/4") long**Test Data:**

By ASTM C:457

Air Void Content %	9.4
Entrained, % < 0.040"(1mm)	8.0
Entrapped, % > 0.040"(1mm)	1.4
Air Voids/inch	24.1
Specific Surface, in ² /in ³	1030
Spacing Factor, inches	0.002
Paste Content, % estimated	22.4
Magnification	75x
Traverse Length, inches	100
Test Date	6/28/12



Magnification: 15x

Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:

Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

AET PROJECT NO: 24-00425

ATTN: Larry Sutter, PhD

DATE: June 28, 2012

Sample Number:

FG4

Conformance:

The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

By ASTM C457

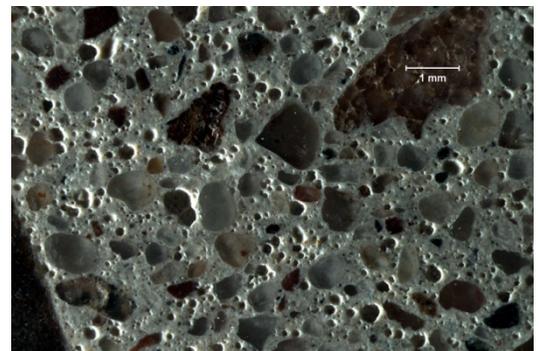
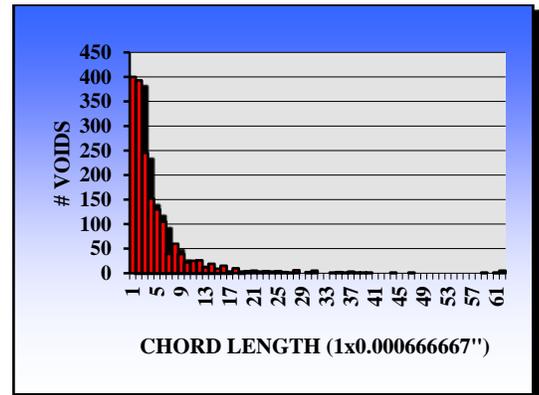
Description: Hardened Concrete Core

Dimensions: 145mm (5 3/4") diameter by
165mm (6 1/2") long

Test Data:

By ASTM C:457

Air Void Content %	6.0
Entrained, % < 0.040"(1mm)	5.6
Entrapped, % > 0.040"(1mm)	0.4
Air Voids/inch	24.1
Specific Surface, in ² /in ³	1180
Spacing Factor, inches	0.003
Paste Content, % estimated	19.1
Magnification	75x
Traverse Length, inches	100
Test Date	6/28/12



Magnification: 15x

Description: Hardened air void system.

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 1



SAMPLE ID: FG1 DESCRIPTION: Core sample taken directly through a joint as received. Top surface is left.

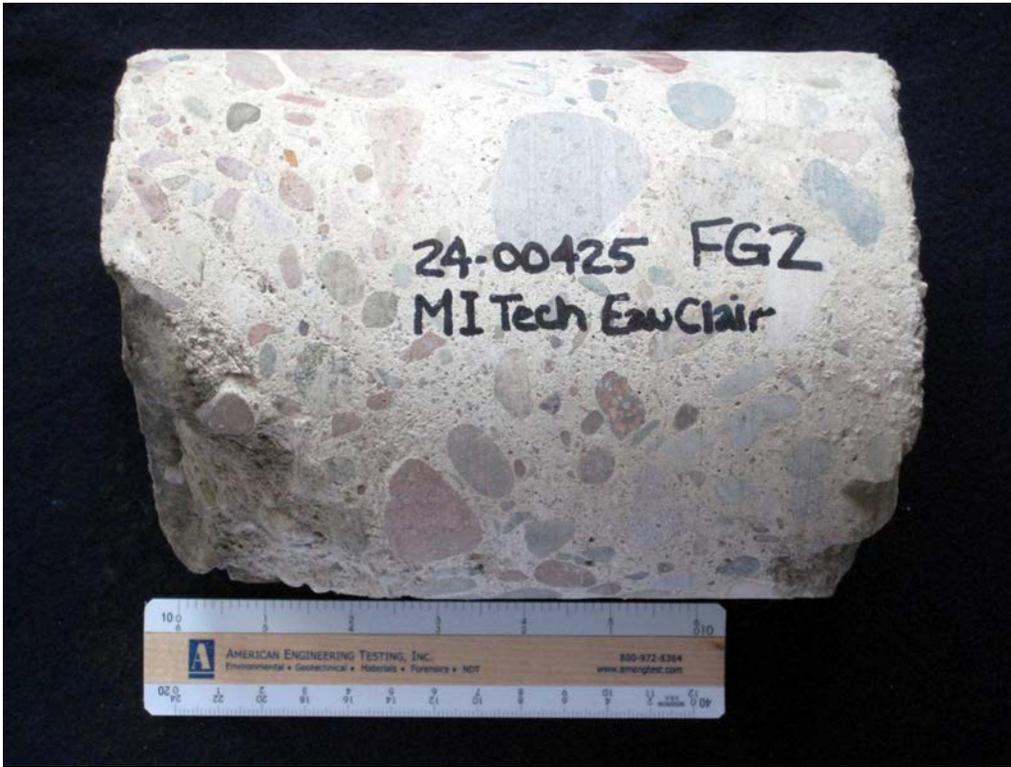
PHOTO: 2



SAMPLE ID: FG1 DESCRIPTION: Top surface of the core as received. Note core was taken through a sawcut and silicone sealed control joint.

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 3



SAMPLE ID: FG2 DESCRIPTION: Core sample taken directly through a joint as received. Top surface is left.

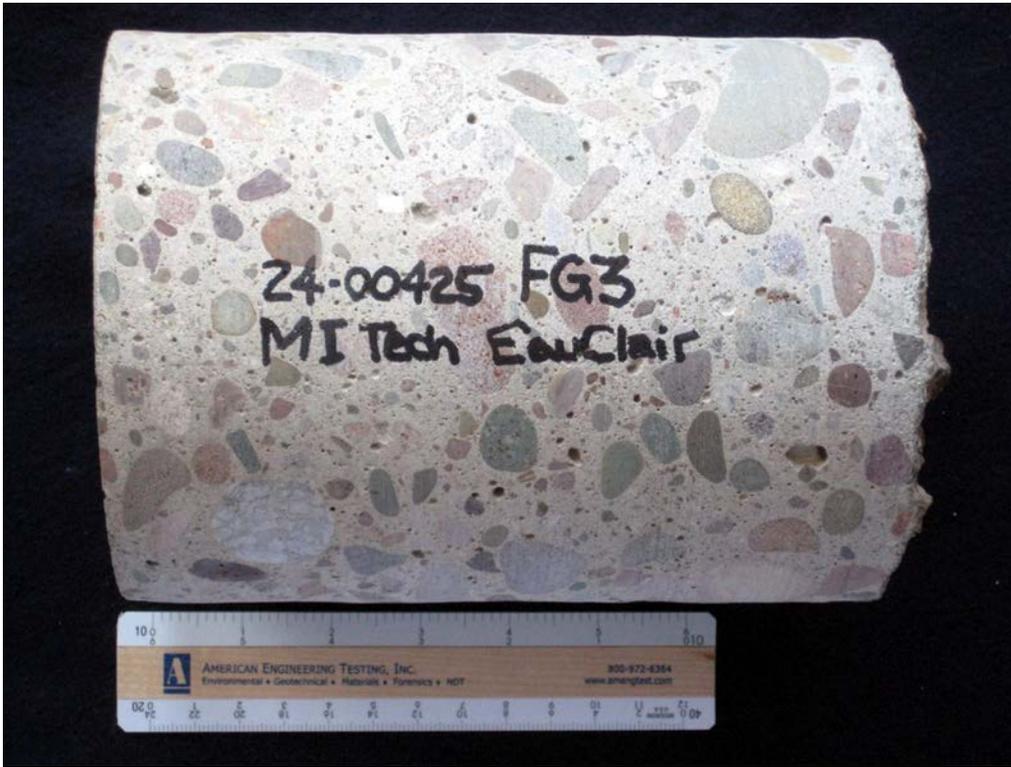
PHOTO: 4



SAMPLE ID: FG2 DESCRIPTION: Top surface of the core as received. Note core was taken in distress apparently directly adjacent to a control joint..

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 5



SAMPLE ID: FG3 DESCRIPTION: Core sample as received. Top surface is left.

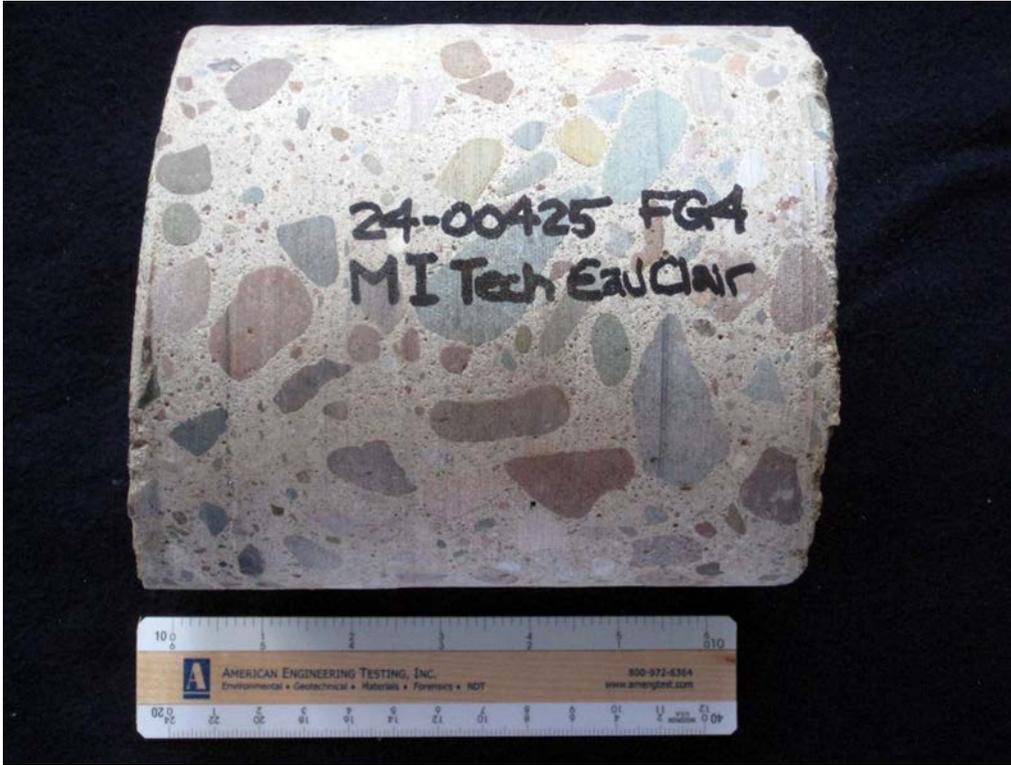
PHOTO: 6



SAMPLE ID: FG3 DESCRIPTION: Screeded, tined and traffic worn top surface of the core as received.

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 7



SAMPLE ID: FG4 DESCRIPTION: Core sample as received. Top surface is left.

PHOTO: 8



SAMPLE ID: FG4 DESCRIPTION: Mortar eroded top surface of the core as received.

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI



PHOTO: 9

SAMPLE ID: FG-1 **DESCRIPTION:** Sawcut and lapped cross section of core taken through a sawcut control joint. Some microcracking is mapped in red ink. Heavily concentrated microcracking and distressed paste is marked with arrows.

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

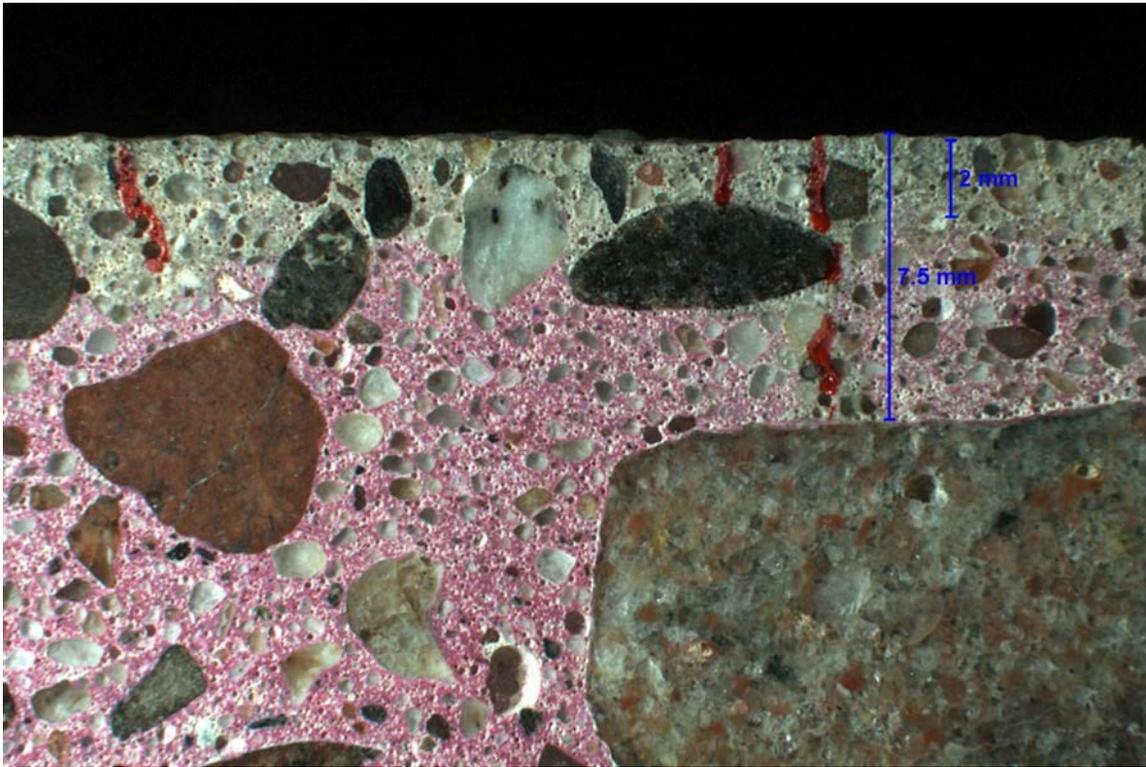


PHOTO: 10

SAMPLE ID: FG-2 DESCRIPTION: Sawcut and lapped cross section of core apparently taken directly adjacent to a distressed control joint. Microcracking is mapped in red ink.

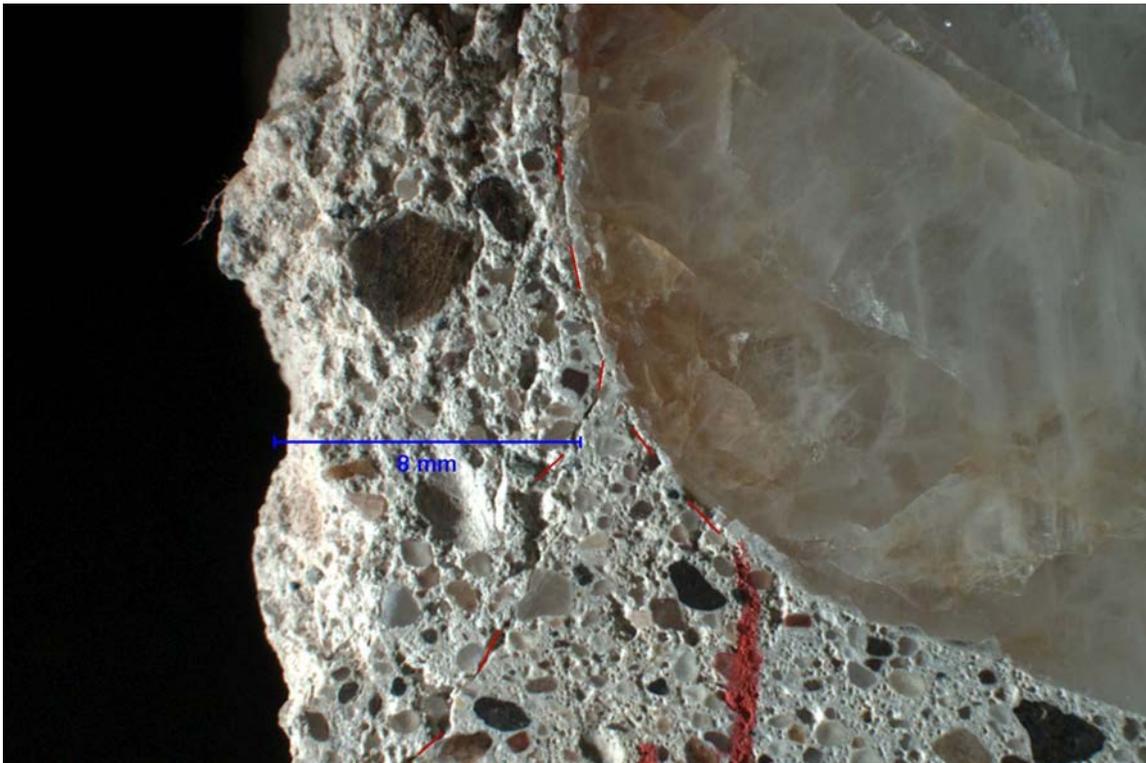
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 11



SAMPLE ID: FG1 DESCRIPTION: Carbonation (unstained paste) ranges from 2mm to 7.5mm depth (in this view) along fine drying shrinkage microcracking mapped in red ink.
MAG: 5x

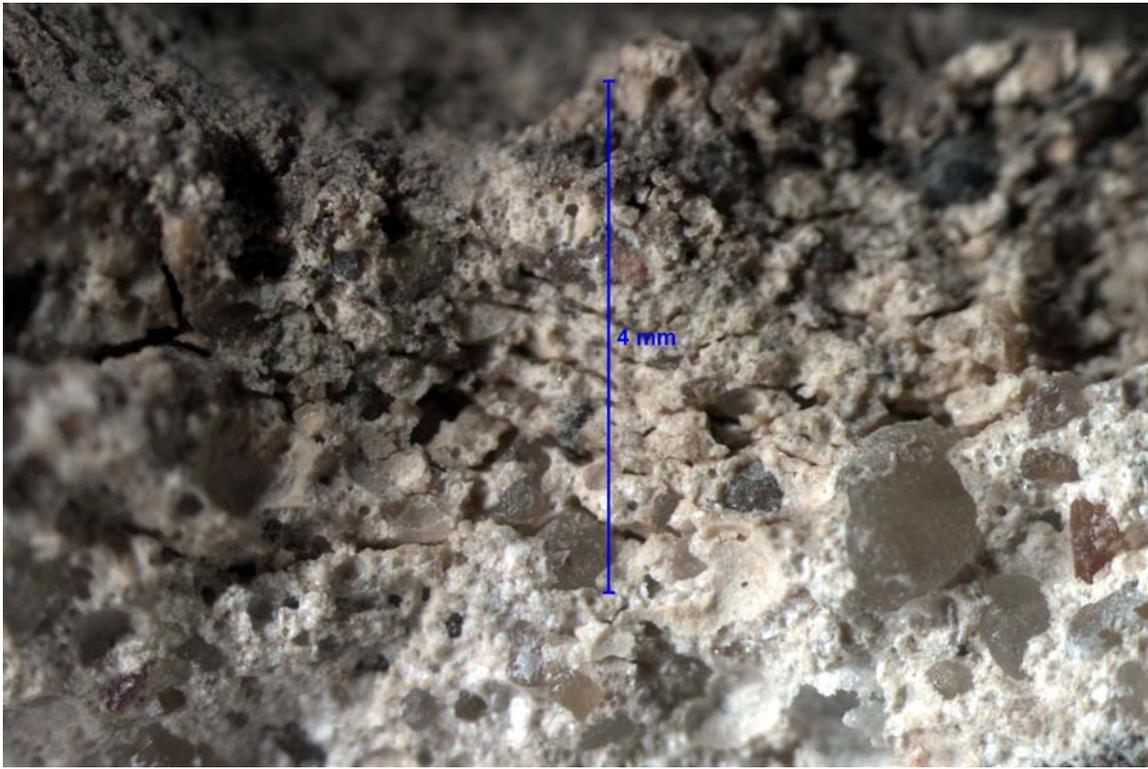
PHOTO: 12



SAMPLE ID: FG1 DESCRIPTION: Highly distressed paste directly adjacent to the joint crack at approx. 160mm depth in the core. The paste is lighter colored, softer, and filled with concentrated fine microcracking.
MAG: 5x

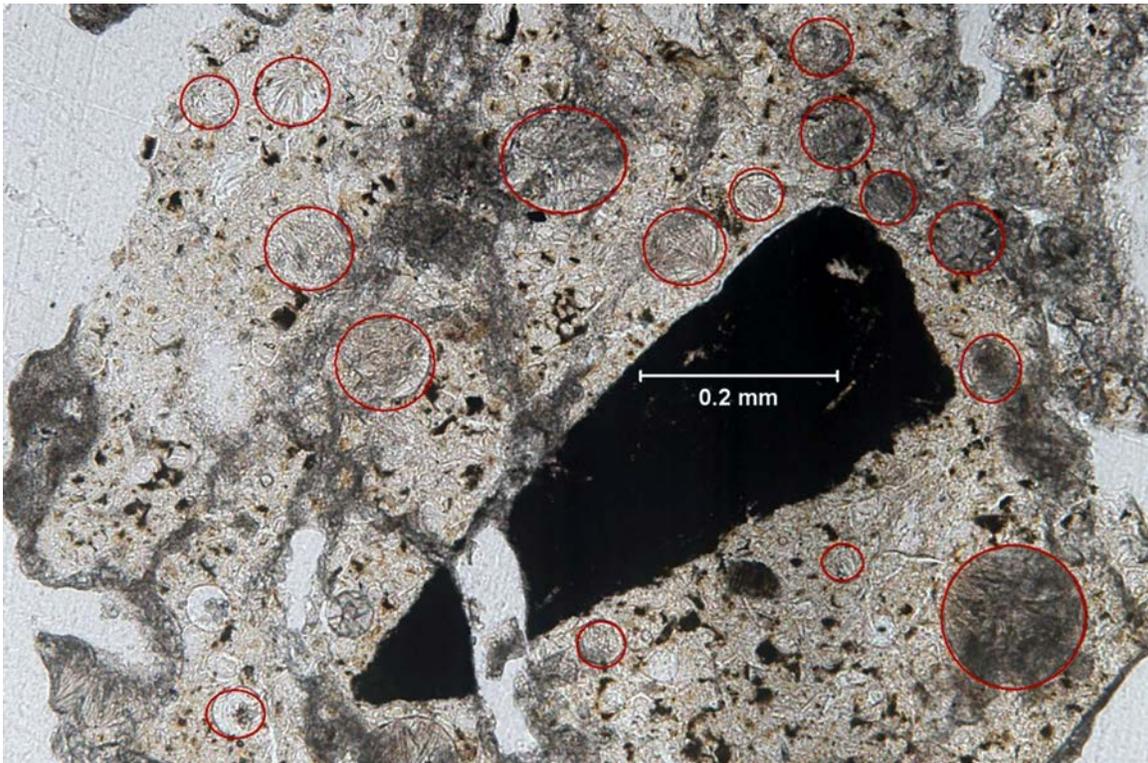
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 13



SAMPLE ID: FG1 DESCRIPTION: Highly concentrated anastomosing microcracking in carbonated paste directly adjacent to distressed joint plane (top of image); in freshly fractured cross sectional surface of core.
MAG: 15x

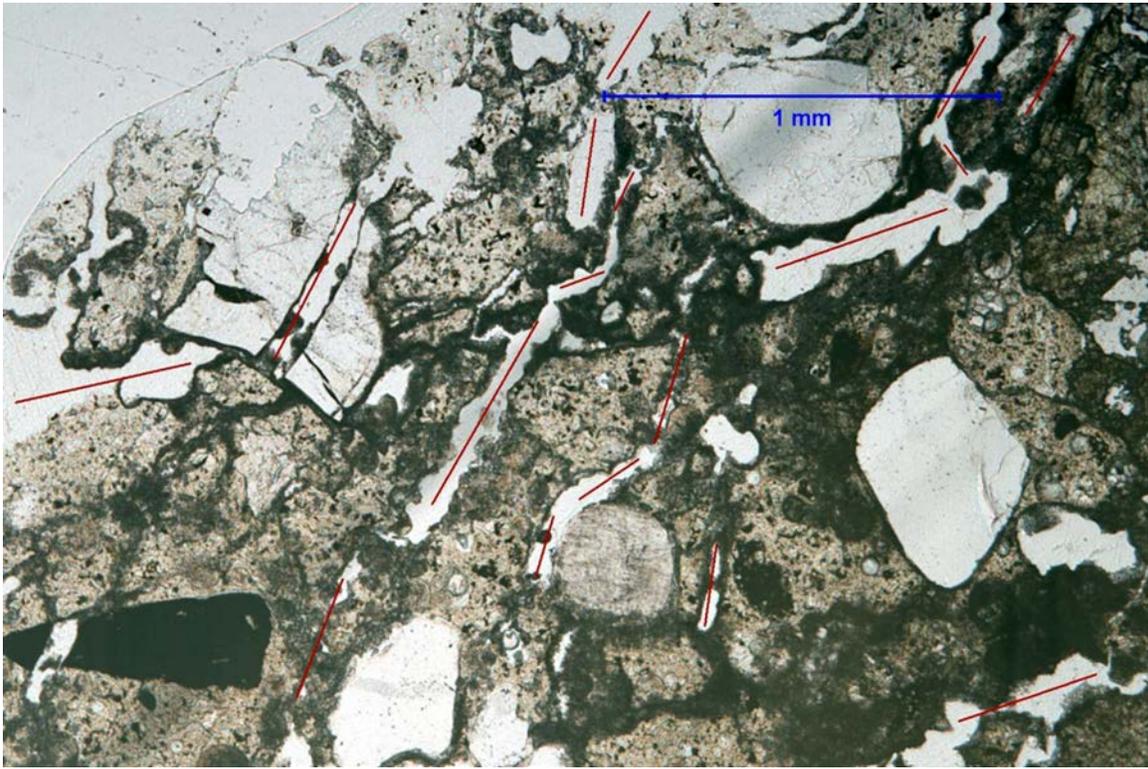
PHOTO: 14



SAMPLE ID: FG1 DESCRIPTION: Secondary ettringite and calcite fills fine air voidspaces (outlined in red) in thin section of the altered and highly distressed paste directly adjacent to the joint crack at below approx. 75mm depth in the core.
MAG: 100x

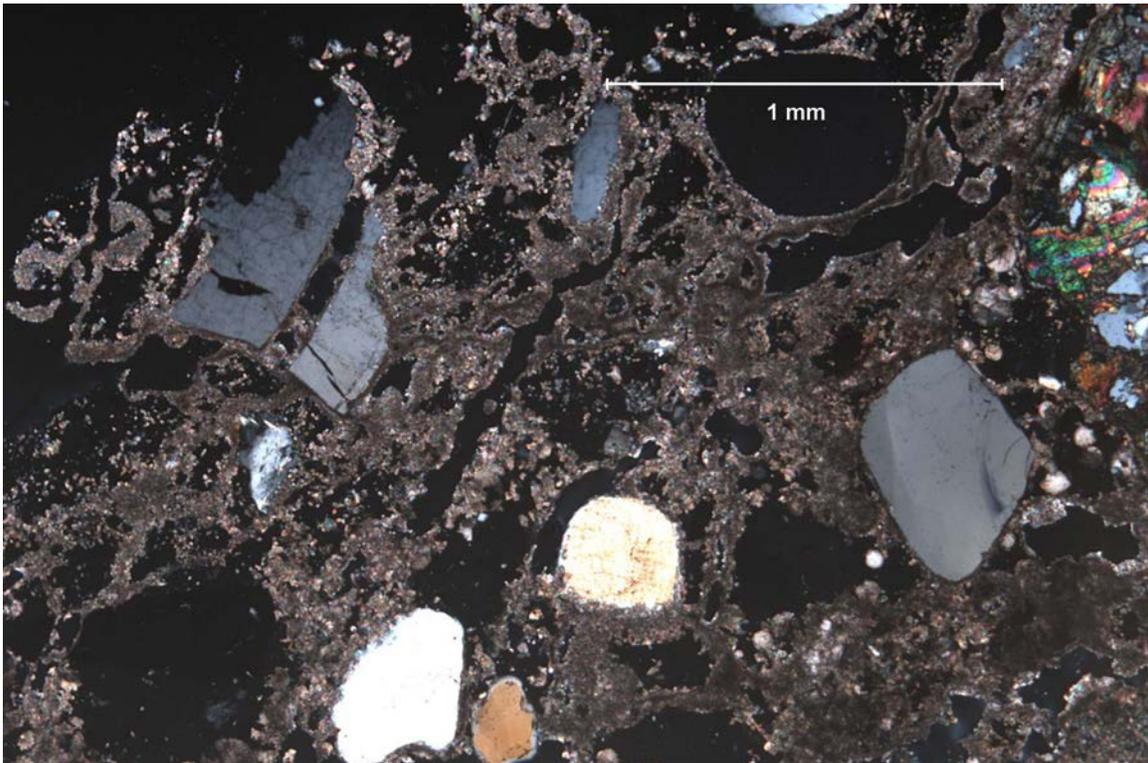
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 15



SAMPLE ID: FG1 DESCRIPTION: Highly concentrated anastomosing microcracking (mapped in red dashed line) in carbonated paste directly adjacent to the distressed joint plane (top of image); in thin section concrete under plane polarized light.
MAG: 40x

PHOTO: 16



SAMPLE ID: FG1 DESCRIPTION: Previous view of the concrete thin section under cross polarized light. Note brightly colored, carbonated to "bi-carbonated" paste.
MAG: 40x

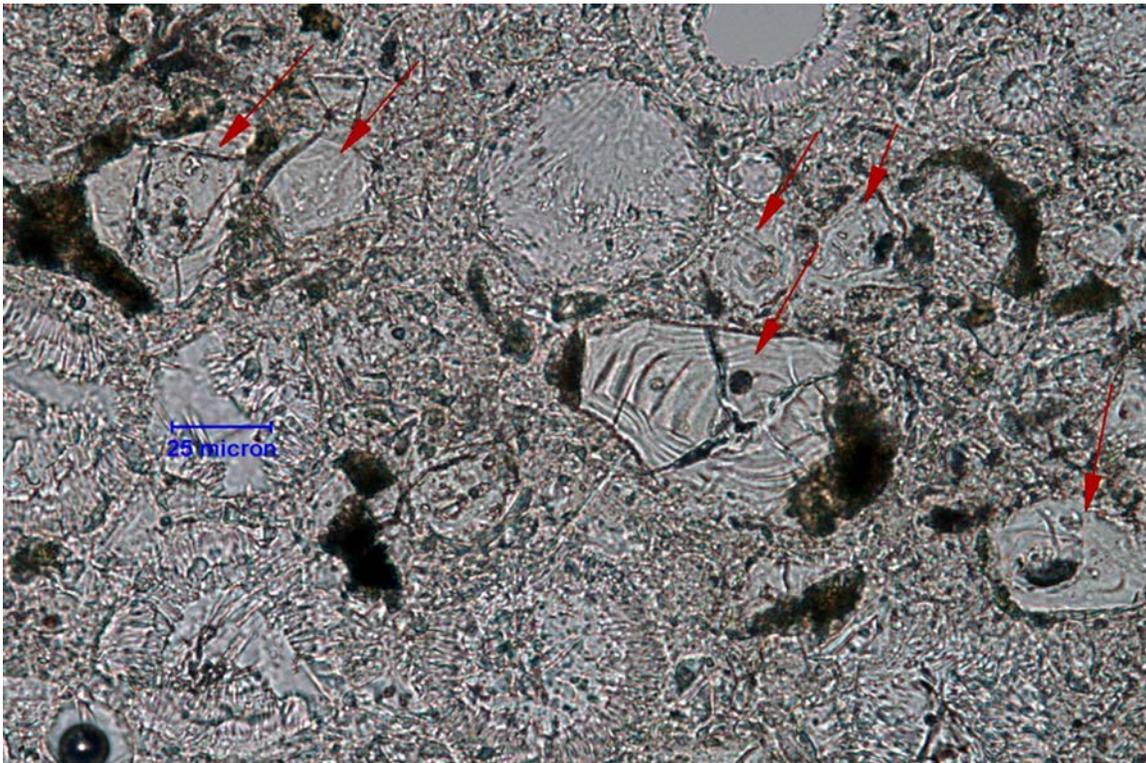
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 17



SAMPLE ID: FG1 DESCRIPTION: Secondary calcite spar in voidspaces (outlined in red) in the carbonated paste directly adjacent to the distressed joint plane (top of image); in thin section of concrete paste under plane polarized light.
MAG: 200x

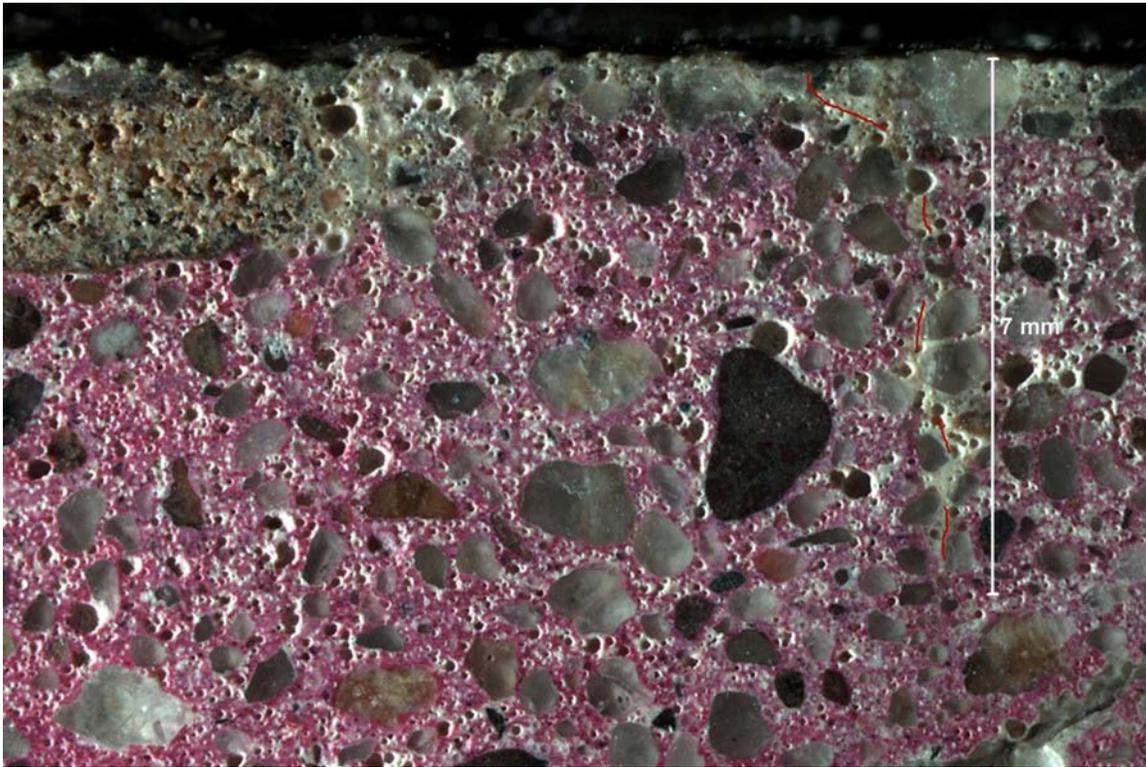
PHOTO: 18



SAMPLE ID: FG1 DESCRIPTION: Fully hydrated alite portland cement clinker relicts in thin section of concrete paste under plane polarized light.
MAG: 400x

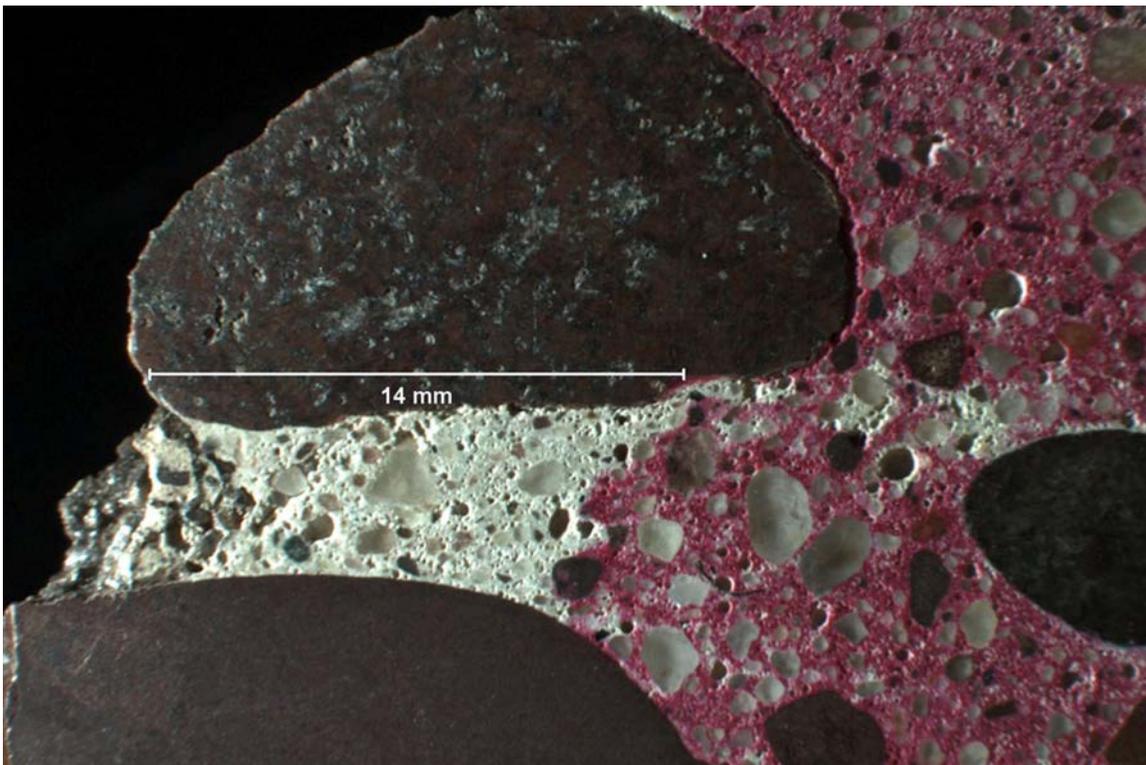
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 19



SAMPLE ID: FG2 DESCRIPTION: Carbonation (unstained paste) ranges from <1mm to 7mm depth (in this view) along fine drying shrinkage microcracking mapped in red dashed line.
MAG: 10x

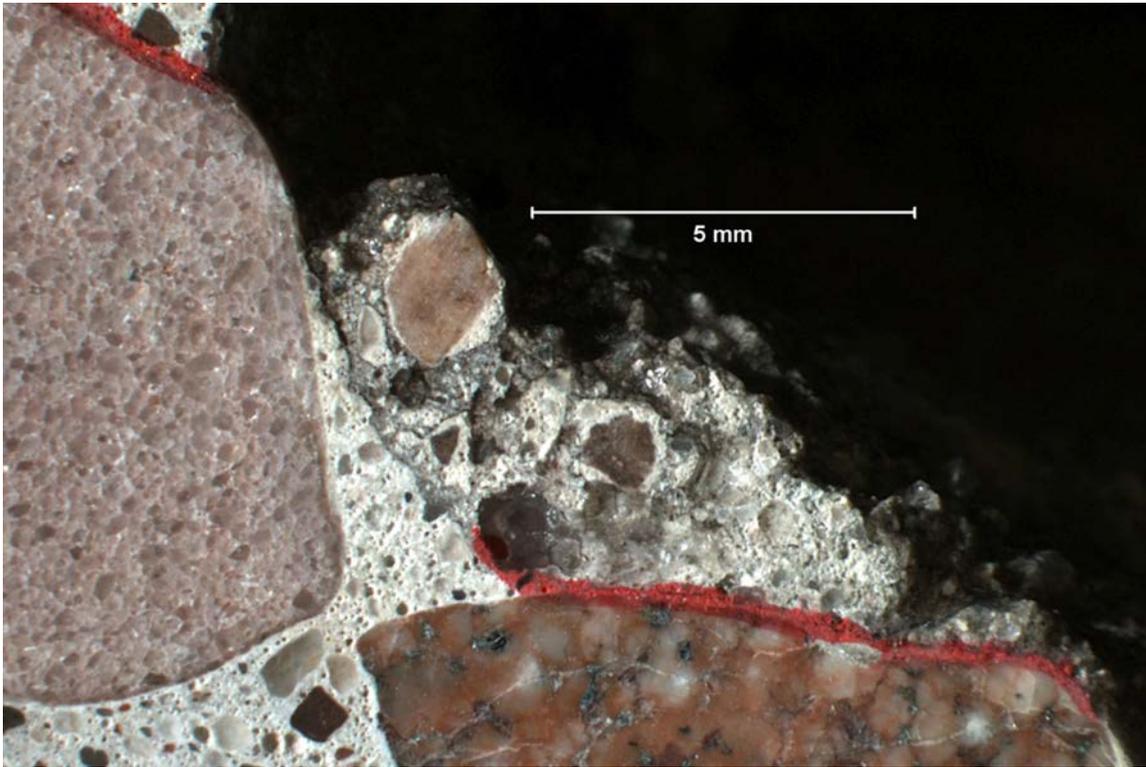
PHOTO: 20



SAMPLE ID: FG2 DESCRIPTION: Carbonation (unstained paste) proceeds continuously to 14mm from the distressed joint plane at approx. 16mm depth in the core.
MAG: 5x

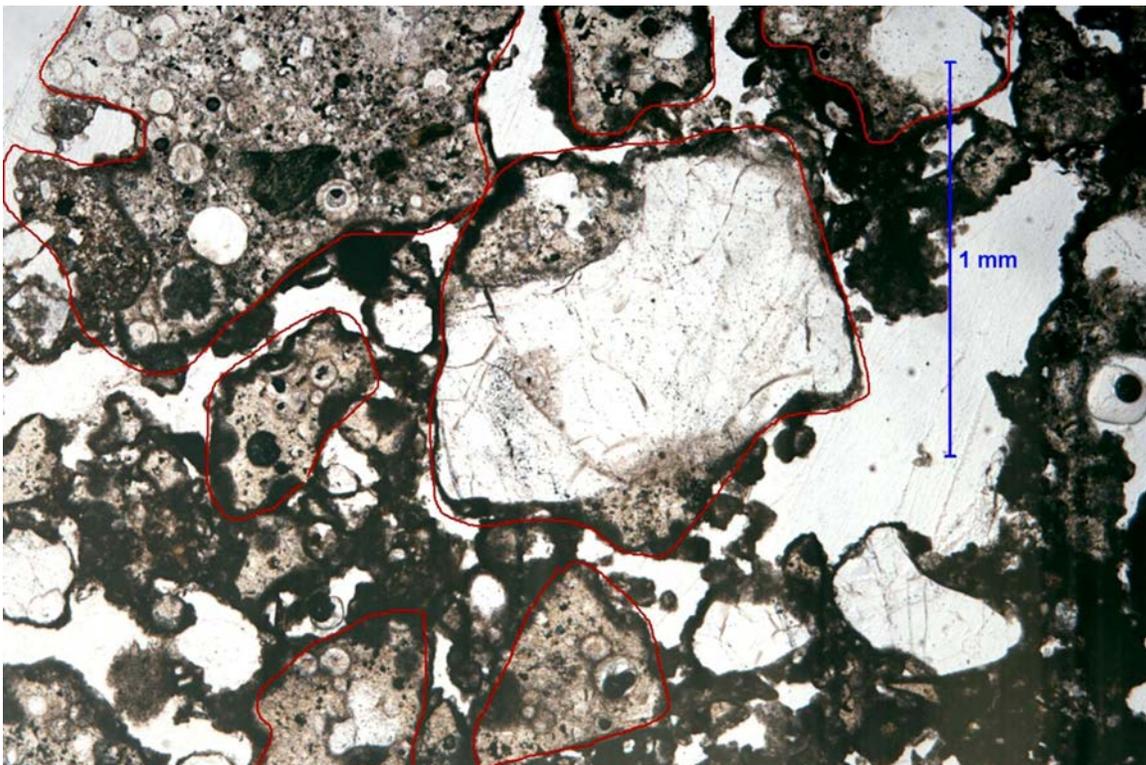
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 21



SAMPLE ID: FG2 DESCRIPTION: Concrete fragments along the distressed edge of the core; apparently lightly cemented with calcite and stabilized with epoxy for preparation.
MAG: 10x

PHOTO: 22



SAMPLE ID: FG2 DESCRIPTION: Concrete fragments in thin section (outlined in red) along the distressed edge of the core; apparently lightly cemented with calcite and stabilized with epoxy for preparation
MAG: 40x

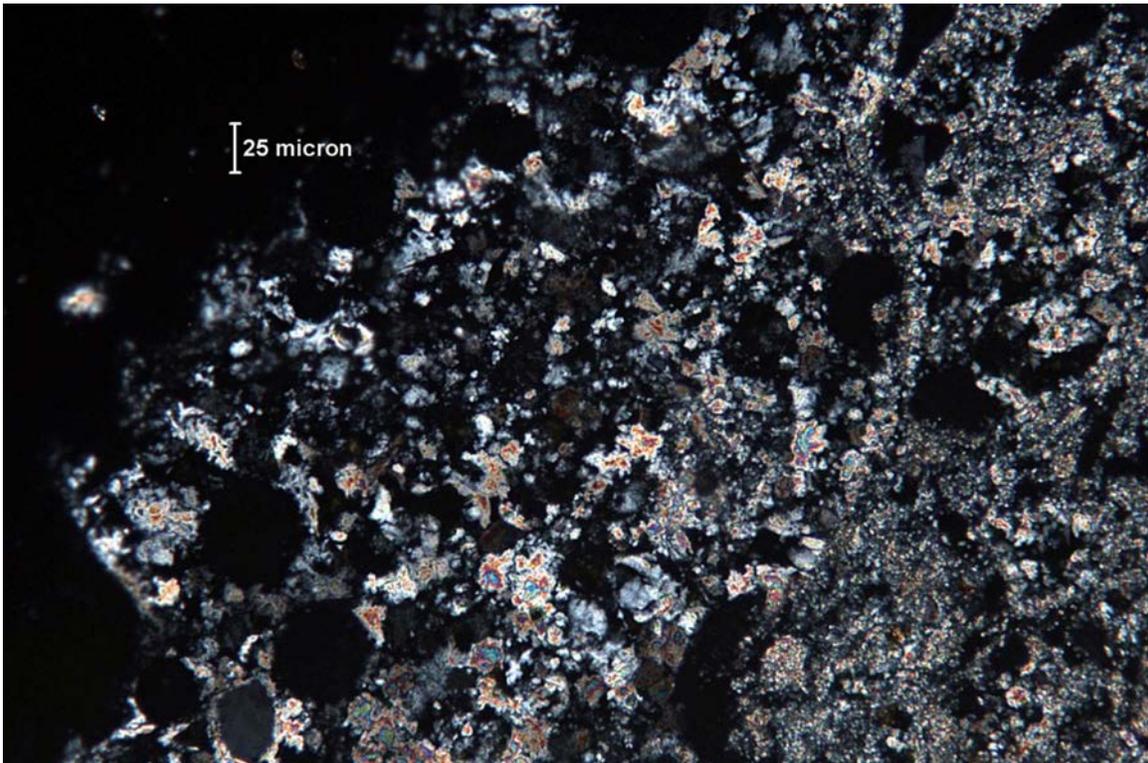
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 23



SAMPLE ID: FG2 DESCRIPTION: Brightly colored, carbonated paste directly adjacent to the distressed joint plane (upper left); in thin section under cross polarized light.
MAG: 40x

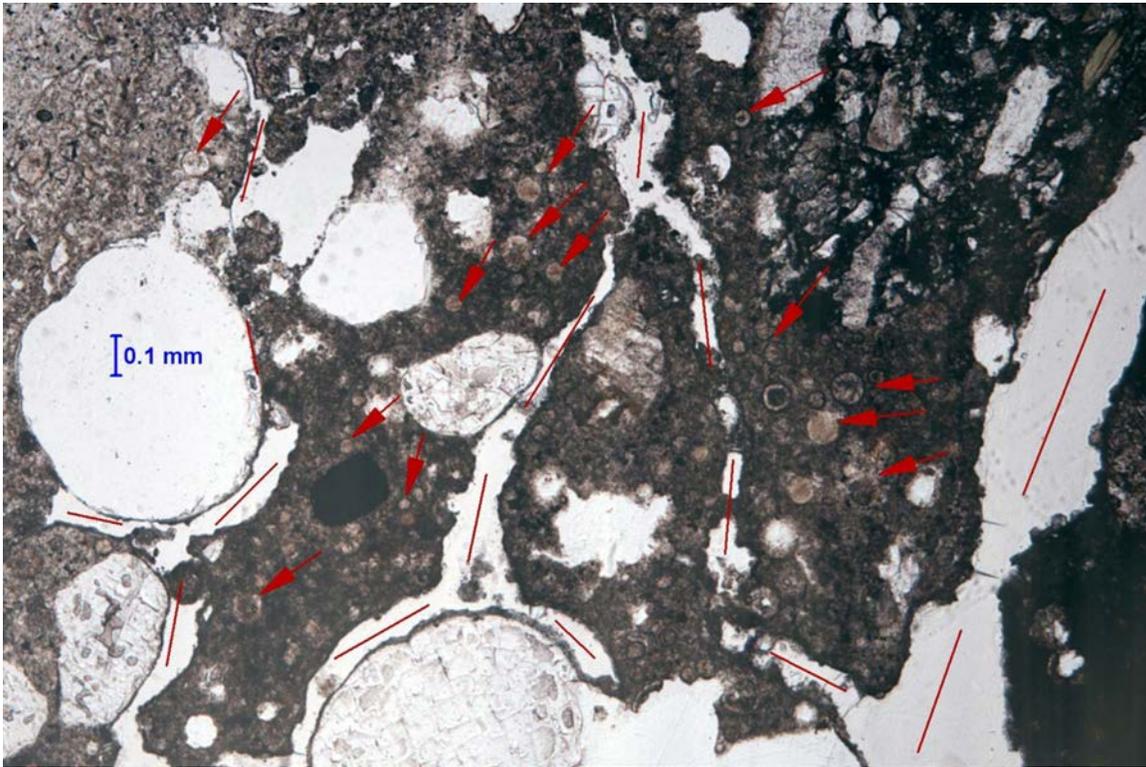
PHOTO: 24



SAMPLE ID: FG2 DESCRIPTION: The paste directly adjacent to the distressed surface appears "bi-carbonated" and exhibits a relatively coarse crystalline appearance under cross polarized light.
MAG: 200x

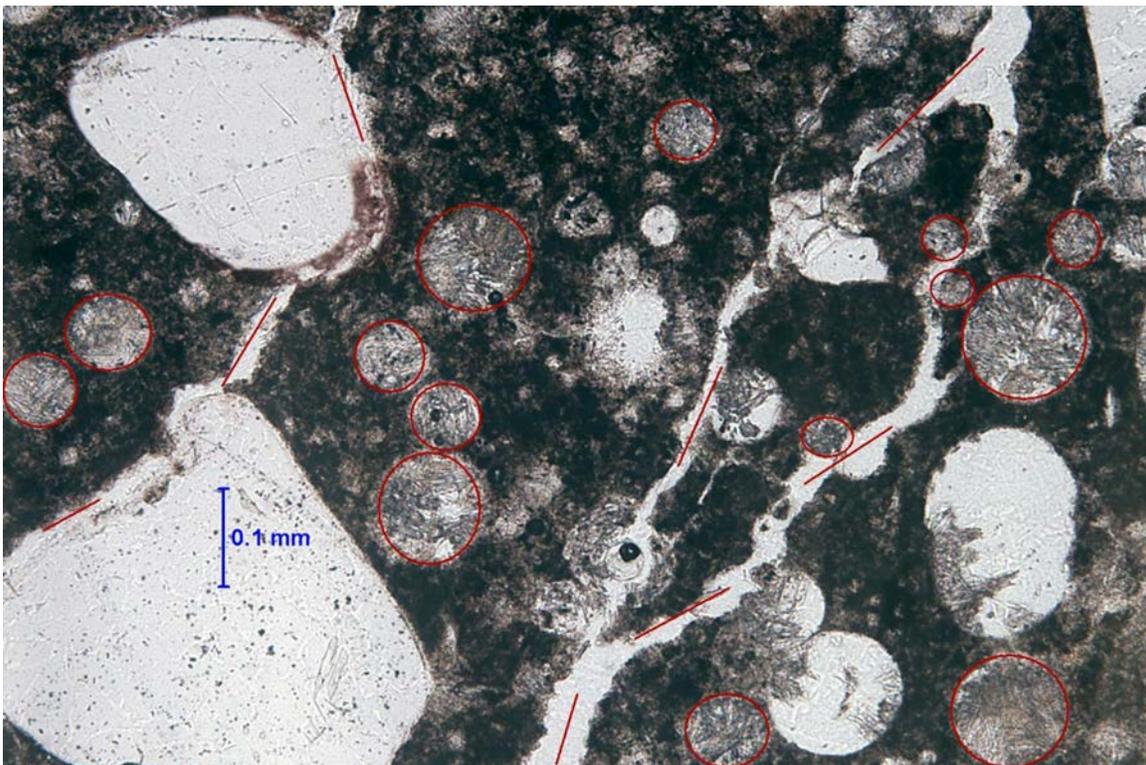
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 25



SAMPLE ID: FG2 DESCRIPTION: The paste within a few millimeters of the distressed surface exhibits significant secondary ettringite air void fillings (outlined in red); in thin section of heavily microcracked paste (red dashed lines) under plane polarized light.
MAG: 40x

PHOTO: 26



SAMPLE ID: FG2 DESCRIPTION: The paste within a few millimeters of the distressed surface exhibits significant secondary ettringite air void fillings (outlined in red); in thin section of heavily microcracked paste under plane polarized light.
MAG: 100x

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

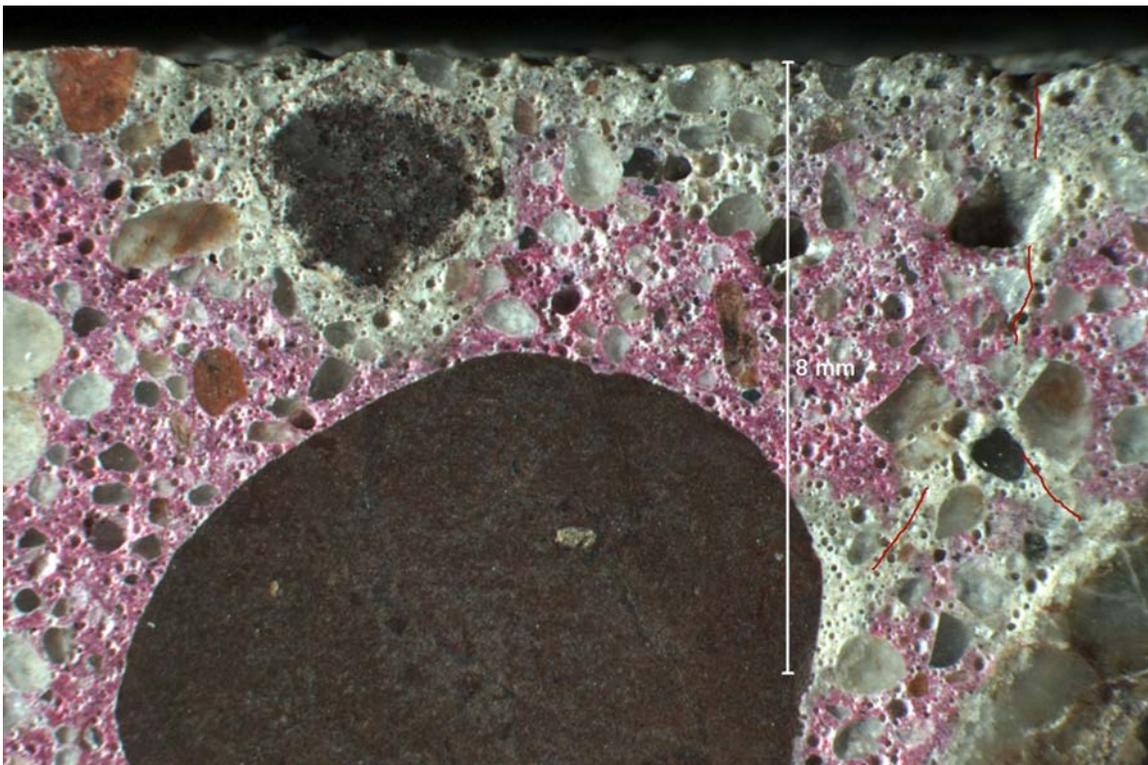
PHOTO: 27



SAMPLE ID: FG3 DESCRIPTION: Traffic-worn top surface of the concrete under magnification

MAG: 10x

PHOTO: 28

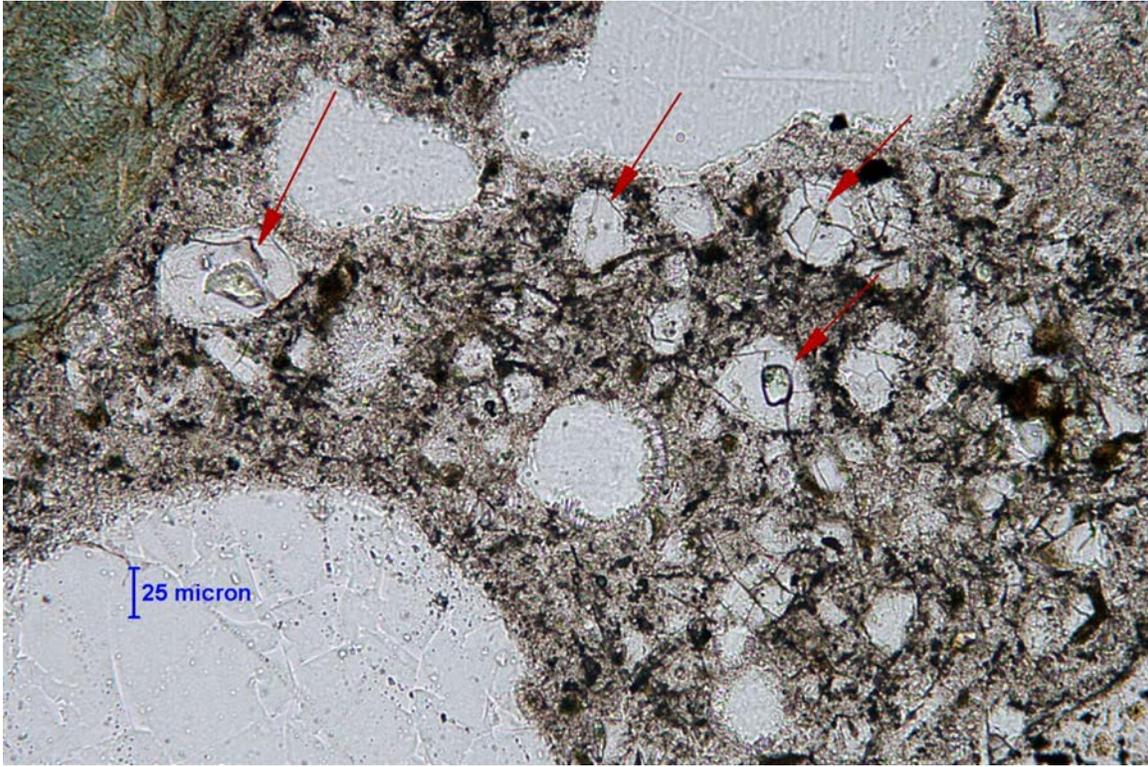


SAMPLE ID: FG3 DESCRIPTION: Carbonation (unstained paste) proceeds up to 8mm depth from the top surface, "spiking" along sub-vertical drying shrinkage microcracking mapped in red dashed line.

MAG: 10x

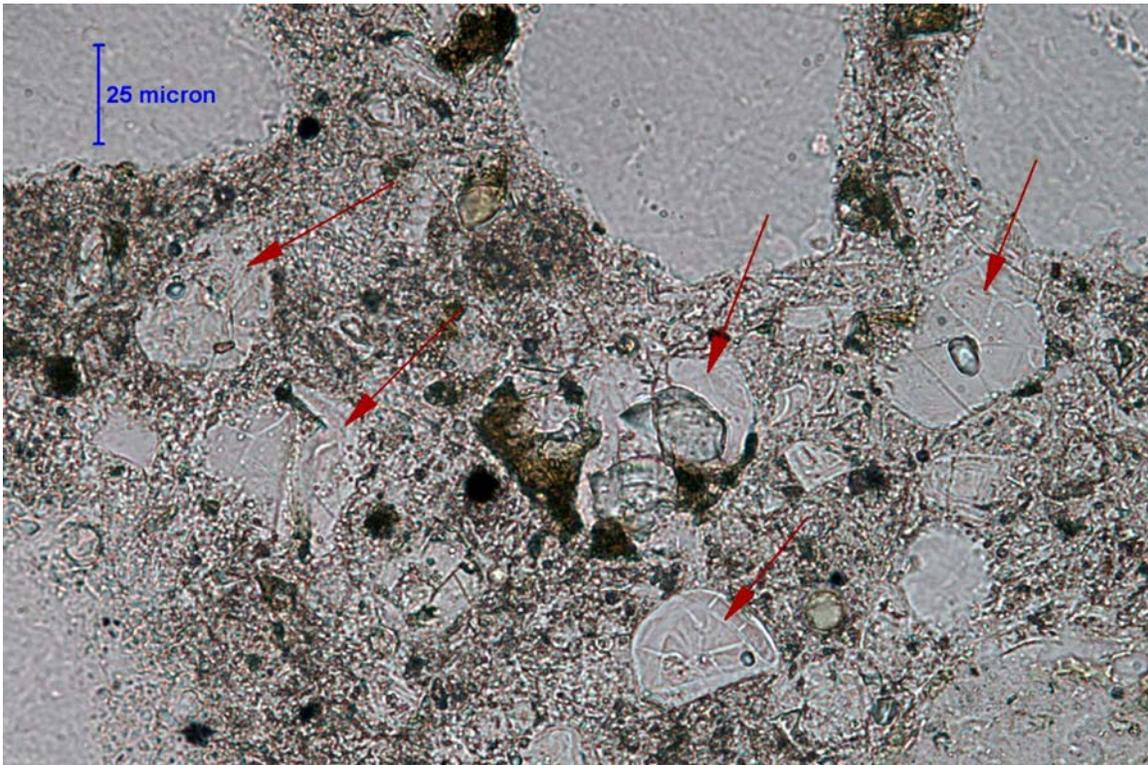
PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 29



SAMPLE ID: FG3 DESCRIPTION: Well to fully hydrated alite portland cement clinker particles in thin section of concrete paste under plane polarized light.
MAG: 200x

PHOTO: 30



SAMPLE ID: FG4 DESCRIPTION: Well to fully hydrated alite portland cement clinker particles in thin section under plane polarized light. Note spherical flyash pozzolan particles.
MAG: 400x

PROJECT: Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

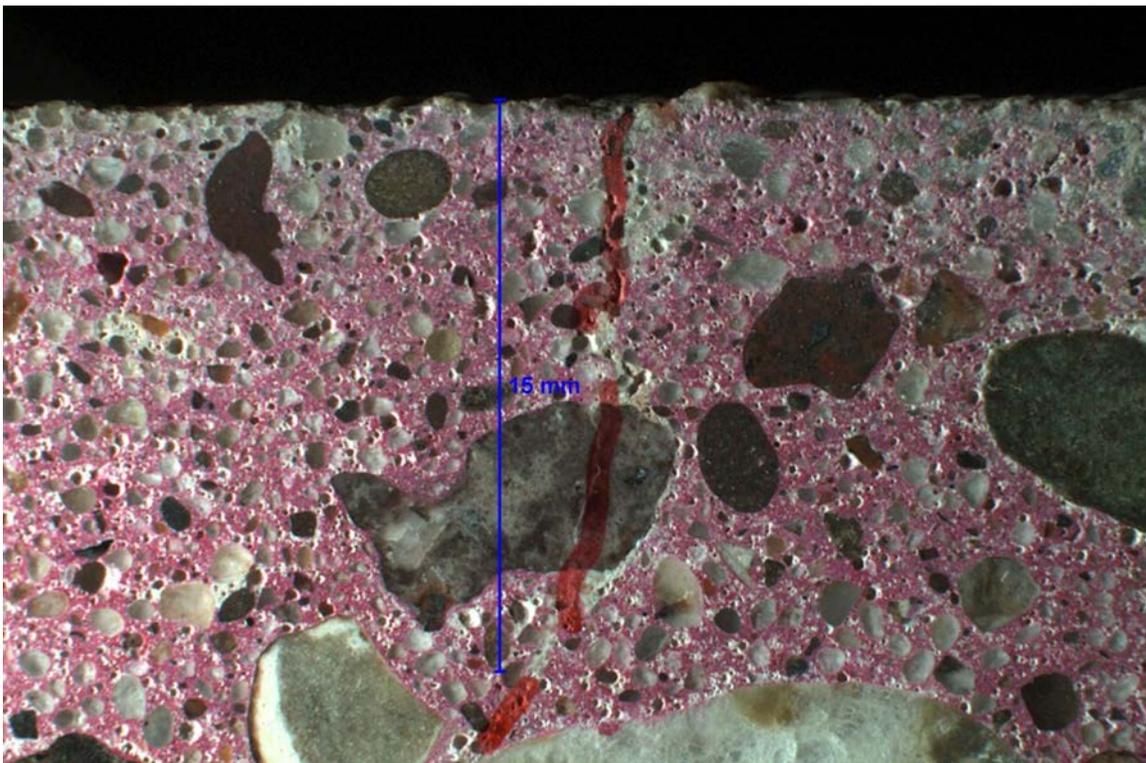
PHOTO: 31



SAMPLE ID: FG4 DESCRIPTION: Traffic-worn and mortar eroded top surface of the core under magnification.

MAG: 5x

PHOTO: 32



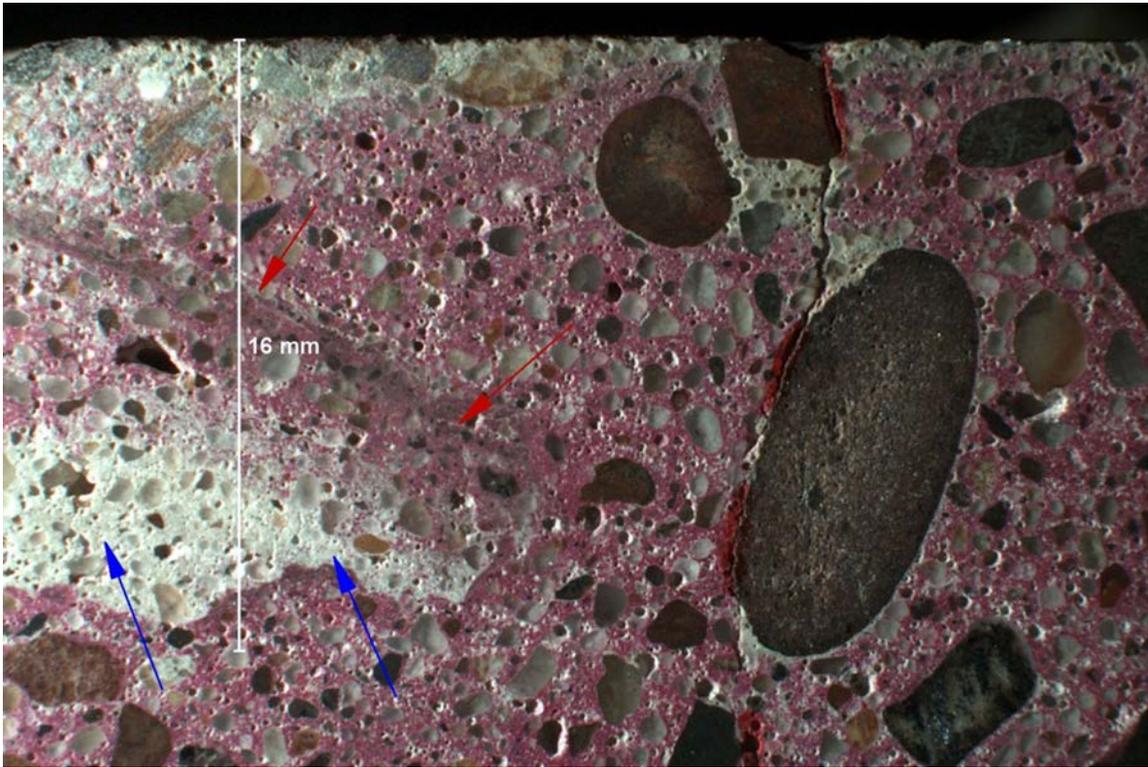
SAMPLE ID: FG4 DESCRIPTION: Carbonation (unstained paste) ranges from negligible up to 15mm depth, intermittently, from the top surface of the core, along sub-vertical drying shrinkage microcracking; mapped in red ink.

MAG: 5x

PROJECT:

Joint Distress Study
First Avenue & Grand Avenue
Eau Claire, WI

PHOTO: 33



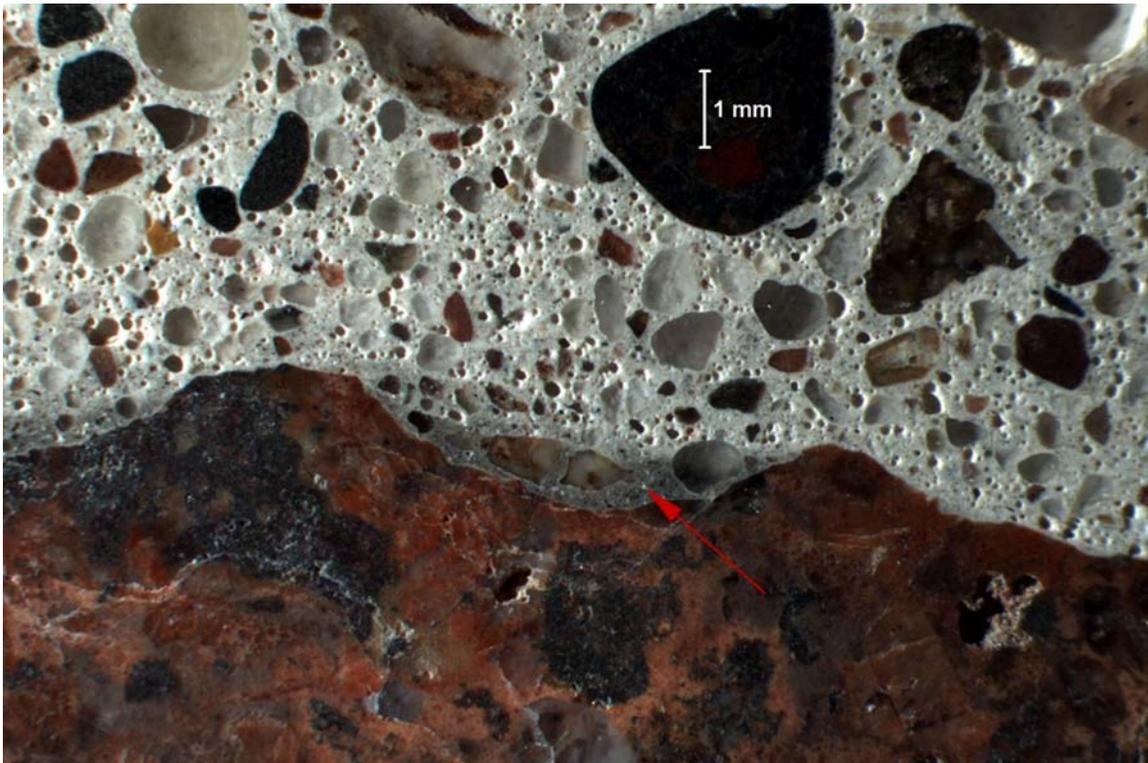
SAMPLE ID:

FG4 **DESCRIPTION:** Mixing anomaly within 16mm of the top surface of the core. Note darker, denser layer of concrete (red arrows) and layer of carbonated (unstained paste) excessive w/cm paste (blue arrows).

MAG:

5x

PHOTO: 34



SAMPLE ID:

FG4 **DESCRIPTION:** Darker colored, denser paste in concave coarse aggregate notch suggest multiple additions of water to the concrete.

MAG:

10x

APPENDIX B.

INVESTIGATION OF LOCALIZED JOINT DETERIORATION IN AMES, IOWA

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INTRODUCTION

The aim of the work described in this report is to continue collecting information about potential causes of joint deterioration by looking at appropriate field examples.

Reports have been received from projects in several Midwest states that concrete, at joints, is deteriorating prematurely in various types of pavement from 5 to 30 years old.

It is likely that several mechanisms are contributing to the distress at the same time and possible that different deterioration locations are the result of different combinations of these mechanisms.

The work in this report covers an investigation of localized damage occurring on a city street in Ames, Iowa.

BACKGROUND

Loop Drive is a two-lane city street in a research park serving three office buildings. The street is approximately 1/2 mile long. It was reportedly paved in 1997 in one day using a full-width slipform paver running from southwest to northeast. An unusual feature for the area is that it is built on a drainable base.

This drainable base is evidenced by the dry joints and wet surface observed after a rainstorm in the summer of 2011 (Figure 1). At the time, it was noted that the drains were running with water.



Figure 1. Evidence of joints that are draining well

In winter, it is not uncommon for mist to be observed coming out of the drains indicating, again, that water is running freely through them.

The original detail was for the joints to be left unsealed, but a maintenance crew had installed a hot-seal material in some of the joints at some time in the last few years.

In 2010, it was noted that deterioration was occurring at some joints and an investigation was initiated.

TASKS

The extent of the distress was mapped, along with details of where joints had been sealed. (Figure 2).

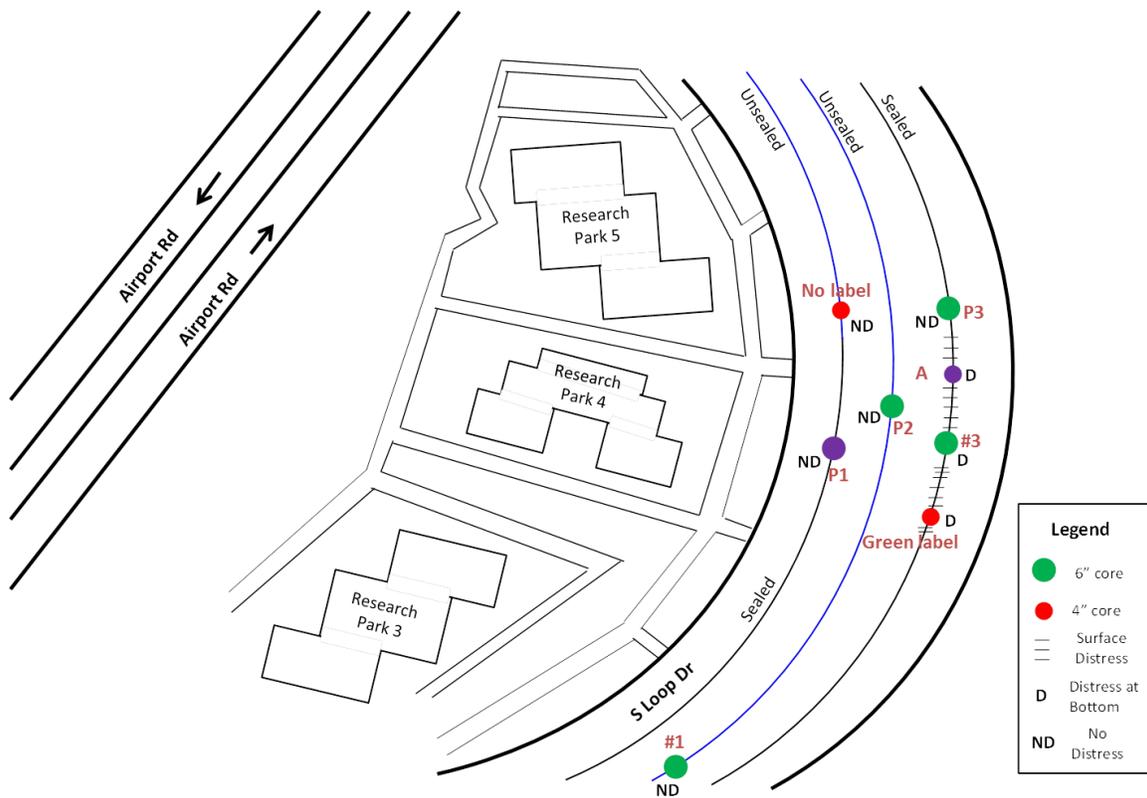


Figure 2. Plan of coring and distress

Several cores were extracted from the pavement over a period of two years. Two cores were sent for petrographic examination. One is marked as D for distressed in purple in Figure 2, from a distressed joint, and the other is marked as ND for no distress, also in purple, from a sound joint.

The cores are labeled D and P1, respectively, in the petrographic report. The cores were taken from locations about 10 ft. apart.

The diagram also shows the extent of the distress. Assuming that the concrete affected filled about half the width of the road, it was calculated that about three truckloads of concrete would have been required to fill that volume.

It is also noted that there is faulting starting to occur in the left-most joint, particularly at the northeast end of the road (Figure 3).



Figure 3. Faulting and loss of aggregate interlock

This faulting is likely related to the use of the drainable base, meaning that the slabs had been able to move apart enough to lose aggregate interlock.

Permeability of the base was also assessed using a system developed as part of this project.

There does not appear to be a correlation between the presence of sealant and the joint deterioration (Figure 2).

During the winter of 2011/2012 shortly after a light snow event, it was noted that contrary to the pattern observed in Figure 1, the joints appeared to be wet while the rest of the pavement had started to dry out. This is attributed to salts collecting in the joints and slowing the rate of drying (Figure 4).



Figure 4. Wet joints and dry pavement

PETROGRAPHIC DATA

The full petrographic report is included at the end of this appendix. The findings may be summarized as follows:

- The original air void systems of both the good (P1) and damaged (D) cores were satisfactory, but had been filled with ettringite (Table 1)
- Both samples contained about 10 to 20% fly ash
- Some D-cracking was observed, particularly in the distressed sample
- The w/cm of the undamaged sample was slightly lower than that of the damaged sample
- Despite the reportedly compromised air void system of sample P1, it is still in reasonable condition

Table 1. Petrographic data

	Non-Distressed	Distressed
Original air content %	6.4	6.7
Effective air content, %	4.5	5.3
Original spacing factor, in.	0.007	0.005
Effective spacing factor, in.	0.013	0.009
Estimated w/cm	0.40-0.45	0.42-0.47

PERMEABILITY TESTS

The permeability test was developed to provide an indication of the rate of water movement through the base layer of a pavement. The test comprises the following (as shown in Figures 5 through 7):

- Insert device into a core hole (Figure 5 shows the rubber gasket at the bottom that is inflated after seating)
- Seal the bottom of the device against the concrete using an inflatable rubber tube
- Fill the device with water
- Monitor the rate of water loss from the device over a period of 60 minutes



Figure 5. Inserting the device into a core hole



Figure 6. Filling the device with water

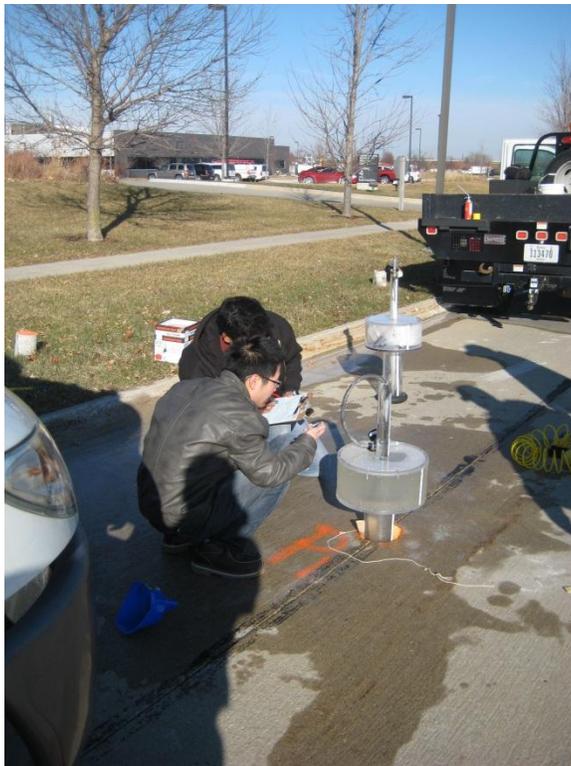


Figure 7. Monitoring water loss

Tests were conducted at P1, P2, and P3 as shown in Figure 2. The data are shown in Figure 8.

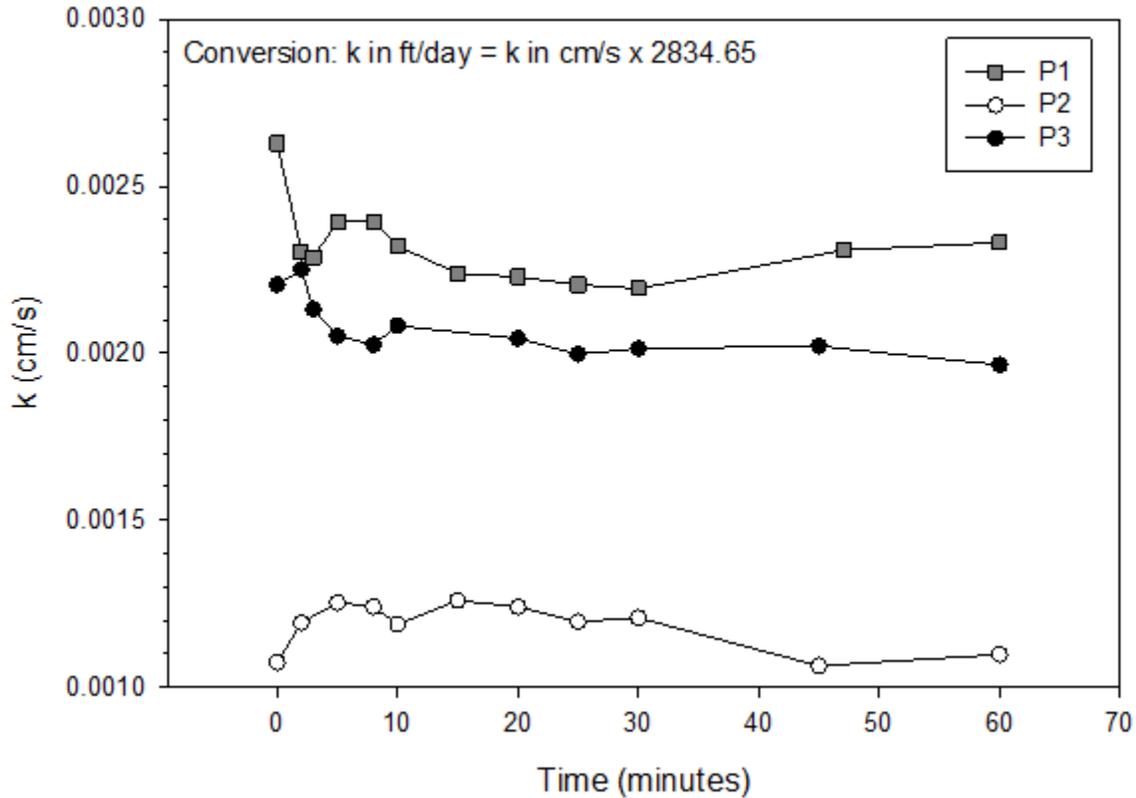


Figure 8. Permeability results

The lowest permeability was observed under the center-line joint. There is little difference between the area with or without distress. There is no trend associated with the sealed and unsealed areas.

DISCUSSION

The primary goal of the work at this location was to assess potential differences between “good” and “bad” joints in close proximity in the same street.

The findings indicate that the primary difference between the distressed and sound samples is the water/cementitious ratio. It would seem that small differences in a set of three deliveries was enough to put the system over the edge.

The abundance of ettringite in the samples is somewhat surprising, because the system was free draining, and ettringite is normally an indicator of abundant water continually in contact with the concrete. One possible explanation may be that salts absorbed into the surface of the joints

retains water, thus increasing saturation.

There was evidence that the salt solution did preferentially penetrate the system through the interfacial zone.

PETROGRAPHIC REPORT

The site report follows in this appendix.

REPORT OF CONCRETE ANALYSIS

PROJECT:

Joint Distress Study
South Loop Drive
Ames, Iowa

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

ATTN: Larry Sutter, PhD

AET PROJECT NO: 24-00427

DATE: June 29, 2012

INTRODUCTION

This report presents the results of laboratory work performed by our firm on two concrete core samples submitted by Jialke Zhang of the Department of Civil, Construction, and Environmental Engineering at Iowa State University on January 11, 2012. We understand the cores were obtained from a distressed concrete pavement joint and an un-distressed joint in South Loop Drive in Ames, Iowa. The pavement was reportedly placed 15 years ago. The scope of our work was limited to performing petrographic analysis on the two core samples to document the general overall quality, composition, and condition of the concrete cores and determine the cause of the joint distress.

CONCLUSIONS

Based on our observations, test results, and past experience, our conclusions are as follows:

1. The cause of the distress observed in core "D" was cyclic freeze/thaw action on saturated concrete which originally contained an entrained air void system of good quality. The air void system has been compromised by secondary crystalline fillings. Excessive secondary ettringite deposition has filled many of the smallest air voids in the paste adjacent to the joint and created "non-durable" concrete.
2. In general, the coarse aggregate was hard and durable. However, some coarse aggregate particles at depth in the joint in core "D" appear to exhibit susceptibility to cyclic freeze-thaw action while saturated. Microcracking, which appears to concentrate within in the coarse aggregate, occurs at below the sawcut joint to 100mm depth in mostly sub-vertical orientations and in mostly sub-horizontal orientations at below 100mm depth. A single coarse aggregate, intersected by the joint crack in core "P1", exhibits concentrated sub-vertical microcracking. The particles appear relatively porous. Significant amounts of highly alkali-silica reactive (ASR) fine shale aggregate particles were observed scattered in both core samples. The reactive shales are not a source of distress.

3. Both core samples originally contained air void systems with parameters required for freeze-thaw resistance under severe exposure conditions. However, the copious amounts of secondary ettringite have in-filled the finer sized air void spaces pushing the spacing factor parameter of the air void systems adjacent to the joints near (D) or out (P1) of the acceptable limit for freeze-thaw resistance. Core sample "D" originally contained 5.4% of "entrained-sized" air void space. Infilling of fine air voidspaces by secondary ettringite has reduced the percentage of "entrained sized" air void space to 3.5% in the 0-0.5" of concrete directly adjacent to the joint crack plane and pushed the original 0.127mm (0.005") spacing factor to 0.229mm (0.009"). Core sample "P1" originally contained 4.9% of "entrained-sized" air void space. Infilling of fine air voidspaces by secondary ettringite has reduced the percentage of "entrained sized" air void space to 2.9% and pushed the original 0.178mm (0.007") spacing factor to 0.330mm (0.013") in the 0-25mm of concrete directly adjacent to the distressed joint plane.
4. The infilling by ettringite is occurring during the saturation of the concrete paste by solutions of deicers and does not require the concrete to be "distressed" before the infilling occurs. Surrounding soils and traditionally mined sodium chloride mineral sources may contain sulfate available for the production of the ettringite. However, it is possible enough sulfate was available in the concrete making materials to fuel the ettringite growth. The concrete paste containing the now "compromised" air void systems were made poorly resistant to cyclic freeze-thaw action by the infilling and are subjected to distress as would any originally poor quality air void system. The distress is progressive at the joints. Poor joint drainage allows constant supply of deicer laden solutions, saturation, and severe freeze-thaw cycling.
5. Carbonation ranges from negligible up to 6mm depth from the top surfaces of the cores; generally proceeding along fine, sub-vertical, drying shrinkage microcracks. The carbonation is relatively minor and expected for the w/cm and age of the concrete. Both concretes were placed at a "moderately-low" w/cm, estimated to be between 0.40 and 0.47. Carbonation ranged from negligible to 12mm depth from the joint crack plane in core "D" and from negligible to 4mm depth from the joint crack plane in core "P1". No other chemical alteration of the paste was detected.
6. Hot-pour joint sealant was utilized in the single-sawcut joints. The hot pour material was wholly de-bonded from one side of the joint in core "P1". The present hot pour joint sealant in core "D" appears to have been placed after substantial damage to the top of the joint. Core "D" exhibits a relatively planar, "ground" surface embossed with abundant, flat, corroded steel metal masses. Apparent plow impacting has produced sliver spalling across nearly one whole side of the joint and incorporating most of the depth of the sawcut. The present hot pour partly adheres to the spalled surfaces. Incipient spalling on the mostly intact side of the joint occurs to 17mm depth into the sawcut.

SAMPLE IDENTIFICATION

Sample ID:	D	P1
Sample Location:	Distressed Longitudinal Int. South Loop Drive	Un-distressed Joint Adjacent Lane, South Loop Drive
Sample Type:	Hardened Concrete Cores	
Sample Dimensions:	90mm (3 1/2") diameter by 175mm (6 7/8")	147mm (5 3/4") diameter by 185mm (7 1/4")

TEST RESULTS AND SUMMARY OF GENERAL CONCRETE PROPERTIES

Our complete petrographic analysis test results appear on the attached sheets entitled 00 LAB 001 "Petrographic Examination of Hardened Concrete, ASTM:C856." A brief summary of these results is as follows:

1. The coarse aggregate in both cores was comprised of 25mm (1") nominal sized crushed carbonate composed chiefly of an oolitic and fossiliferous limestone that appeared well graded and exhibited fair overall distribution. The fine aggregate was a natural quartz, feldspar, and lithic glacial sand.
2. The paste color of core "D" was light gray. The paste color of core "P1" was slightly darker and judged to be medium light gray. The paste in both cores was judged to be "relatively hard" but slightly harder in core "P1". The paste/aggregate bond in both cores was judged to be good.
3. The top surface condition of core "D" was relatively planar and exhibits a ground appearance with adhered metal masses from impacting from a metal object. The top surface of core "P1" was fairly rough and screeded and exhibited mortar erosion exposing many fine aggregates. The depth of carbonation ranged from negligible up to 6mm from the top surfaces along fine sub-vertical drying shrinkage microcracking.
4. The w/cm of core "D" was estimated to be between 0.42 and 0.47 with approximately 8 to 10% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 to 20% replacement of portland cement. The w/cm of core "P1" was estimated to be between 0.40 and 0.45 with approximately 10 to 12% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 to 20% replacement of portland cement.

Air Content Testing

Sample ID	D "Original Air"	D "Effective Air 0-0.5in Depth from Joint"	P1 "Original Air"	P1 "Effective Air 0-1in from Joint"
Total Air Content (%)	6.7	5.3	6.4	4.5
"Entrained" Air (%) voids < 1mm (0.040")	5.4	3.5	4.9	2.9
"Entrapped" Air (%) voids > 1mm (0.040")	1.3	1.8	1.5	1.6
Spacing Factor, in.	0.005	0.009	0.007	0.013

TEST PROCEDURES

Laboratory testing was performed on January 11, 2012 and subsequent dates. Our procedures were as follows:

Petrographic Analysis

A petrographic analysis was performed in accordance with Standard Operating Procedure 00 LAB 001, "Petrographic Examination of Hardened Concrete," ASTM:C856-latest revision. The petrographic analysis consisted of reviewing the cement paste and aggregate qualities on a whole basis on sawcut and lapped, and fractured sections. Reflected light microscopy was performed under an Olympus SZX-12 binocular stereozoom microscope at magnifications up to 160x. The depth of carbonation was documented using a phenolphthalein pH indicator solution applied on freshly sawcut and lapped surfaces of the concrete sample.

The water/cementitious of the concrete was estimated by viewing a thin section of each concrete under an Olympus BX-51 polarizing light microscope at magnifications of up to 1000x. Thin section analysis was performed in accordance with Standard Operating Procedure 00 LAB 013, "Determining the Water/Cement of Portland Cement Concrete, APS Method." An additional, smaller, sawcut subdivision of each concrete sample is epoxy impregnated, highly polished, and then attached to a glass slide using an optically clear epoxy. Excess sample is sawcut from the glass and the thin slice remaining on the slide is lapped and polished until the concrete reaches 25 microns or less in thickness. Thin section analysis allows for the observation of portland cement morphology, including: phase identification, an estimate of the amount of residual material, and spatial relationships. Also, the presence and relative amounts of supplementary cementitious materials and pozzolans may be identified and estimated.

Air Content Testing

Air content testing was performed using Standard Operating Procedure 00 LAB 003, "Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete, ASTM:C457-latest revision." The linear traverse method was used. The concrete core was sawcut perpendicular with respect to the horizontal plane of the concrete as placed and then lapped prior to testing. The contrast between ettringite filled and unfilled voids was enhanced through the use of phenolphthalein pH indicator solution.

REMARKS

The test samples will be retained for a period of at least sixty days from the date of this report. Unless further instructions are received by that time, the samples may be discarded. Test results relate only to the items tested. No warranty, express or implied, is made.

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
MN License #30023

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00427
Sample ID: P1

Date: May 1, 2012
Performed by: G. Moulzolf

I. General Observations

1. Sample Dimensions: The core was taken directly through a distressed pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut "normal" to the distressed joint measuring (in total) 185mm (7 1/4") x 147mm (5 3/4") x 33mm (1 1/4") thick cross section, an approx. 185mm (7 1/4") x 141mm (5 1/2") x 51mm (2") thick cross section, and two 70mm (2 3/4") x up to 52mm (2") wide thin sections that were sawcut and prepared from the original 147mm (5 3/4") diameter x 185mm (7 1/4") long core. The thin sections were located between 43mm and 113mm depth and 116mm and the bottom surface of the core, in cross section and along the distressed surface of the joint.
2. Surface Conditions:
Top: Rough screeded surface with mortar erosion exposing many fine aggregate particles; fully covered by a thick coat of orange marking paint.
Bottom: Rough, irregular, formed surface; placed upon sub-grade.
3. Reinforcement: None observed.
4. General Physical Conditions: The core exhibits fair overall condition. The core was taken through a minor to moderately distressed pavement joint, at depth. The joint exhibits a few intermittent chevron-shaped sliver spalls at the top surface and vertical scaling/spalling at depth in the joint crack. The joint was characterized by a single approx. 6mm wide sawcut proceeding at least 48mm (1 7/8") depth from the top surface. A 6mm thick and approx. 40mm deep, black, hot-pour bitumen joint sealant resides in the joint. The hot-pour has cleanly de-bonded from one side of the joint. The sliver spalling occurs on one side of the joint; proceeding up to 8mm depth into the concrete at the top surface from the sawcut plane and ending (thinly) at up to 25mm depth in the joint. Incipient sliver spalling on the mostly intact side of the joint was present within 4mm of the joint plane at the top surface and up to 14mm depth into the joint. After removal of the orange paint with acetone, a single corroded mass of iron metal were observed embossed upon an exposed and ground fine aggregate surface. Numerous, other "ground" or truncated and shattered fine aggregate surfaces were observed in topographic highs in the screeded top surface proximate to the joint. Topographic lows in the screeded top surface were partly filled with remnants of joint sealant to 46mm distance from the joint.

Incipient vertical scaling/spalling starts at as shallow as 48mm (1 7/8") depth, just below the sawcut joint and incorporates between 3mm and 7mm of apparent total concrete paste and dolostone aggregate between the two sides of the joint crack to approx. 90mm depth. Below this depth, the mass lost ranged up to 12mm in total; encompassing a large coarse limestone aggregate particle bisected by the joint crack. Concentrated sub-vertical microcracks (incipient spalling) was observed within the coarse aggregate to approx. 12mm distance from the spalled surface. Several other thin incipient spalls (sub-vertical microcracks), occur at random depths and within a few millimeter of the distressed joint surface.

The concrete was fairly well consolidated, with no voidspaces observed in excess of 6mm in diameter. The concrete was purposefully air entrained and originally contained a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air-void parameters include a 4.9% entrained air void volume with a 0.178mm (0.007") spacing factor. Secondary ettringite, with some portlandite, fills many of the smaller entrained sized voidspaces throughout the depth of the core; apart from the top approx. 35mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling within 20mm of the distressed joint plane. Actual measured air void parameters, excluding the ettringite void fillings, in a band between approx. 0mm and 25mm (0"-1.0") depth from the distressed joint surface, are 2.9% entrained volume (a loss of 2.0% volume) with a 0.013" spacing factor.

II. Aggregate

1. Coarse: 25mm (1") nominal sized crushed carbonate composed chiefly of variably buff to pale yellowish brown-colored, oolitic and fossiliferous limestone. The coarse aggregate appeared well graded and exhibited fair overall distribution.

2. Fine: Natural quartz, feldspar, and lithic (granite, graywacke, carbonates, chert, and numerous reactive shale grains) sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 6.4% total original air.
2. Depth of carbonation: Ranged from negligible up to 5mm depth from the top surface of the core, along sub-vertical microcracking and a porous aggregate particle exposed on the surface. Ranged from negligible up to 2mm depth from the sawcut joint surface. Carbonation ranged from negligible up to 4mm depth from the distressed joint plane.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Good.
5. Paste color: Medium Light Gray (Munsell® N6) becoming Medium Gray (N5) below 85mm depth in the core and Medium Dark gray (N4) in the bottom approx. 12mm. Sub-vitreous.
6. Paste hardness: Relatively hard (>Moh's 3.5)
7. Microcracking: Several, fine, sub-vertical drying shrinkage microcracks proceed up to a 12mm maximum depth from the top surface. Several microcracks (incipient spalling) occur within 2mm of and oriented sub-parallel to sliver spalling, to 14mm depth, on one side of the joint. Concentrated sub-vertical microcracking (incipient spalling) was observed generally within a limestone coarse aggregate bisected by the joint crack between 90mm and 130mm depth from the top surface of the core. Other sub-vertical microcracks (incipient spalls) occur at random depths and within a few millimeters of the spalled crack plane. Microcracks were common within, surrounding, and shallowly radiating from numerous alkali-silica reactive shale fine aggregate particles.
8. Secondary deposits: White needly ettringite and a small amount of clear tabular portlandite fills many of the smaller entrained sized voidspaces throughout the depth of the core apart from the top approx. 35mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling below 80mm depth and within 20mm of the distressed joint plane. Clear to white ASR gel product lines or fills voidspaces adjacent to numerous reactive fine aggregate particles.
9. w/cm: Estimated at between 0.40 and 0.45 with approximately 10 to 12% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 to 20% replacement of portland cement.
10. Cement hydration: Alites: Well to fully.
Belites: Moderate.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00427
Sample ID: D

Date: April 30, 2012
Performed by: G. Moulzolf

I. General Observations

1. Sample Dimensions: The core was taken directly through a distressed pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut "normal" to the distressed joint measuring (in total) 175mm (6 ⁷/₈") x 90mm (3 ¹/₂") x 33mm (1 ¹/₄") thick cross section, an approx. 175mm (6 ⁷/₈") x 90mm (3 ¹/₂") x 27mm (1") thick cross section, and two 65mm (3") x up to 52mm (2") wide thin sections that were sawcut and prepared from the original 90mm (3 ¹/₂") diameter x 175mm (6 ⁷/₈") long core. The thin sections were located between 43mm and 110mm depth and 110mm and the bottom surface of the core, in cross section and along the distressed surface of the joint.
2. Surface Conditions:
Top: Flat, planar surface with mortar erosion exposing many fine aggregate particles; fully covered by a thick coat of orange marking paint.
Bottom: Rough, irregular, formed surface; placed upon sub-grade.
3. Reinforcement: None observed.
4. General Physical Conditions: The core exhibits poor overall condition. The core was taken through a moderately to severely distressed pavement joint. The joint exhibits sliver spalling at the top surface and vertical scaling/spalling at depth in the joint crack. The joint was characterized by a single approx. 7mm wide sawcut proceeding at least 44mm (1 ³/₄") depth from the top surface. A completely de-bonded, maximum 6mm thick and 35mm deep, black, hot-pour bitumen joint sealant resides in the joint. The hot pour appear to have been applied after significant sliver spalling had occurred in the joint. The sliver spalling occurs mostly within one side of the joint; as wide, semi-circular spalls proceeding up to 13mm depth into the concrete at the top surface from the sawcut plane and ending (thinly) at up to 29mm depth in the joint. Incipient sliver spalling on the mostly intact side of the joint was present within 4mm of the joint plane at the top surface and up to 17mm depth into the joint. After removal of the orange paint, numerous corroded masses of iron metal were observed embossed upon the mortar eroded and exposed fine aggregate surfaces.

Incipient vertical scaling/spalling starts at as shallow as 35mm (1 ³/₈") depth in the sawcut joint and incorporates between 6mm and 10mm of total concrete paste and dolostone aggregate between the two sides of the joint crack to 100mm depth. Below this depth, the mass lost ranges from 12mm to over 50mm width at the bottom surface. The spalling incorporates portions of the coarse aggregates. Concentrated sub-vertical microcracks (incipient spalling) were observed generally within the paste and limestone aggregates within 12mm of the distressed joint surface between the sawcut and 100mm depth from the top surface of the core. Other, mostly sub-horizontal microcracks, occur at random depths, proceeding through more internally microcracked limestone coarse aggregates.

The flat and planar top surface of the core exhibits a moderate degree of mortar erosion; exposing many fine aggregate particles. The concrete was fairly well consolidated, with no voidspaces observed in excess of 6mm in diameter. The concrete was purposefully air entrained and originally contained a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air-void parameters include a 5.4% entrained air void volume with a 0.127mm (0.005") spacing factor. Secondary ettringite, with some portlandite, fills many of the smaller entrained sized voidspaces throughout the depth of the core; apart from the top approx. 8mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling within 10mm of the distressed joint plane. Actual measured air void parameters, excluding the ettringite void fillings, in a band between approx. 0mm and 12mm (0"-0.5") depth from the distressed joint surface (at below 40mm depth in the core), are 3.5% entrained volume (a loss of 1.9% volume) with a 0.009" spacing factor.

II. Aggregate

1. Coarse: 25mm (1") nominal sized crushed carbonate composed chiefly of variably buff to pale yellowish brown-colored, oolitic and fossiliferous limestone. The coarse aggregate appeared well graded and exhibited good overall distribution.

2. Fine: Natural quartz, feldspar, and lithic (granite, graywacke, carbonates, chert, and numerous reactive shale grains) sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 6.7% total original air.
2. Depth of carbonation: Ranged from negligible up to 6mm depth from the top surface of the core, along sub-vertical microcracking, and ranged from negligible up to 3mm depth from the sawcut joint surface. Carbonation ranged from negligible up to 12mm depth from the distressed joint plane.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Good.
5. Paste color: Light Gray (Munsell® N7). Sub-vitreous.
6. Paste hardness: Relatively hard (>Moh's 3)
7. Microcracking: A few, fine, sub-vertical drying shrinkage microcracks proceed up to 3mm depth from the top surface. Several microcracks (incipient spalling) occur within 4mm of and oriented sub-parallel to the sliver spalling. Concentrated sub-vertical microcracks (incipient spalling) were observed generally within the paste and limestone aggregates within 12mm of the distressed joint surface between the sawcut and 100mm depth from the top surface of the core. Other, mostly sub-horizontal microcracks, occur at random depths, proceeding through more internally and randomly microcracked limestone coarse aggregates. Microcracks were common within, surrounding, and shallowly radiating from numerous alkali-silica reactive shale fine aggregate particles.
8. Secondary deposits: White needly ettringite and a small amount of tabular portlandite fills many of the smaller entrained sized voidspaces throughout the depth of the core apart from the top approx. 8mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling within 10mm of the distressed joint plane. Clear to white ASR gel product lines or fills voidspaces adjacent to numerous reactive fine aggregate particles.
9. w/cm: Estimated at between 0.42 and 0.47 with approximately 8 to 10% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 to 20% replacement of portland cement.
10. Cement hydration: Alites: Mostly fully.
Belites: Moderate to fully.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
South Loop Drive

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

ATTN: Dr. Peter Taylor

AET PROJECT NO: 24-00427

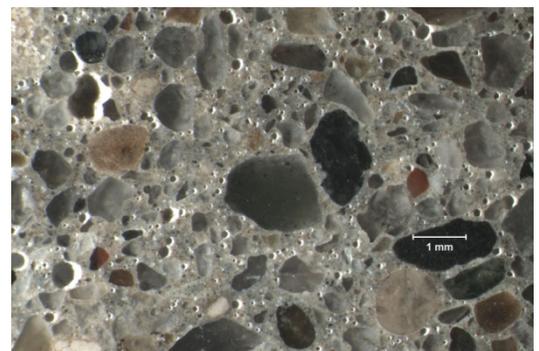
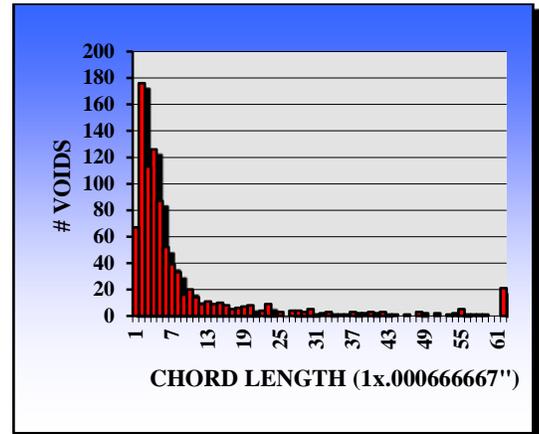
DATE: April 30, 2012

Sample Number: P1 "original air"
Conformance: The concrete sample originally contained an air void system which was consistent with current technology for freeze-thaw resistance.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 147mm (5 ¾") diameter by 185mm (7 ¼") long

Test Data: By ASTM C:457

Air Void Content %	6.4
Entrained, % < 0.040"(1mm)	4.9
Entrapped, % > 0.040"(1mm)	1.5
Air Voids/inch	9.6
Specific Surface, in ² /in ³	600
Spacing Factor, inches	0.007
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	96
Test Date	4/20/12



Magnification: 15x
Description: Air void system- 15mm depth in the core.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
South Loop Drive

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

ATTN: Dr. Peter Taylor

AET PROJECT NO: 24-00427

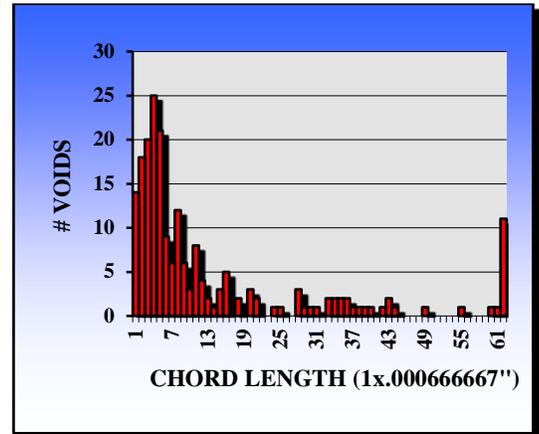
DATE: April 30, 2012

Sample Number: P1 "effective air 0-1in from joint"
Conformance: The section of concrete sample contained an air void system which was not consistent with current technology for freeze-thaw resistance.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 147mm (5 ¾") diameter by 185mm (7 ¼") long

Test Data: By ASTM C:457

Air Void Content %	4.5
Entrained, % < 0.040"(1mm)	2.9
Entrapped, % > 0.040"(1mm)	1.6
Air Voids/inch	4.2
Specific Surface, in ² /in ³	380
Spacing Factor, inches	0.013
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	48
Test Date	4/19/12



Magnification: 15x
Description: Air void system- 145mm depth in core at the joint.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
South Loop Drive

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

ATTN: Dr. Peter Taylor

AET PROJECT NO: 24-00427

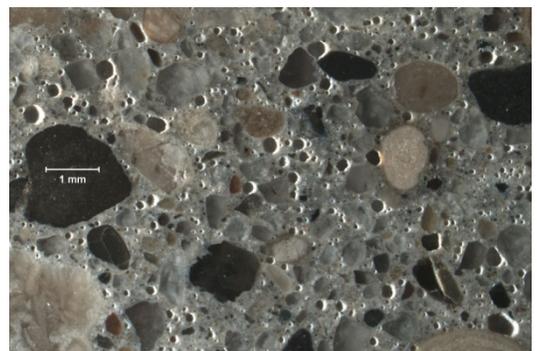
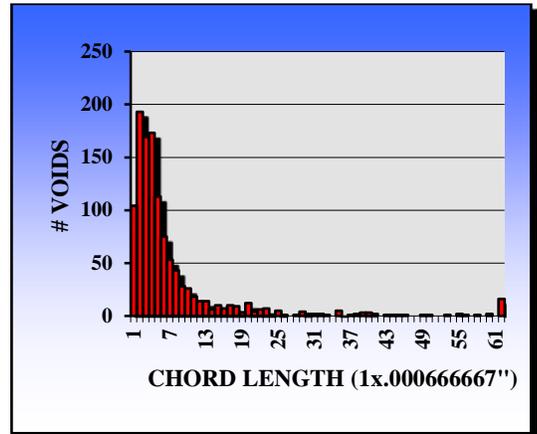
DATE: April 30, 2012

Sample Number: D "original air"
Conformance: The sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data
Description: Hardened Concrete Core
Dimensions: 90mm (3 1/2") diameter by 175mm (6 7/8") long
By ASTM C457

Test Data: By ASTM C:457

Air Void Content %	6.7
Entrained, % < 0.040"(1mm)	5.4
Entrapped, % > 0.040"(1mm)	1.3
Air Voids/inch	12.2
Specific Surface, in ² /in ³	730
Spacing Factor, inches	0.005
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	95
Test Date	4/22/12



Magnification: 15x
Description: Air void system- top 10mm of core.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
South Loop Drive

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

ATTN: Dr. Peter Taylor

AET PROJECT NO: 24-00427

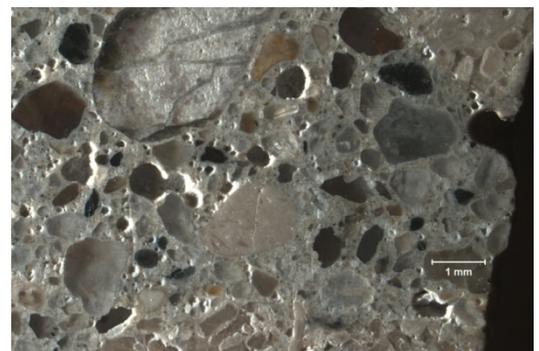
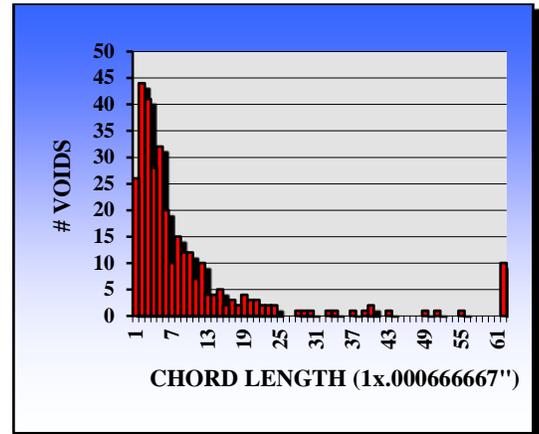
DATE: April 30, 2012

Sample Number: D "effective air 0-0.5in from joint"
Conformance: The section of concrete sample contained an air void system which was not consistent with current technology for freeze-thaw resistance.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 90mm (3 1/2") diameter by
175mm (6 7/8") long

Test Data: By ASTM C:457

Air Void Content %	5.3
Entrained, % < 0.040"(1mm)	3.5
Entrapped, % > 0.040"(1mm)	1.8
Air Voids/inch	7.0
Specific Surface, in ² /in ³	520
Spacing Factor, inches	0.009
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	45
Test Date	4/22/12



Magnification: 15x

Description: Air void system- 60mm depth in core @ joint.

PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 1



SAMPLE ID: D DESCRIPTION: Core sample as received.

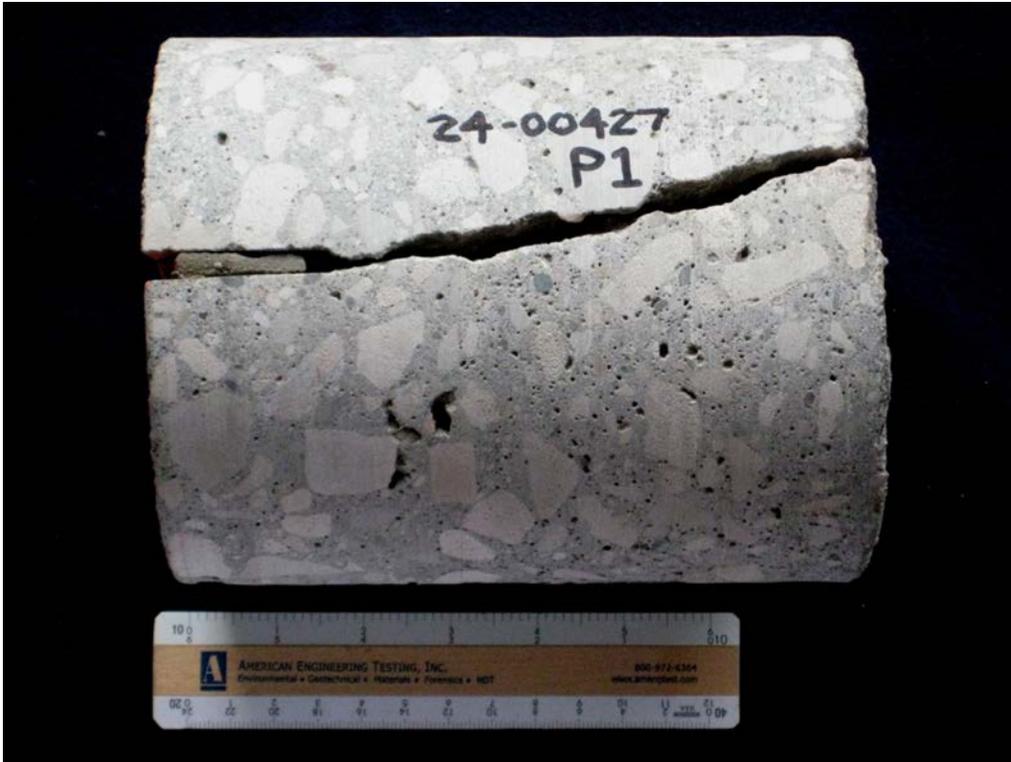
PHOTO: 2



SAMPLE ID: D DESCRIPTION: Top surface of the core as received; covered by orange marking paint. Note core was taken through sawcut control joint; which subsequently "sliver spalled" and was filled with hot-pour joint sealant (now de-bonded).

PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 3



SAMPLE ID: P1 DESCRIPTION: Core sample as received.

PHOTO: 4



SAMPLE ID: P1 DESCRIPTION: Top surface of the core as received; covered by orange marking paint. Note core was taken through a sawcut control joint; which exhibits intermittent "sliver spalling". The joint was filled with hot-pour joint sealant.

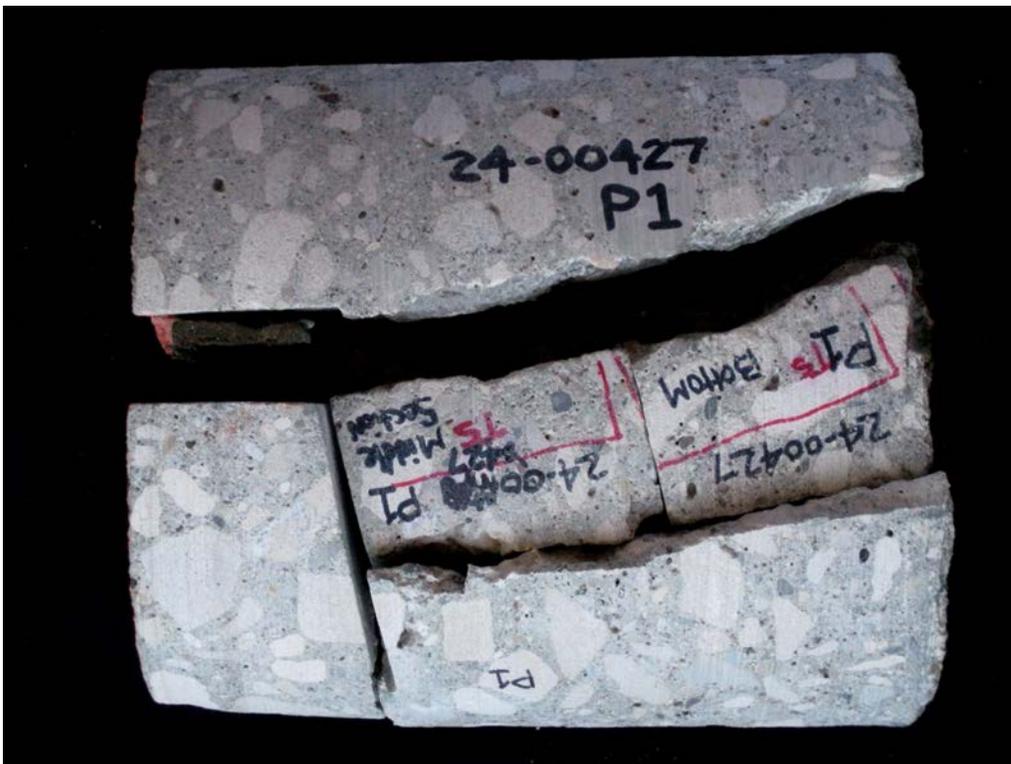
PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 5



SAMPLE ID: D DESCRIPTION: Locations of the thin section produced for analysis.

PHOTO: 6



SAMPLE ID: P1 DESCRIPTION: Locations of the thin section produced for analysis.

PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 7



SAMPLE ID: D **DESCRIPTION:** Sawcut and lapped cross section of core taken through joint. Microcracking is mapped in red ink. Note mass lost along the joint crack and cracking within coarse aggregate particles.

PROJECT: Evaluation of Joint Distress
South Loop Drive

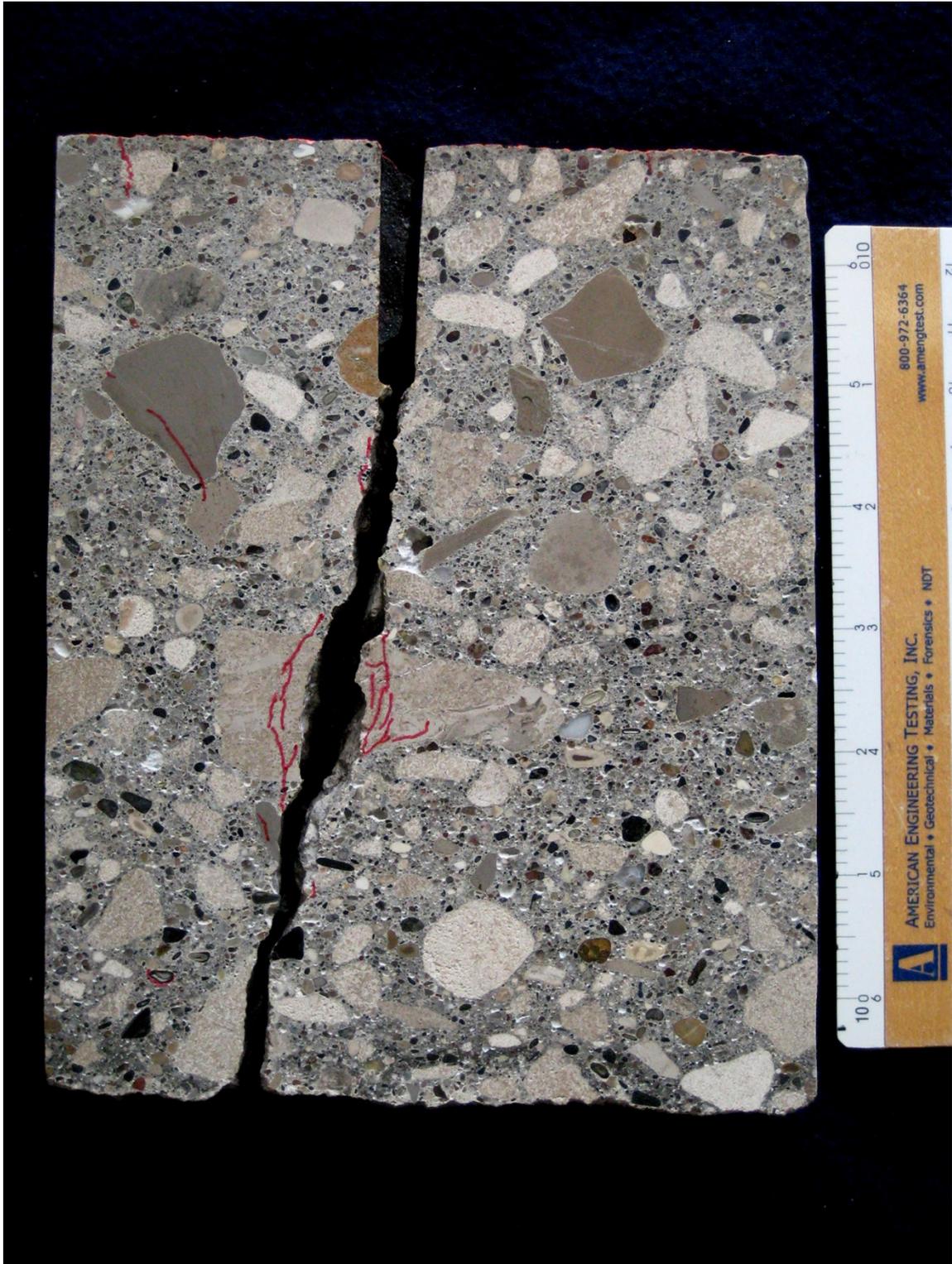


PHOTO: 8

SAMPLE ID: P1 **DESCRIPTION:** Sawcut and lapped cross section of core taken through joint. Microcracking is mapped in red ink. Note mass lost along the joint crack and cracking within the coarse aggregate particle bisected by the joint.

PROJECT: Evaluation of Joint Distress
South Loop Drive

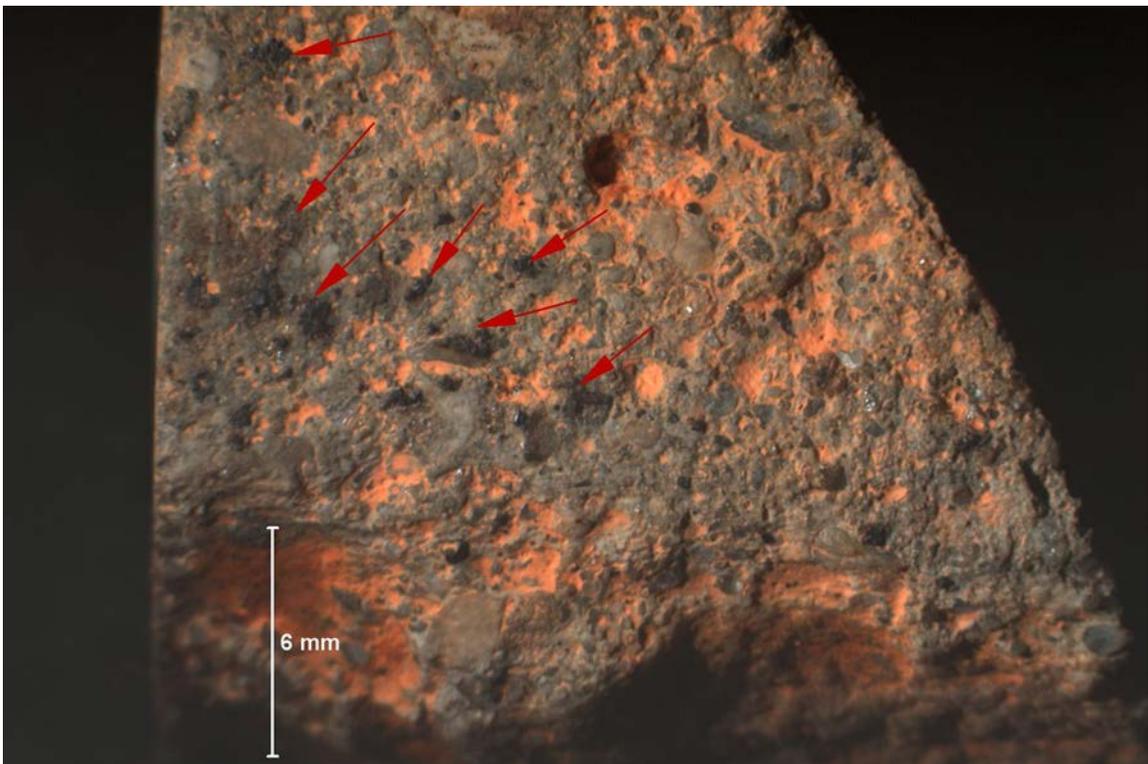
PHOTO: 9



SAMPLE ID: D DESCRIPTION: Mortar-eroded top surface mostly cleaned of orange marking paint.

MAG: 5x

PHOTO: 10



SAMPLE ID: D DESCRIPTION: Sawcut portion of the top surface and joint (bottom of image) exhibiting sliver spalling. Arrows mark corroded metal adhered to exposed aggregates on the top surface.

MAG: 5x

PROJECT: Evaluation of Joint Distress
South Loop Drive

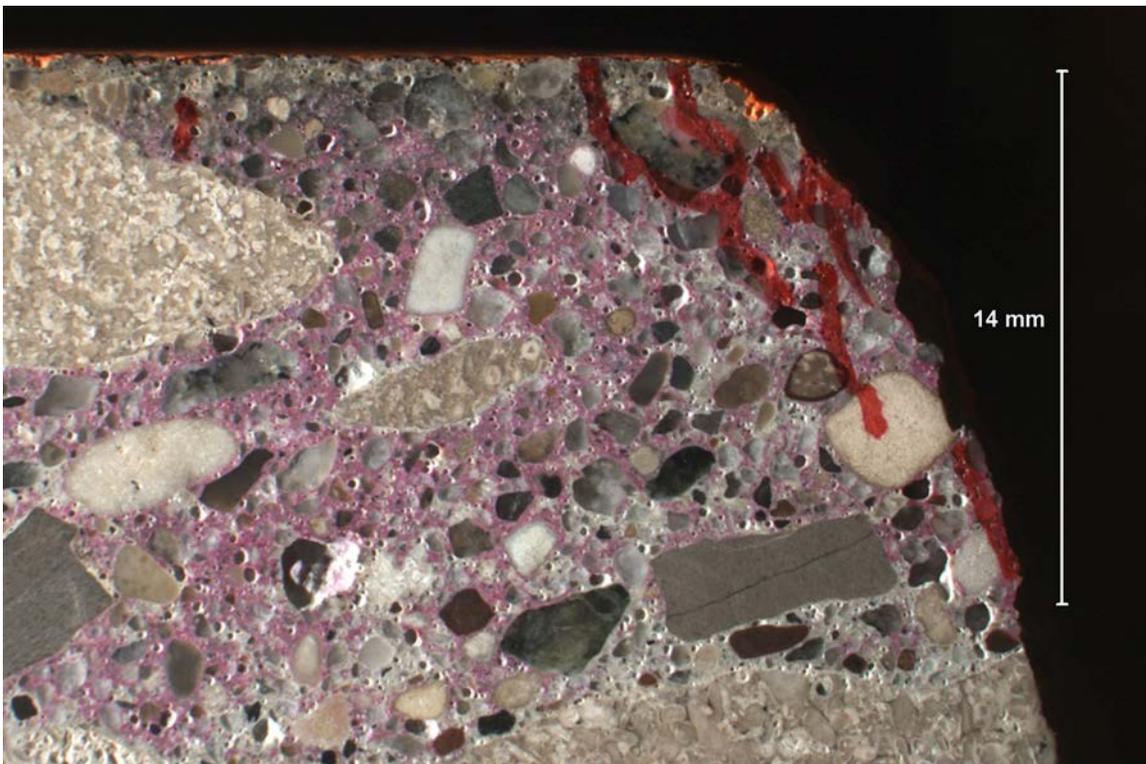
PHOTO: 11



SAMPLE ID: D DESCRIPTION: Incipient sliver spalling in sawcut and lapped cross section of concrete at joint (left).

MAG: 5x

PHOTO: 12



SAMPLE ID: D DESCRIPTION: Another sawcut and lapped section of core exhibiting sliver spalling and incipient spalling mapped in red ink.

MAG: 5x

PROJECT: Evaluation of Joint Distress
South Loop Drive

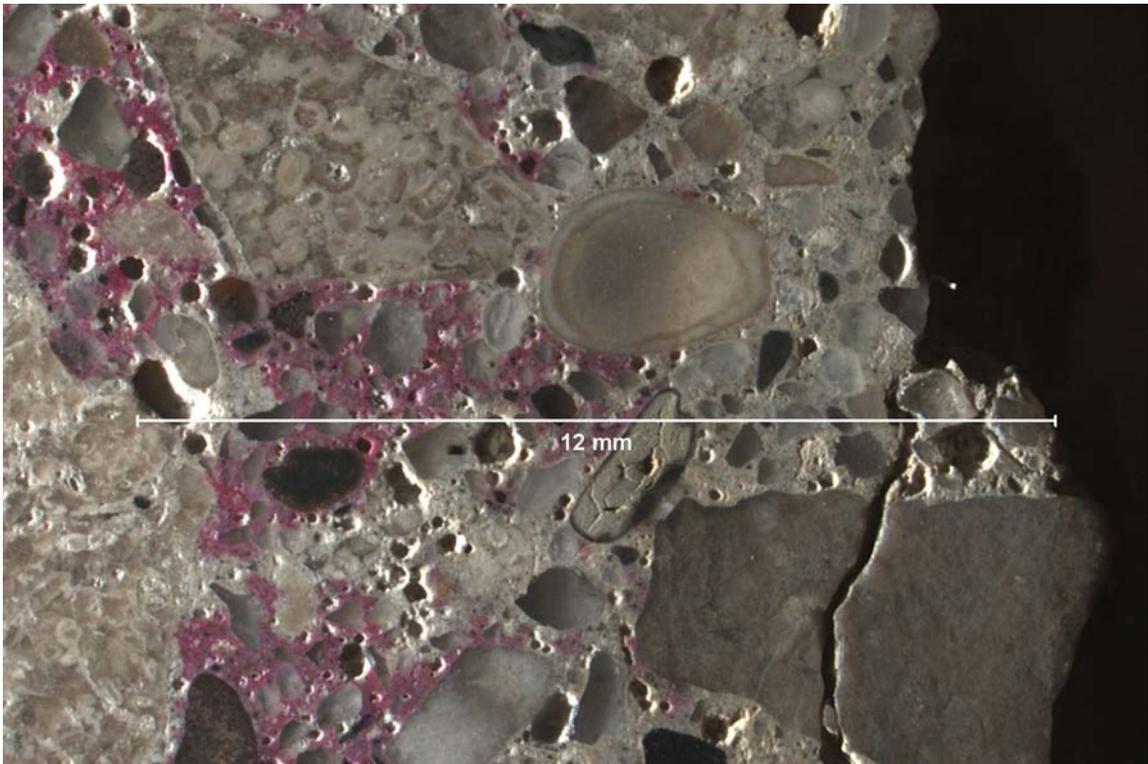
PHOTO: 13



SAMPLE ID: D DESCRIPTION: Carbonation (unstained paste) to 2mm depth from the top surface, in this view.

MAG: 10x

PHOTO: 14

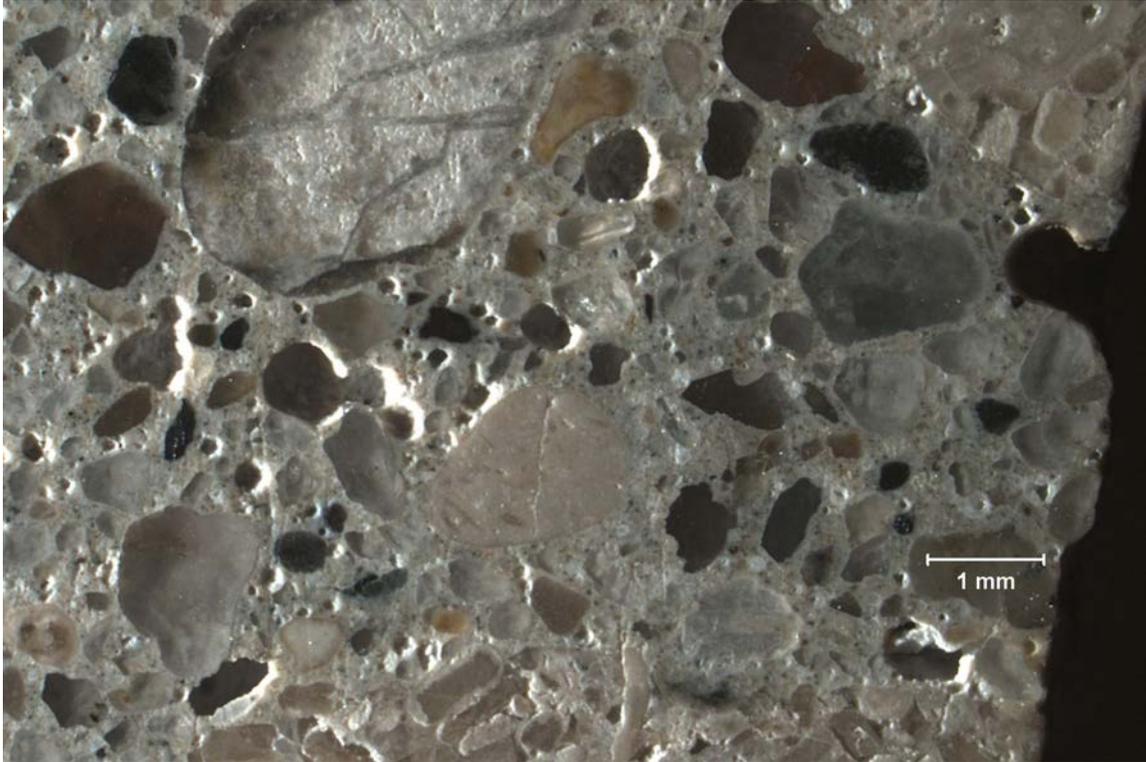


SAMPLE ID: D DESCRIPTION: Apparent carbonation (unstained paste) proceeds up to 12mm depth from the distressed joint plane at approx.75mm depth from the top surface.

MAG: 10x

PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 15



SAMPLE ID: D DESCRIPTION: The great majority of fine spherical entrained air voidspaces at 60mm depth in the core and directly adjacent to the distressed joint (left) are filled with secondary ettringite.
MAG: 15x

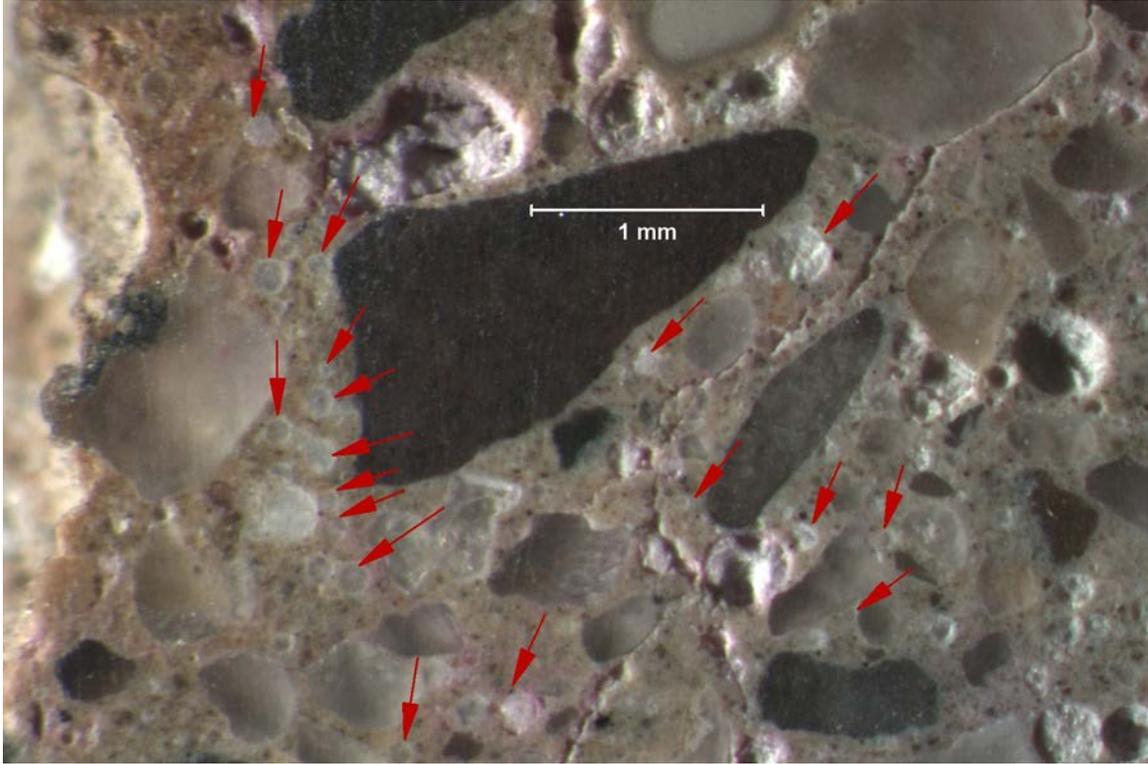
PHOTO: 16



SAMPLE ID: D DESCRIPTION: The great majority of fine spherical entrained air voidspaces at 98mm depth in the core and directly adjacent to the distressed joint (left) are filled with secondary ettringite. Microcracking, oriented sub-parallel to the distressed joint plane, is marked in red dashed line.
MAG: 15x

PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 17

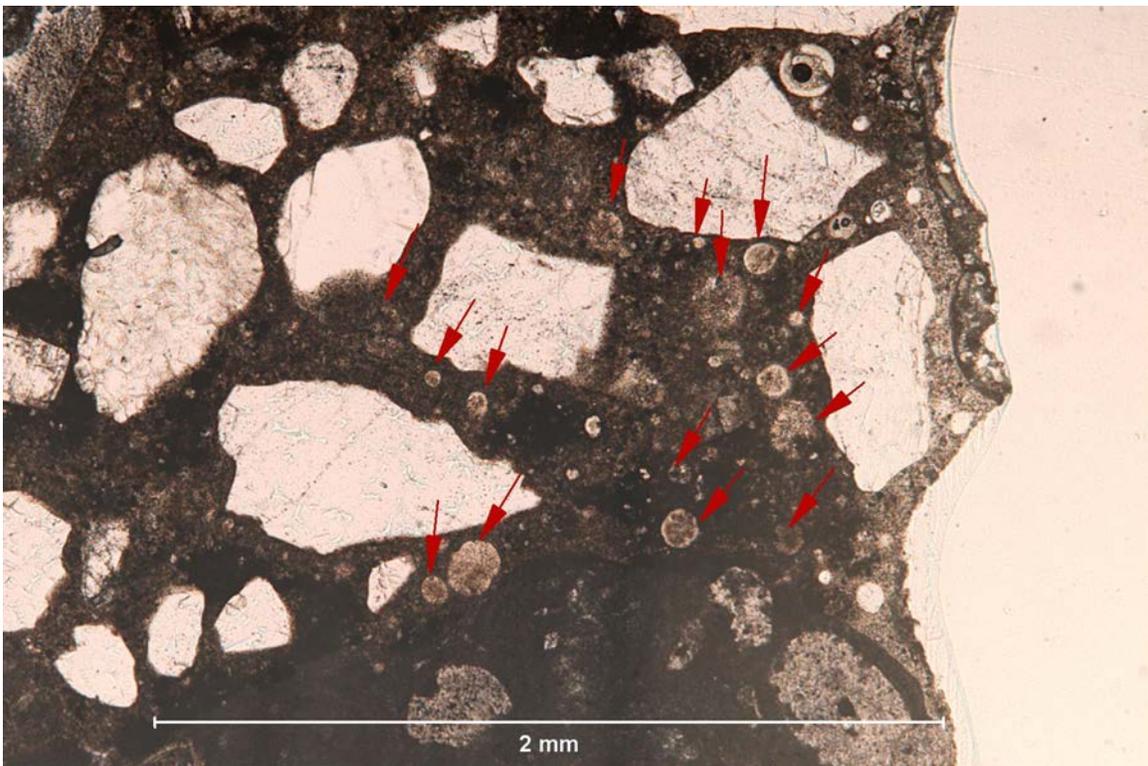


SAMPLE ID: D

DESCRIPTION: The great majority of fine spherical entrained air voidspaces at 98mm depth in the core and directly adjacent to the distressed joint (left) are filled with secondary ettringite.

MAG: 30x

PHOTO: 18



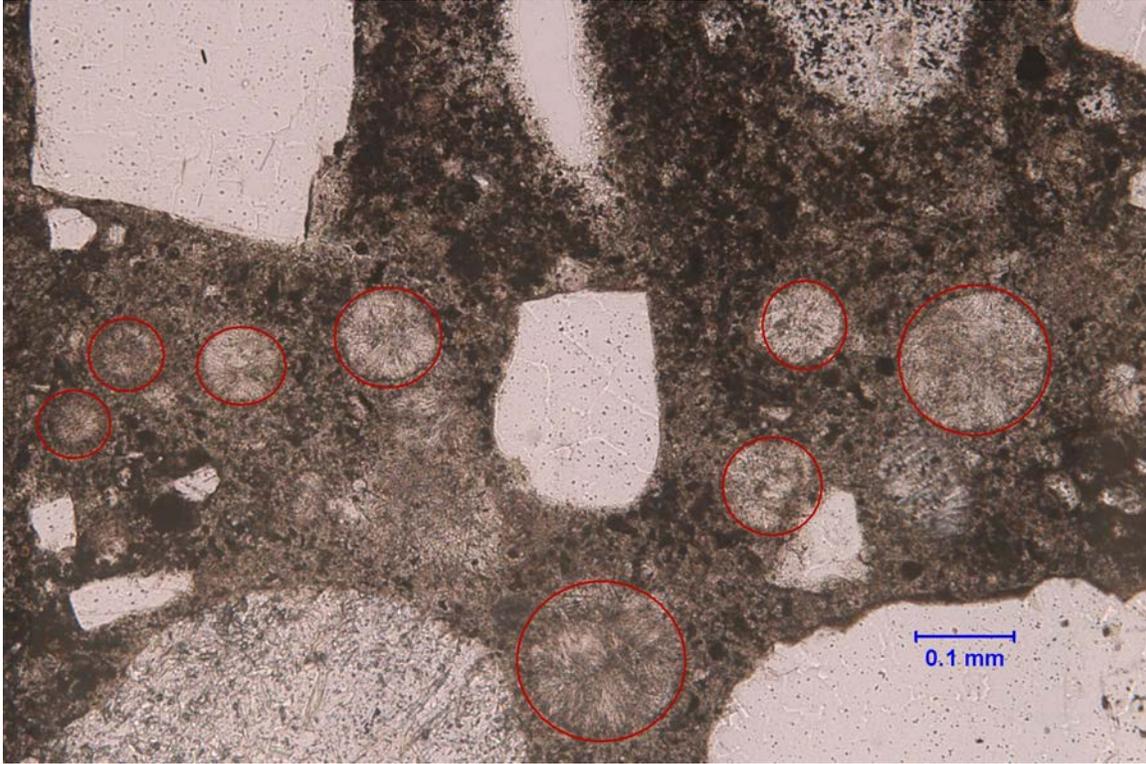
SAMPLE ID: D

DESCRIPTION: Fine spherical entrained air voidspaces at depth in the core, and directly adjacent to the distressed joint (right) are filled with secondary ettringite; in thin section under plane polarized light.

MAG: 40x

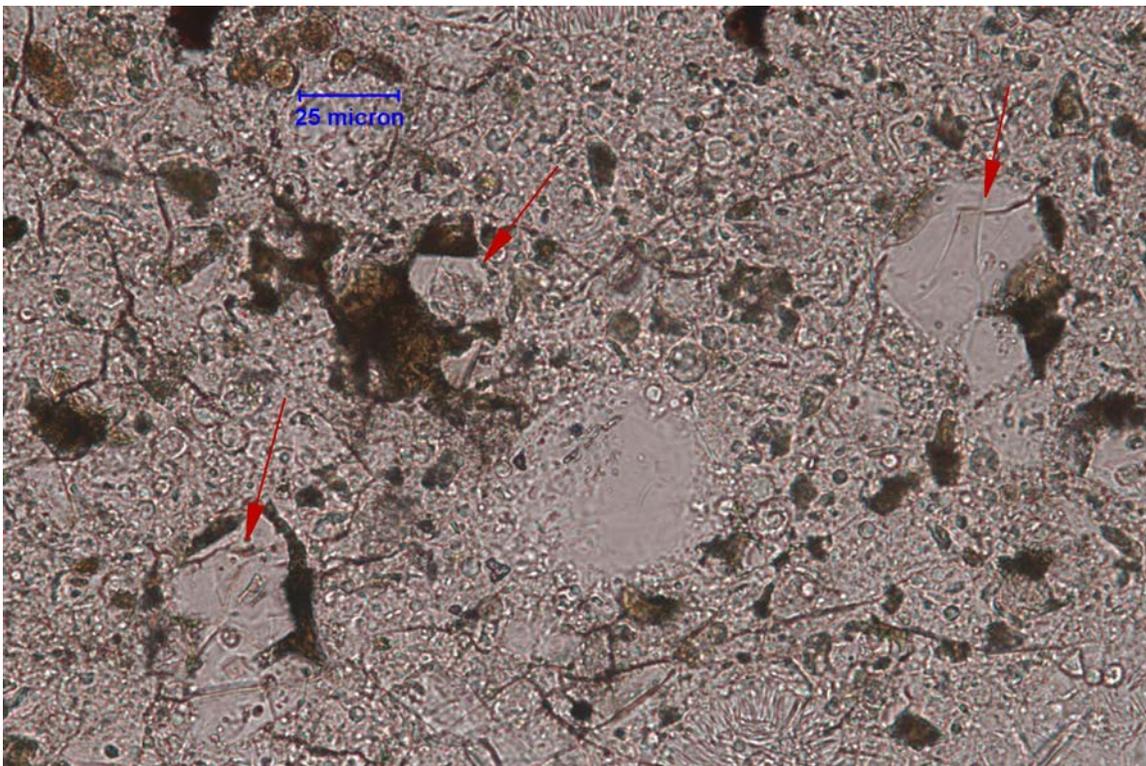
PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 19



SAMPLE ID: D DESCRIPTION: The great majority of fine spherical entrained air voidspaces at depth in the core and directly adjacent to the distressed joint, are filled with secondary ettringite.
MAG: 100x

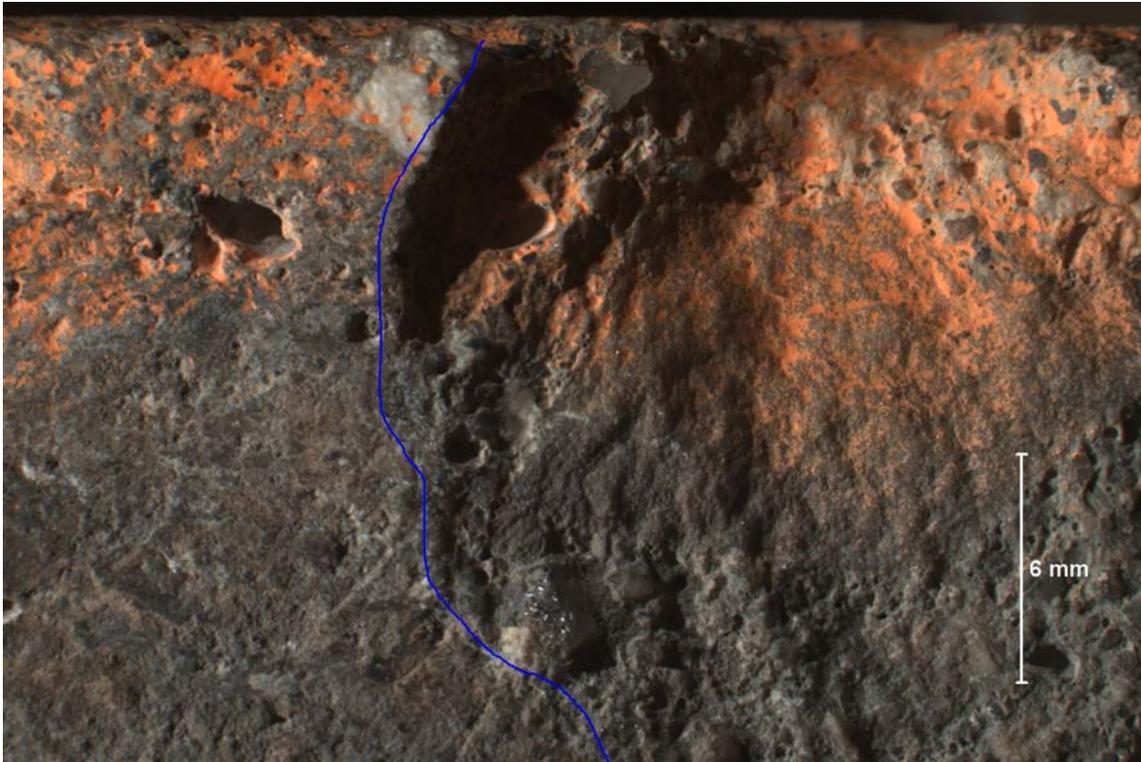
PHOTO: 20



SAMPLE ID: D DESCRIPTION: Fully hydrated alite portland cement clinker relicts (arrows) in thin section of concrete paste under plane polarized light. Note abundant spherical flyash pozzolan particles.
MAG: 400x

PROJECT: Evaluation of Joint Distress
South Loop Drive

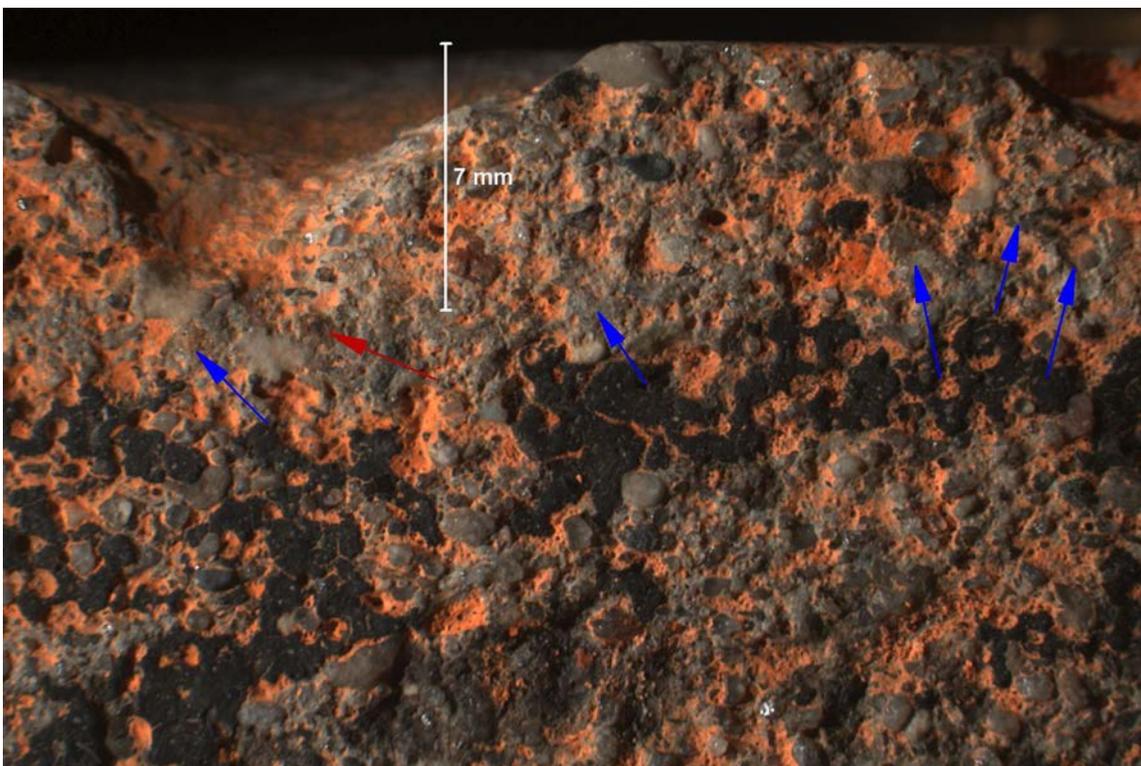
PHOTO: 21



SAMPLE ID: P1 DESCRIPTION: Thin, semi-circular sliver spall (outlined in blue) viewed from within the joint.

MAG: 5x

PHOTO: 22

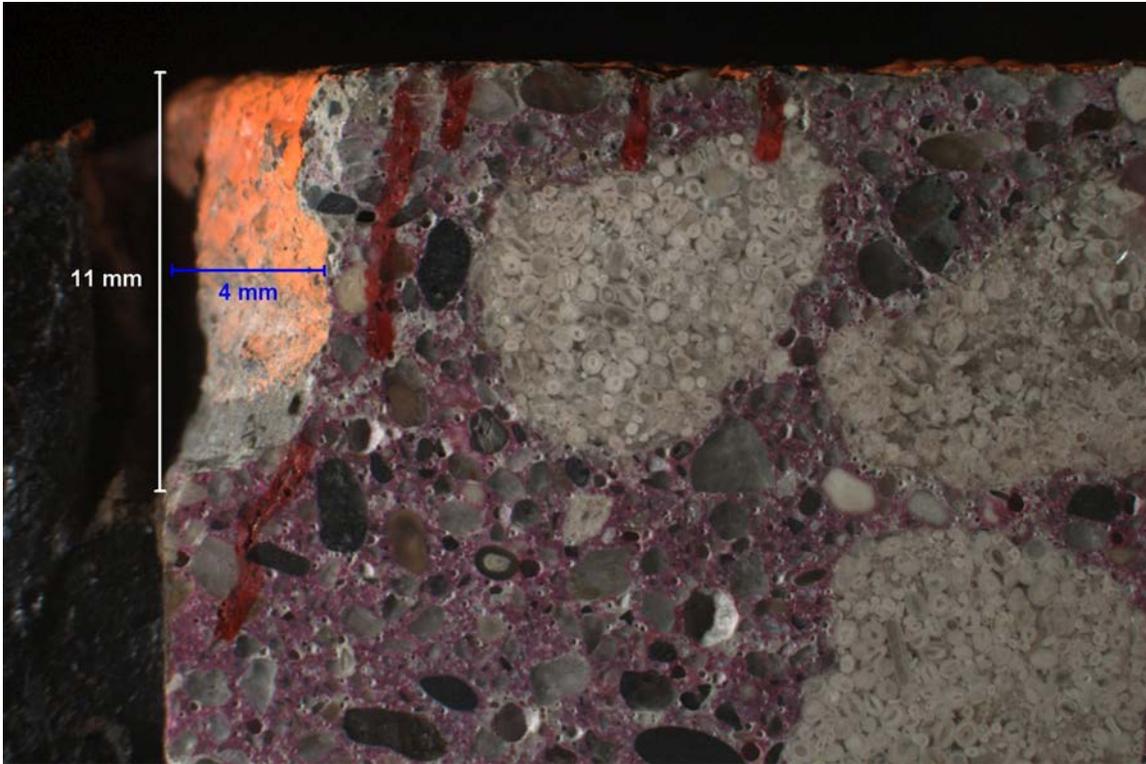


SAMPLE ID: P1 DESCRIPTION: View of the mortar eroded top surface and joint (top of image) exhibiting 7mm wide sliver spalling. Arrows mark corroded metal adhered to exposed aggregates on the top surface.

MAG: 5x

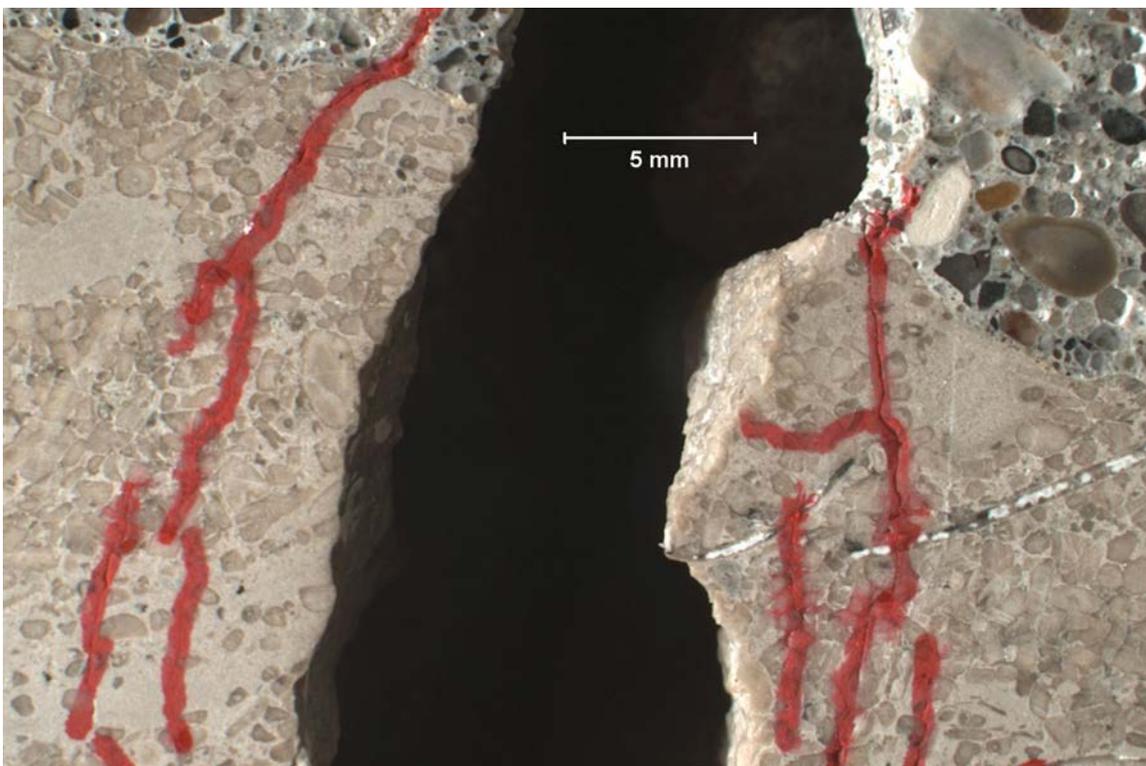
PROJECT: Evaluation of Joint Distress
South Loop Drive

PHOTO: 23



SAMPLE ID: P1 DESCRIPTION: Corner or "sliver" spall viewed in sawcut and lapped cross section of core at the sawcut and sealed joint (left).
MAG: 5x

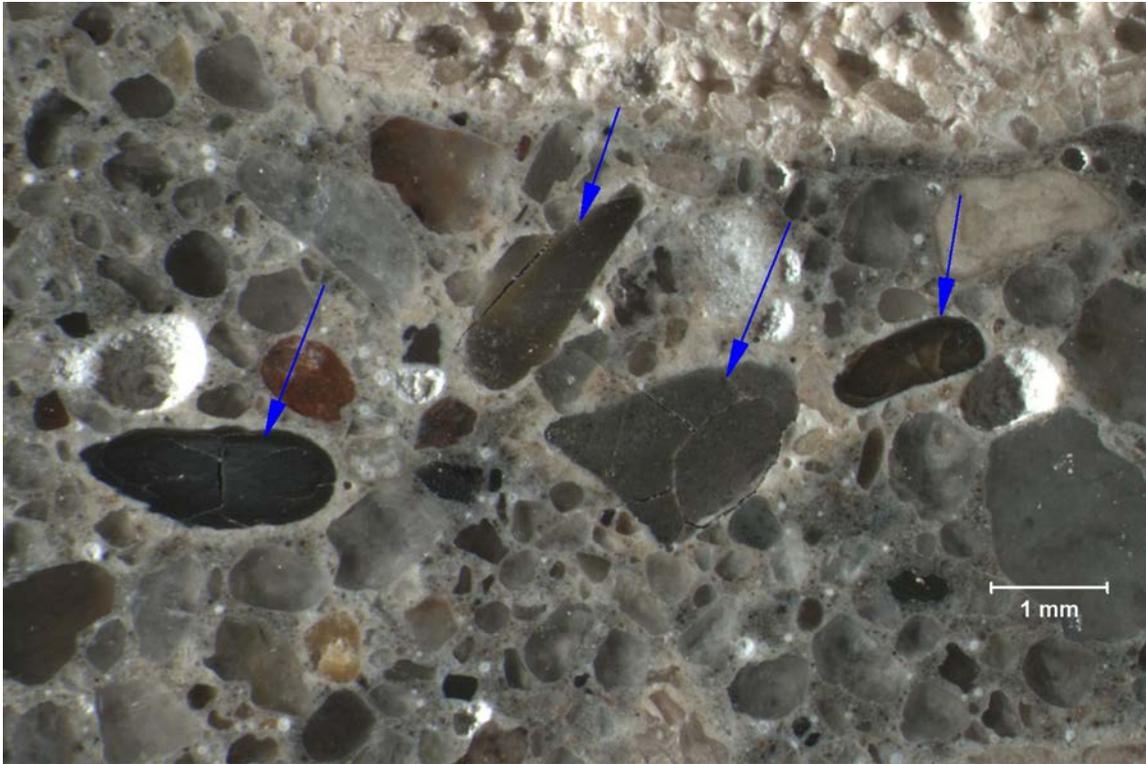
PHOTO: 24



SAMPLE ID: P1 DESCRIPTION: Concentrated microcracking within a coarse aggregate particle bisected by the joint crack and located at below 95mm depth in the core.
MAG: 5x

PROJECT: Evaluation of Joint Distress
South Loop Drive

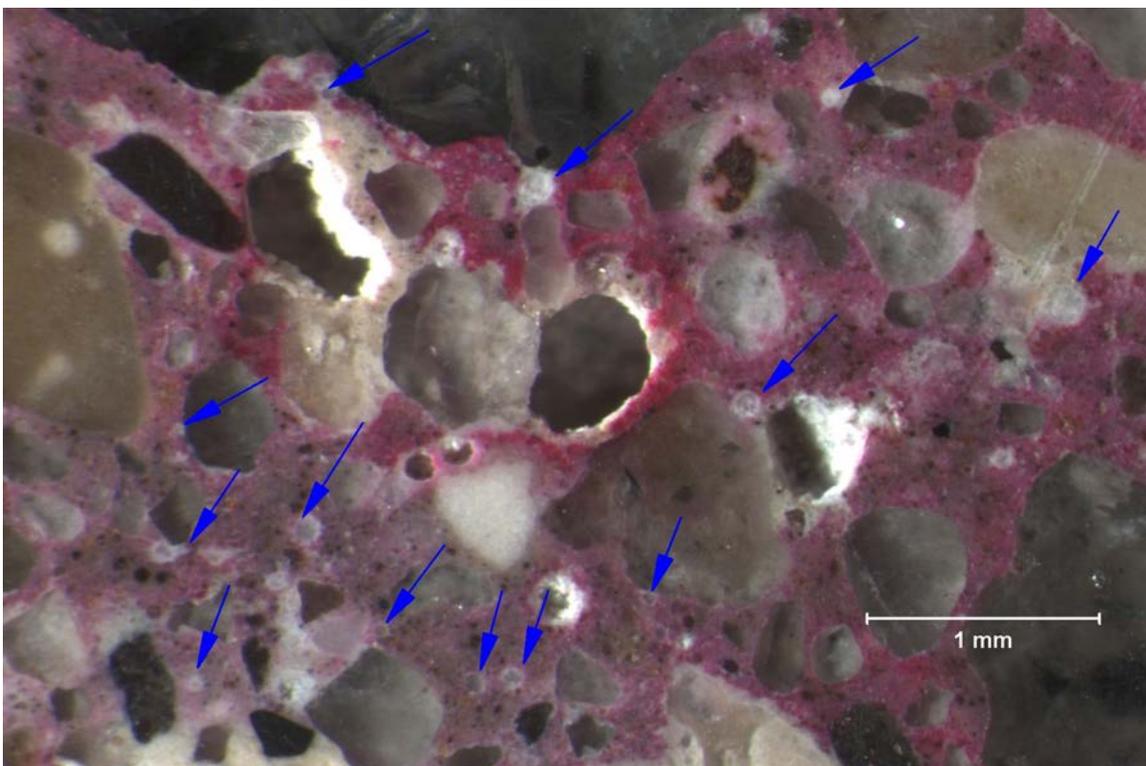
PHOTO: 25



SAMPLE ID: P1 DESCRIPTION: Abundant reactive shale particles at depth in the core.

MAG: 15x

PHOTO: 26



SAMPLE ID: P1 DESCRIPTION: White to clear ettringite-filled voids in phenolphthalein-stained paste within 20mm of the joint.

MAG: 30x

APPENDIX C.

INVESTIGATION OF LOCALIZED JOINT DETERIORATION IN ANKENY, IOWA

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INTRODUCTION

The aim of the work described in this report is to continue collecting information about potential causes of joint deterioration by looking at appropriate field examples.

Reports have been received from projects in several Midwest states that concrete, at joints, is deteriorating prematurely in various types of pavement from 5 to 30 years old.

It is likely that several mechanisms are contributing to the distress at the same time and possible that different deterioration locations are the result of different combinations of these mechanisms.

The work in this report covers an investigation of localized damage occurring on a city street in Ankeny, Iowa.

BACKGROUND

Delaware Avenue is a two-lane arterial street in a suburban neighborhood. The 7 in. portland cement concrete (PCC) pavement was paved in 1976 and was in good condition for 34 years until some joint deterioration became evident, in the last 1.5 to 2 years, at intersections.

Two cores were extracted in 2011 with the intent of investigating the effects of deicing salts on the rate of deterioration. One core (Number 1) was taken at the intersection with 36th Street, a location that is heavily salted because it is a stop street. The other core (Number 2) was taken several panels to the south, where salting is less aggressive, and distress appeared to be less marked at the surface.

The pavement was constructed with a 6 in. crushed stone base that was day-lighted out to the side ditches. Because of clay soil migration into the rock base after 35 years, it is not surprising that there is evidence of saturation in the concrete, particularly at the joints.

PETROGRAPHIC DATA

The full petrographic report is included at the end of this appendix. The findings may be summarized as follows:

- Both cores are damaged, although the degree of distress is lower in Core 2
- The original air void systems of both cores were satisfactory, but had been filled with ettringite (Table 1)
- Some D-cracking was observed

Table 1. Petrographic data

	Core 1	Core 2
Original air content %	5.3	5.7
Effective air content, %	3.3	4.5
Original spacing factor, in.	0.007	0.008
Effective spacing factor, in.	0.012	0.011
Estimated w/cm	0.43-0.48	0.44-0.49

DISCUSSION

The primary goal of the work at this location was to assess potential differences between “heavily-salted” and “moderately-salted” joints.

The less-salted sample appears to be in slightly better condition, particularly at the surface. This finding is supported by the higher effective air content. However, failure is still likely, albeit slightly later, than at the intersection.

It would also appear that the quality of the aggregate is a contributing factor where it is reaching the end of its life after nearly 30 years in service.

PETROGRAPHIC REPORT

The site report follows in this appendix.

REPORT OF CONCRETE ANALYSIS

PROJECT:

Joint Distress Study
Delaware Avenue @ 36th Street
Ankeny, Iowa

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

ATTN: Larry Sutter, PhD

AET PROJECT NO: 24-00427.1

DATE: June 29, 2012

INTRODUCTION

This report presents the results of laboratory work performed by our firm on two concrete core samples submitted by Robert Steffes of the CP Tech Center at Iowa State University on February 21, 2012. We understand the cores were obtained from distressed concrete pavement joints in Delaware Avenue @ 36th Street in Ankeny, Iowa. The pavement was reportedly placed in 1982. The scope of our work was limited to performing petrographic analysis on the two core samples to document the general overall quality, composition, and condition of the concrete cores and determine the cause of the joint distress.

CONCLUSIONS

Based on our observations, test results, and past experience, our conclusions are as follows:

1. The cause of the distress observed in the concrete cores was cyclic freeze/thaw action on saturated concrete which contained unsound coarse aggregate; generally referred to as "D-Cracking". Further, the apparent originally good quality entrained air void system was compromised by secondary crystalline fillings. Excessive secondary ettringite deposition has filled many of the smallest air voids throughout the paste and created "non-durable" air void parameters.
2. In general, the coarse aggregate was hard and durable. However, the aggregate appears to have proven unsound after approximately 29 years of cyclic freeze-thaw while saturated. The particles appear relatively porous. A majority of the cracking in the concrete occurs at various depths and orientations in the cores and appears to concentrate within the coarse aggregate particles. Significant amounts of highly alkali-silica reactive (ASR) fine shale aggregate particles were observed scattered in the core samples. The reactive shales are not a source of the distress.

3. Carbonation ranges from negligible up to 9mm depth from the moderately traffic-worn top surfaces; proceeding along common, fine, sub-vertical, drying shrinkage microcracks. The carbonation is relatively minor and expected for the w/cm and age of the concrete. Both concretes were placed at a "moderately-low" w/cm, estimated to be between 0.43 and 0.49.
4. Both core samples originally contained air void systems with parameters required for freeze-thaw resistance under severe exposure conditions. However, the copious amounts of secondary ettringite have in-filled the finer sized air void spaces pushing the spacing factor parameter of the air void system out of the acceptable limit for freeze-thaw resistance. Core sample #1 originally contained 3.5% of "entrained-sized" air void space. Infilling of fine air voidspaces by secondary ettringite has reduced the percentage of "entrained sized" air void space to 1.9% in the 0-1" of concrete directly adjacent to the distressed joint plane and pushed the original 0.007" spacing factor to 0.012". Core sample #2 originally contained 4.2% of "entrained-sized" air void space. Infilling of fine air voidspaces by secondary ettringite has reduced the percentage of "entrained sized" air void space to 3.3% and pushed the original 0.008" spacing factor to 0.011".
5. The infilling by ettringite is occurring during the saturation of the concrete paste by solutions of deicers and does not require the concrete to be "distressed" before the infilling occurs. Surrounding soils and traditionally mined sodium chloride mineral sources may contain sulfate available for the production of the ettringite. However, it is possible enough sulfate was available in the concrete making materials to fuel the ettringite growth. The concrete paste containing the now "compromised" air void systems were made poorly resistant to cyclic freeze-thaw action by the infilling and are subjected to distress as would any originally poor quality air void system. The distress is progressive at the joints. Poor joint drainage allows constant supply of deicer laden solutions, saturation, and severe freeze-thaw cycling.

SAMPLE IDENTIFICATION

Sample ID:	#1	#2
Sample Location:	NB Delaware	NB Delaware
Sample Type:	147mm (5 3/4") Diameter Hardened Concrete Cores	
Sample Lengths:	180mm (7")	76mm (3")

TEST RESULTS AND SUMMARY OF GENERAL CONCRETE PROPERTIES

Our complete petrographic analysis test results appear on the attached sheets entitled 00 LAB 001 "Petrographic Examination of Hardened Concrete, ASTM:C856." A brief summary of these results is as follows:

1. The coarse aggregate in both cores was comprised of 25mm (1") nominal sized crushed carbonate composed of oolitic and fossiliferous limestone that appeared well graded and exhibited fair overall distribution. The fine aggregate was a natural quartz, feldspar, and lithic glacial sand.
2. Supplementary cementitious materials were not observed in the two concrete samples.
3. The paste color was mottled medium light gray to light tan in core #1 and mostly light gray mottled to light tan. The paste in both cores was judged to be "relatively hard" with the paste/aggregate bond in both cores considered good.
4. The top surface condition of both cores was screeded and tined and now exhibits mortar erosion. The depth of carbonation ranged from negligible up to 6mm from the top surfaces along fine sub-vertical drying shrinkage microcracking.
5. The w/cm in both cores was similar and was estimated to be between 0.43 and 0.49 with approximately 7 to 10% residual portland cement clinker particles.

Air Content Testing

Sample ID	#1 "Original Air"	#1 "Current Air" @ 0-1" Depth from Joint	#2 "Original Air"	#2 "Current Air" Throughout the Sample Depth
Total Air Content (%)	5.3	3.3	5.7	4.5
"Entrained" Air (%) voids < 1mm (0.040")	3.5	1.9	4.2	3.3
"Entrapped" Air (%) voids > 1mm (0.040")	1.8	1.4	1.5	1.2
Spacing Factor, in.	0.007	0.012	0.008	0.011

TEST PROCEDURES

Laboratory testing was performed on February 22, 2012 and subsequent dates. Our procedures were as follows:

Petrographic Analysis

A petrographic analysis was performed in accordance with Standard Operating Procedure 00 LAB 001, "Petrographic Examination of Hardened Concrete," ASTM:C856-latest revision. The petrographic analysis consisted of reviewing the cement paste and aggregate qualities on a whole basis on sawcut and lapped, and fractured sections. Reflected light microscopy was performed under an Olympus SZX-12 binocular stereozoom microscope at magnifications up to 160x. The depth of carbonation was documented using a phenolphthalein pH indicator solution applied on freshly sawcut and lapped surfaces of the concrete sample.

The water/cementitious of the concrete was estimated by viewing a thin section of each concrete under an Olympus BX-51 polarizing light microscope at magnifications of up to 1000x. Thin section analysis was performed in accordance with Standard Operating Procedure 00 LAB 013, "Determining the Water/Cement of Portland Cement Concrete, APS Method." An additional, smaller, sawcut subdivision of each concrete sample is epoxy impregnated, highly polished, and then attached to a glass slide using an optically clear epoxy. Excess sample is sawcut from the glass and the thin slice remaining on the slide is lapped and polished until the concrete reaches 25 microns or less in thickness. Thin section analysis allows for the observation of portland cement morphology, including: phase identification, an estimate of the amount of residual material, and spatial relationships. Also, the presence and relative amounts of supplementary cementitious materials and pozzolans may be identified and estimated.

Air Content Testing

Air content testing was performed using Standard Operating Procedure 00 LAB 003, "Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete, ASTM:C457-latest revision." The linear traverse method was used. The concrete core was sawcut perpendicular with respect to the horizontal plane of the concrete as placed and then lapped prior to testing. The contrast between ettringite filled and unfilled voids was enhanced through the use of phenolphthalein pH indicator solution.

REMARKS

The test samples will be retained for a period of at least sixty days from the date of this report. Unless further instructions are received by that time, the samples may be discarded. Test results relate only to the items tested. No warranty, express or implied, is made.

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
MN License #30023

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00427.1
Sample ID: #1

Date: June 28, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** The core was taken directly through a distressed pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut "normal" to the distressed joint measuring (in total) 180mm (7") x 147mm (5 3/4") x 25mm (1") thick cross section, an approx. 180mm (7") x 147mm (5 3/4") x 57mm (2 1/4") thick cross section, and two 70mm (2 3/4") x up to 52mm (2") wide thin sections that were sawcut and prepared from the original 147mm (5 3/4") diameter x 180mm (7") long core. The thin sections were located between 30mm and 100mm depth and 100mm and the bottom surface of the core, in cross section and along the distressed surface of the joint.
2. **Surface Conditions:**
Top: Rough screeded and tined surface with mortar erosion exposing many fine aggregate particles; partly covered by a coat of orange marking paint.
Bottom: Rough, irregular, formed surface; placed upon sub-grade.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core exhibits poor overall condition. The core was taken through a moderately distressed pavement joint, at depth. The joint exhibits intermittent sliver spalls at the top surface and vertical scaling/spalling at depth in the joint crack. The original joint was characterized by a single approx. 6mm wide sawcut proceeding to 45mm (1 3/4") depth from the top surface. A joint sealant was not present. The sliver spalling occurs on both sides of the joint; occurring intermittently on one side of the joint to 5mm laterally and to 15mm depth; and proceeding up to 19mm depth into the concrete from the top surface over nearly half the diameter of the core before intersecting vertical spalling in the joint below. Abundant concentrations of corroded mass of iron metal were observed embossed upon exposed fine aggregates and ground topographic concrete surface highs.

Incipient vertical scaling/spalling starts at as shallow as 19mm (3/4") depth, incorporating between approx. 5mm and 25mm of apparent total concrete paste and carbonate aggregate between the two sides of the joint crack. The maximum loss of concrete occurs at approx. 85mm depth. Concentrated sub-vertical microcracks (incipient spalling) were observed at random depths along the distress and within 7mm of the distressed joint surface. Abundant, randomly oriented microcracks occur through the concrete, generally below 1" depth, and appear to concentrate within much of the coarse aggregate.

The concrete was fairly well consolidated, with few voidspaces observed in excess of 6mm in diameter. The concrete was purposefully air entrained and originally contained a well-distributed air void system generally considered freeze-thaw resistant under severe exposure conditions. Original air-void parameters include a 3.5% entrained air void volume with a 0.178mm (0.007") spacing factor. Secondary ettringite, with some portlandite, fills most of the smaller entrained sized voidspaces within 25mm (1") of the distressed joint plane; apart from the top approx. 35mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling within 10mm of the distressed joint plane. Actual measured air void parameters, excluding the ettringite void fillings, in a band between approx. 0mm and 25mm (0"-1.0") depth from the distressed joint surface, are 1.9% entrained volume (a loss of 1.6% volume) with a 0.012" spacing factor.

II. Aggregate

1. **Coarse:** 25mm (1") nominal sized crushed carbonate composed chiefly of variably buff to pale yellowish brown-colored, oolitic and fossiliferous limestone. The coarse aggregate appeared well graded and exhibited fair overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic (granite, graywacke, carbonates, chert, and numerous reactive shale grains) sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 5.3% total original air.
2. Depth of carbonation: Ranged from negligible up to 6mm depth, intermittently from the top surface of the core, along very fine sub-vertical microcracking. Ranged from negligible up to 2mm depth from the sawcut joint surface. Carbonation ranged from negligible up to 11mm depth from the distressed joint plane.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Good.
5. Paste color: Mottled Medium Light Gray (Munsell® N6) to light tan. Sub-vitreous.
6. Paste hardness: Relatively hard (>Moh's 3.5)
7. Microcracking: Several, fine, sub-vertical drying shrinkage microcracks proceed up to a 7mm maximum depth from the top surface. Concentrated sub-vertical microcracks (incipient spalling) were observed at random depths along the distress and within 7mm of the distressed joint surface. Abundant, randomly oriented microcracks occur through the concrete, generally below 1" depth, and appear to concentrate within much of the coarse aggregate. Microcracks were common within, surrounding, and shallowly radiating from numerous alkali-silica reactive shale fine aggregate particles.
8. Secondary deposits: White needly ettringite and a small amount of clear tabular portlandite fills many of the smaller entrained sized voidspaces throughout the depth of the core apart from the top approx. 35mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling below 40mm depth and within 10mm of the distressed joint plane. Clear to white ASR gel product lines or fills voidspaces adjacent to numerous reactive fine aggregate particles.
9. w/cm: Estimated at between 0.43 and 0.48 with approximately 8 to 10% residual portland cement clinker particles.
10. Cement hydration: Alites: Mostly fully.
Belites: Well to mostly fully.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00427.1
Sample ID: #2

Date: June 28, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** The core was taken directly through a distressed pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut "normal" to a the distressed joint measuring (in total) 147mm (5 3/4") x 76mm (3") x 32mm (1 1/4") thick cross section, an approx. 147mm (5 3/4") x 76mm (3") 57mm (2 1/4") thick cross section, and two 70mm (2 3/4") x up to 52mm (2") wide thin sections that were sawcut and prepared from the original 147mm (5 3/4") diameter x 76mm (3") long core. The thin sections were located between 0mm and 75mm depth and 25mm and 75mm depth in the core, in cross section and along the distressed surface of the joint.
2. **Surface Conditions:**
Top: Rough screeded and tined surface with mortar erosion exposing many fine aggregate particles; partly covered by a coat of orange marking paint.
Bottom: Rough, irregular, fractured or spalled surface.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core exhibits poor overall condition. The core was taken through a severely distressed sawcut pavement joint. The joint exhibits vertical spalling to the top surface with no sawcut surface remaining, on one side of the joint, and vertical scaling/spalling at generally below 32mm (1 1/4") depth along the sawcut. However, a shallow spall occurs to approx. 4mm depth into the sawcut and within 10mm depth from the top surface. A complete loss of concrete occurs at below 52mm (2") depth on one side of the joint and below approx. 60mm (2 1/4") depth on the other side of the joint crack. The original joint was characterized by a single approx. 6mm wide sawcut proceeding to at least 35mm depth from the top surface. Remnants of an asphalt "repair" coats much of the spalled side of the joint surface.

Sub-vertical incipient scaling/spalling occurs to 10mm (3/8") depth from the spalled side of the vertical joint before becoming sub-horizontally oriented below 22mm depth in the concrete. On the other side of the joint, concentrated sub-horizontal microcracks (incipient spalling) were observed at between 6mm and 19mm depth and below 32mm depth. The cracking appears to concentrate within several of the coarse aggregates.

The concrete was fairly well consolidated, with few voidspaces observed in excess of 6mm in diameter. The concrete was purposefully air entrained and originally contained a well-distributed air void system generally considered freeze-thaw resistant under severe exposure conditions. Original air-void parameters include a 4.2% entrained air void volume with a 0.203mm (0.008") spacing factor. Secondary ettringite, with some portlandite, fills most of the smaller entrained sized voidspaces below the top approx. 25mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling within 10mm of the distressed joint plane. Actual measured air void parameters, excluding the ettringite void fillings, are 3.3% entrained volume (a loss of 0.9% volume) with a 0.279mm (0.011") spacing factor.

II. Aggregate

1. **Coarse:** 25mm (1") nominal sized crushed carbonate composed chiefly of variably buff to pale yellowish brown-colored, oolitic and fossiliferous limestone. The coarse aggregate appeared well graded and exhibited fair overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic (granite, graywacke, carbonates, chert, and numerous reactive shale grains) sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. **Air Content:** 5.3% total original air.

2. Depth of carbonation: Ranged from negligible up to 6mm depth from the top surface of the core, along very fine sub-vertical microcracking. Ranged from negligible up to 10mm depth from the sawcut joint surface and distressed joint plane.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Good.
5. Paste color: Mostly Light Gray (Munsell® N6) mottled to light tan. Sub-vitreous.
6. Paste hardness: Relatively hard (>Moh's 3.5)
7. Microcracking: Several, fine, sub-vertical drying shrinkage microcracks proceed up to a 5mm maximum depth from the top surface. Concentrated sub-vertical microcracks (incipient spalling) were observed on one side of the joint within 10mm of the distressed joint surface. Microcracks were common within, surrounding, and shallowly radiating from numerous alkali-silica reactive shale fine aggregate particles. On the other side of the joint, concentrated sub-horizontal microcracks (incipient spalling) were observed at between 6mm and 19mm depth and below 32mm depth. The cracking appears to concentrate within several of the coarse aggregates.
8. Secondary deposits: White needly ettringite and a small amount of clear tabular portlandite fills many of the smaller entrained sized voidspaces throughout the depth of the core apart from the top approx. 35mm. The finest void fillings generally increase with depth from the top surface and decrease with distance from the joint, with the greatest degree of void filling below 25mm depth and within 10mm of the distressed joint plane. Clear to white ASR gel product lines or fills voidspaces adjacent to numerous reactive fine aggregate particles. Secondary calcite lines to fills a few fine microcracks oriented sub-parallel and proximate to the distressed surface. Calcite also cements debris to the distressed joint plane.
9. w/cm: Estimated at between 0.44 and 0.49 with approximately 7 to 9% residual portland cement clinker particles.
10. Cement hydration: Alites: Mostly fully.
Belites: Well to mostly fully.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
Delaware @ 36th Street
Ankeny, IA

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

ATTN: Dr. Peter Taylor

AET PROJECT NO: 24-00427

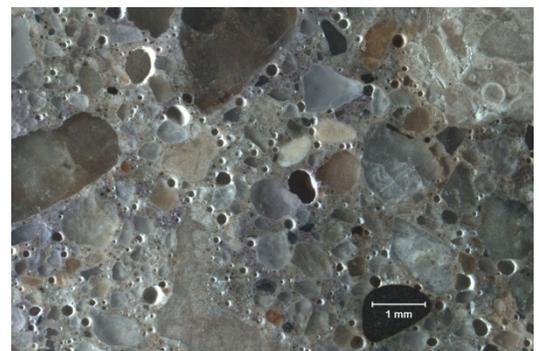
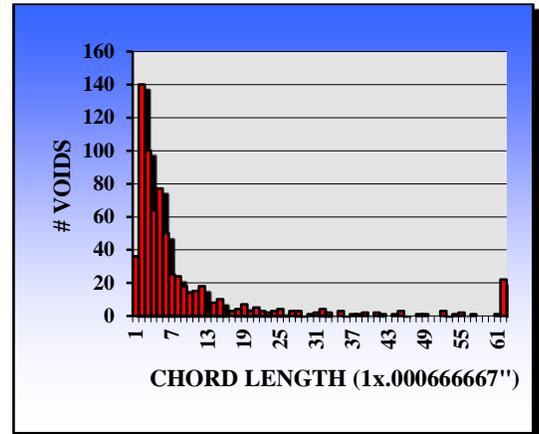
DATE: June 28, 2012

Sample Number: #1 "original air"
Conformance: The sample originally contained an air void system which was generally consistent with current technology for freeze-thaw resistance.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 155mm (6") diameter by 180mm (7") long

Test Data: By ASTM C:457

Air Void Content %	5.3
Entrained, % < 0.040"(1mm)	3.5
Entrapped, % > 0.040"(1mm)	1.8
Air Voids/inch	7.0
Specific Surface, in ² /in ³	540
Spacing Factor, inches	0.007
Paste Content, % estimated	20.9
Magnification	75x
Traverse Length, inches	99
Test Date	5/23/12



Magnification: 15x

Description: Air void system- top 10mm of core.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
Delaware @ 36th Street
Ankeny, IA

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

AET PROJECT NO: 24-00427**ATTN:** Dr. Peter Taylor
DATE: June 28, 2012

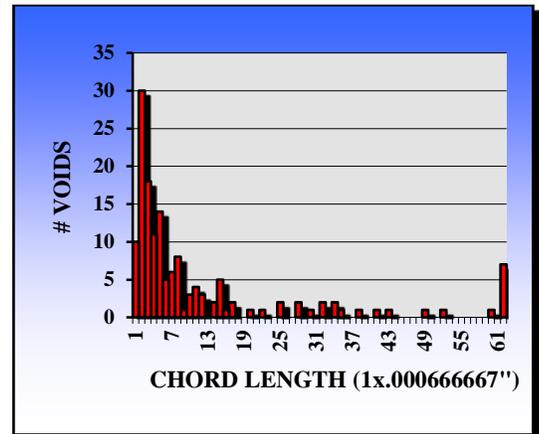
Sample Number: #1 "Current Air"
0-1" Depth from Distress

Conformance: The concrete at this location no longer contains an air void system consistent with current technology for freeze-thaw resistance.

Sample Data
By ASTM C457
Description: Hardened Concrete Core
Dimensions: 155mm (6") diameter by 180mm (7") long

Test Data: By ASTM C:457

Air Void Content %	3.3
Entrained, % < 0.040"(1mm)	1.9
Entrapped, % > 0.040"(1mm)	1.4
Air Voids/inch	3.3
Specific Surface, in ² /in ³	400
Spacing Factor, inches	0.012
Paste Content, % estimated	16.4
Magnification	75x
Traverse Length, inches	45
Test Date	5/24/12



Magnification: 15x

Description: Air void system at joint 140mm depth.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
Delaware @ 36th Street
Ankeny, IA

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

ATTN: Dr. Peter Taylor

AET PROJECT NO: 24-00427

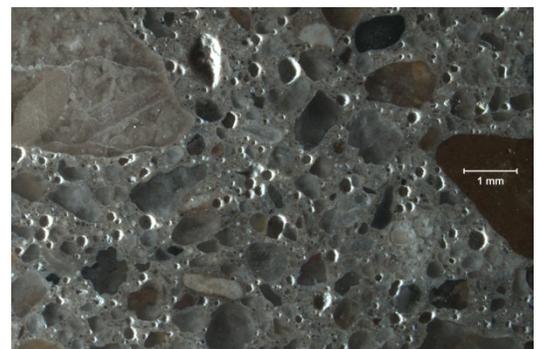
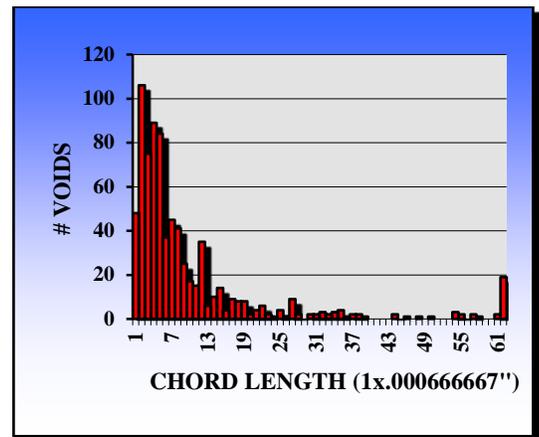
DATE: June 28, 2012

Sample Number: #2 "original air"
Conformance: The sample originally contained an air void system which was generally consistent with current technology for freeze-thaw resistance.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 155mm (6") diameter by 75mm (3") long

Test Data: By ASTM C:457

Air Void Content %	5.7
Entrained, % < 0.040"(1mm)	4.2
Entrapped, % > 0.040"(1mm)	1.5
Air Voids/inch	7.7
Specific Surface, in ² /in ³	540
Spacing Factor, inches	0.008
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	99
Test Date	5/23/12



Magnification: 15x

Description: Air void system- top 10mm of core.

AIR VOID ANALYSIS

PROJECT:

Evaluation of Joint Distress
Delaware @ 36th Street
Ankeny, IA

REPORTED TO:

National Concrete Pavement Technology Center
2711 South Loop Drive, #4700
Ames, IA 50010

AET PROJECT NO: 24-00427**ATTN:** Dr. Peter Taylor
DATE: June 28, 2012**Sample Number:**

#2

Conformance:

“Current Air Void System”
The sample currently contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data

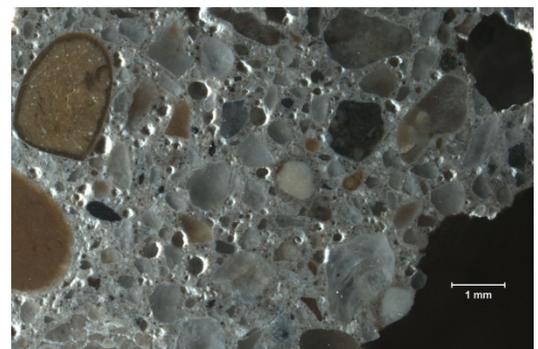
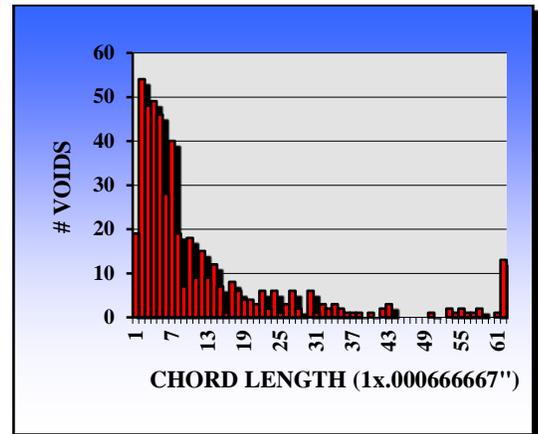
Description: Hardened Concrete Core
Dimensions: 155mm (6”) diameter by
75mm (3”) long

By ASTM C457

Test Data:

By ASTM C:457

Air Void Content %	4.5
Entrained, % < 0.040”(1mm)	3.3
Entrapped, % > 0.040”(1mm)	1.2
Air Voids/inch	4.9
Specific Surface, in ² /in ³	440
Spacing Factor, inches	0.011
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	99
Test Date	5/24/12

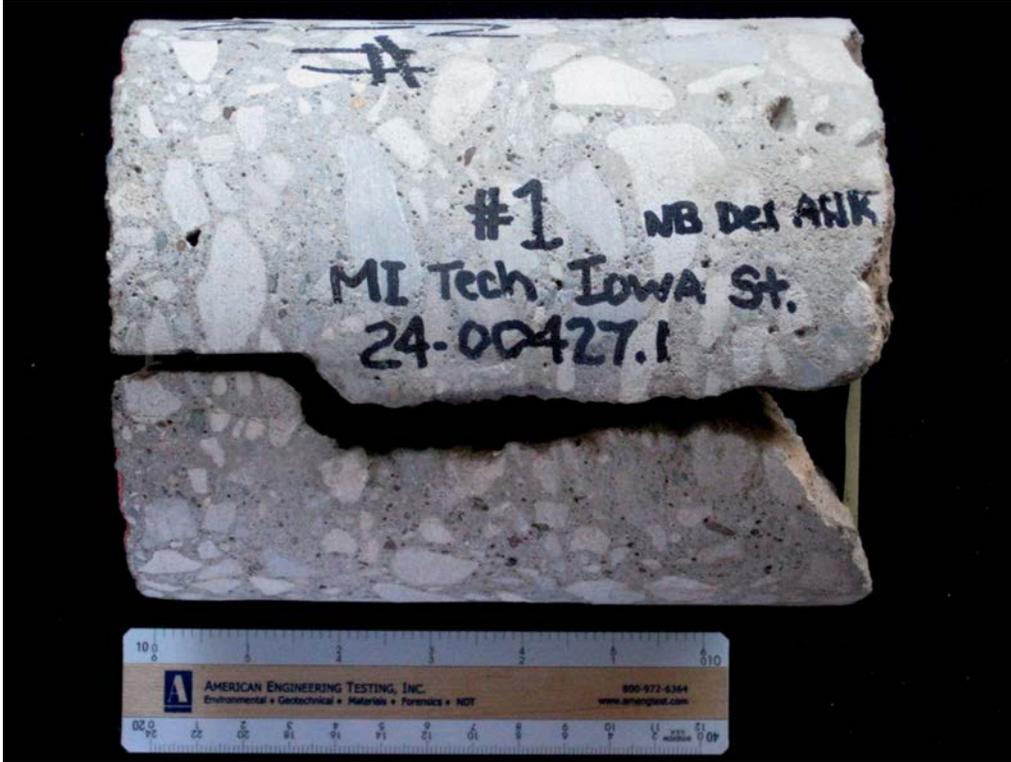


Magnification: 15x

Description: Air void system at joint at 55mm depth..

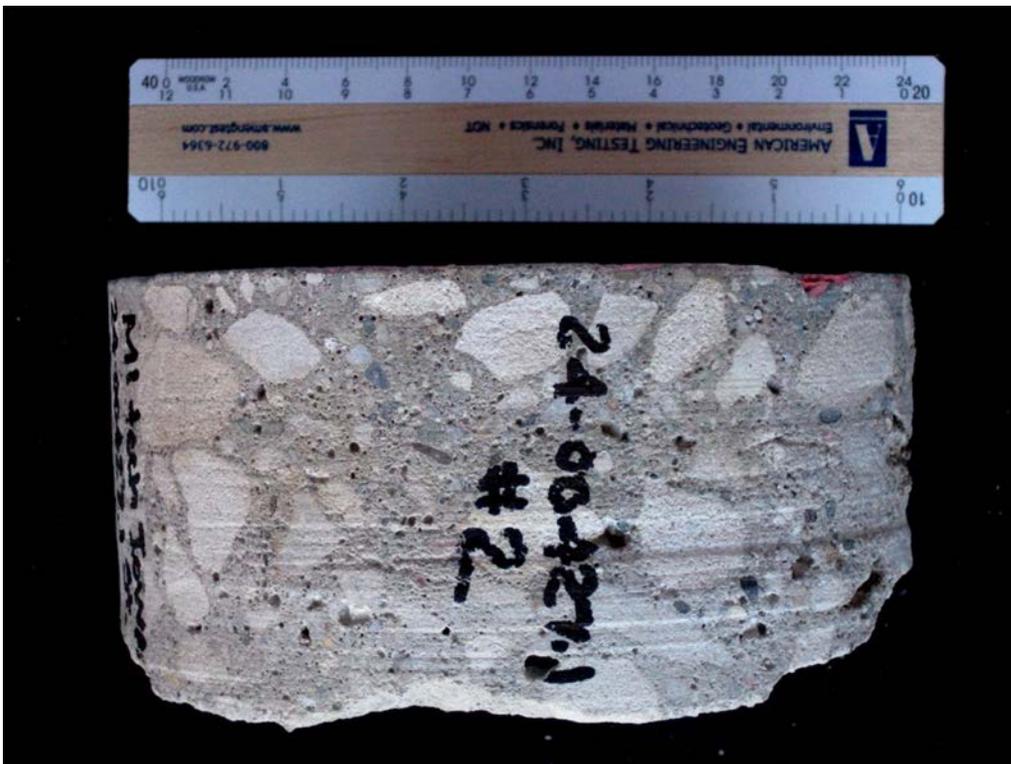
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 1



SAMPLE ID: #1 DESCRIPTION: Core sample as received. The top surface is left.

PHOTO: 2



SAMPLE ID: #2 DESCRIPTION: The 75mm long core sample as received.

PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 3



SAMPLE ID: #1 DESCRIPTION: Top surface of the core sample, taken directly through a joint, as received.

PHOTO: 4



SAMPLE ID: #2 DESCRIPTION: The top surface of the core sample, taken directly through a joint, as received.

PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

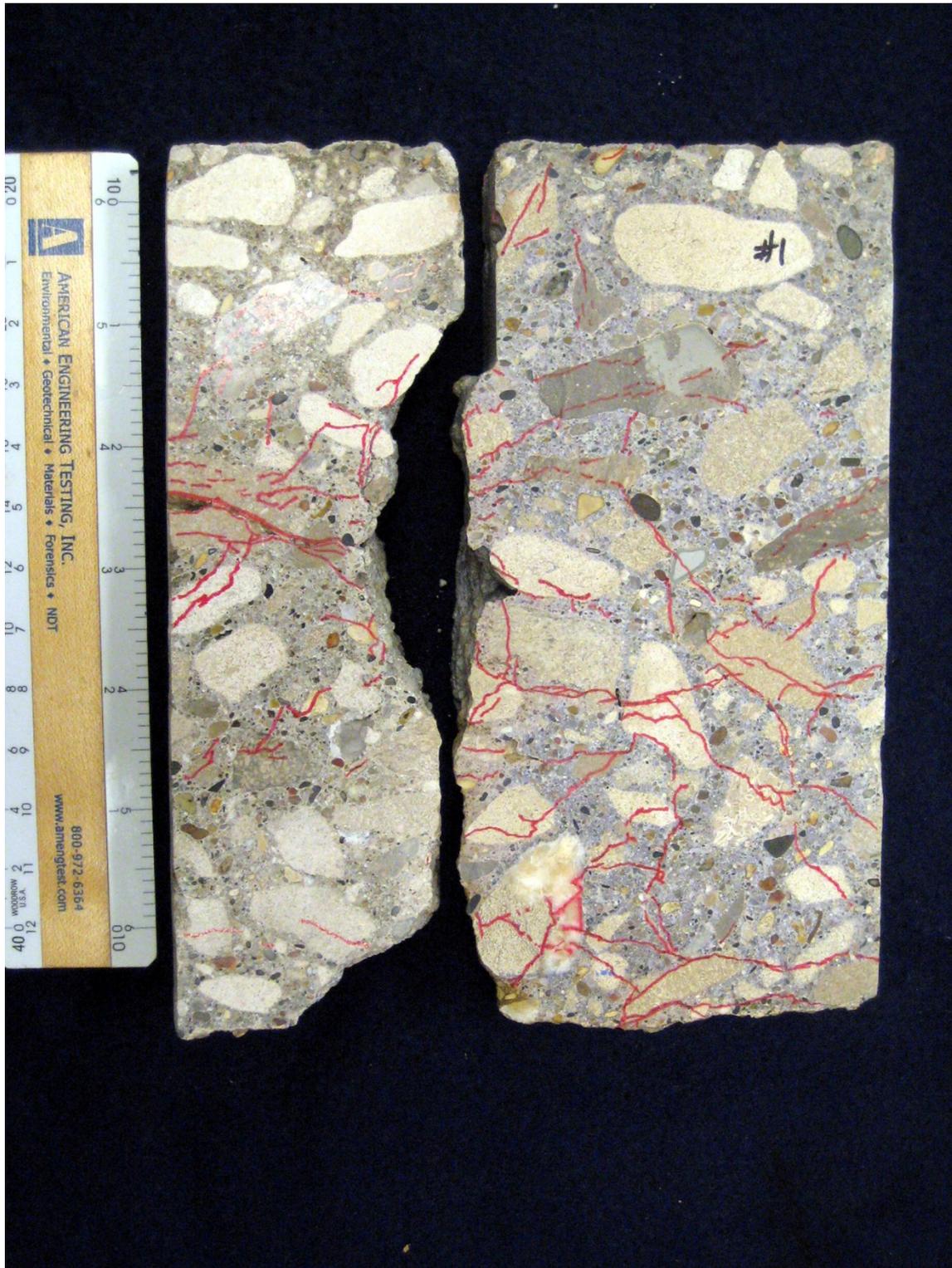
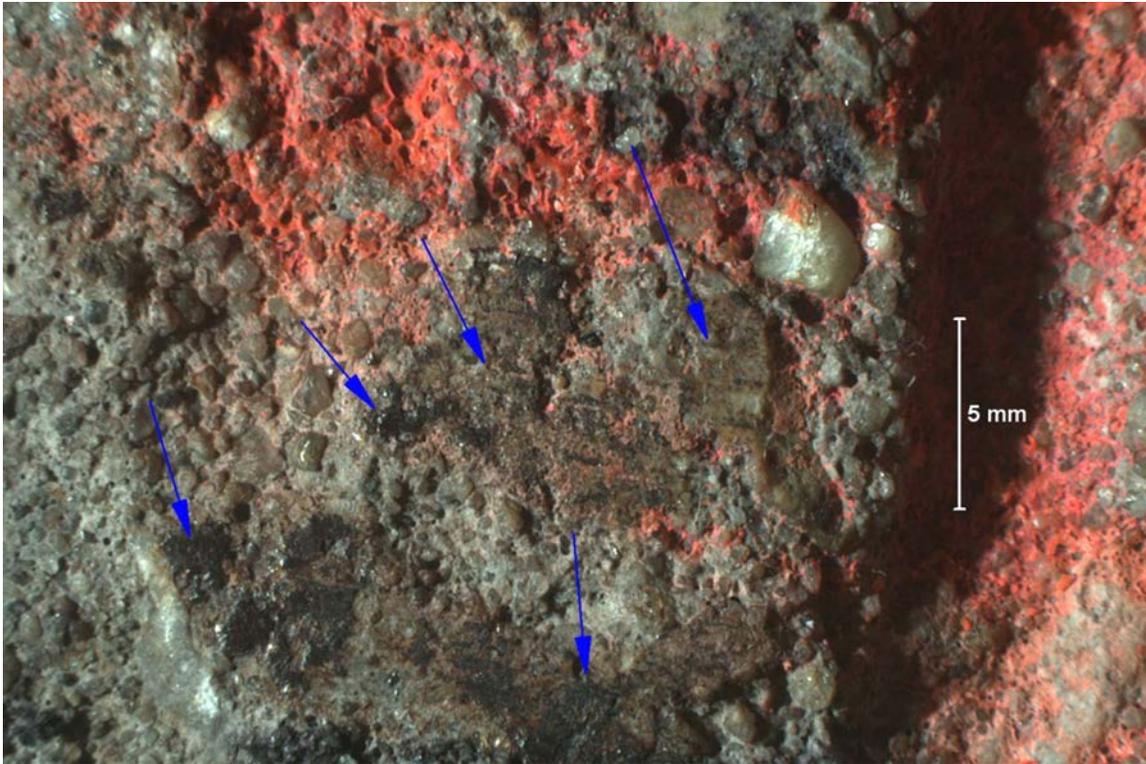


PHOTO: 5

SAMPLE ID: #1 **DESCRIPTION:** Sawcut and lapped cross section of core taken through joint. Microcracking is mapped in red ink. Note mass lost along the joint crack and cracking generally concentrated within coarse aggregate particles.

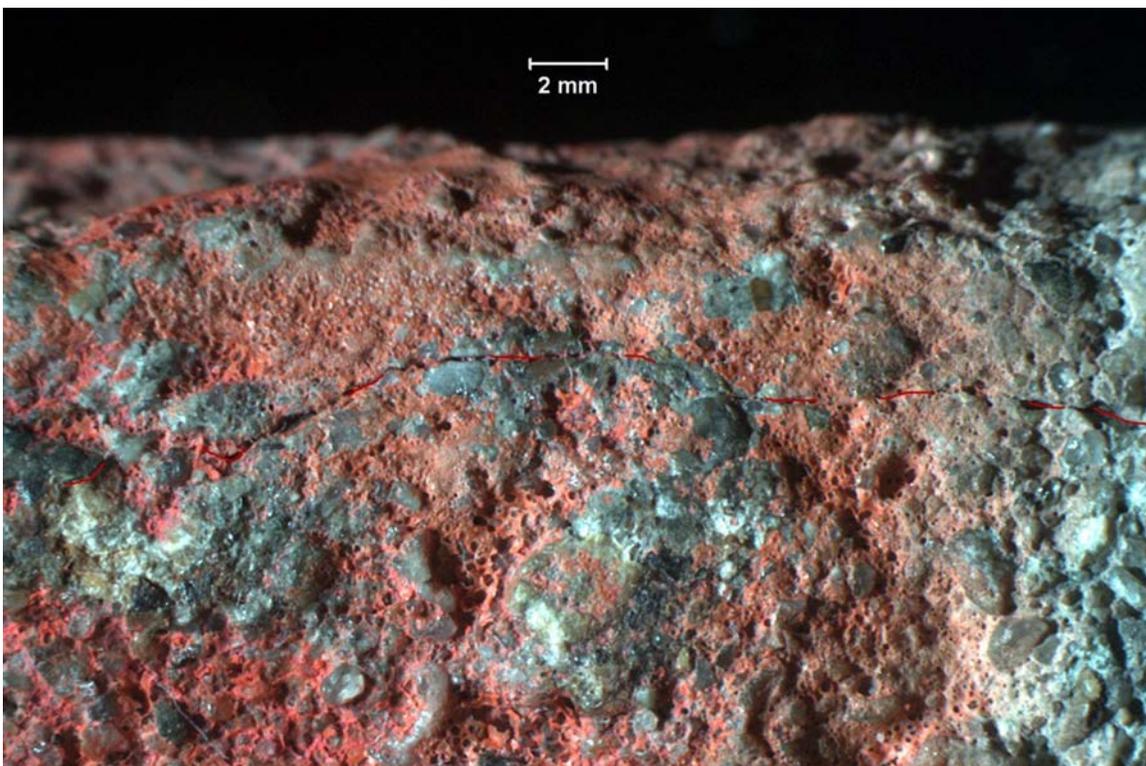
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 6



SAMPLE ID: #1 DESCRIPTION: Mortar eroded top surface of the core sample with corroded metal adhered to topographic highs in the surface.
MAG: 5x

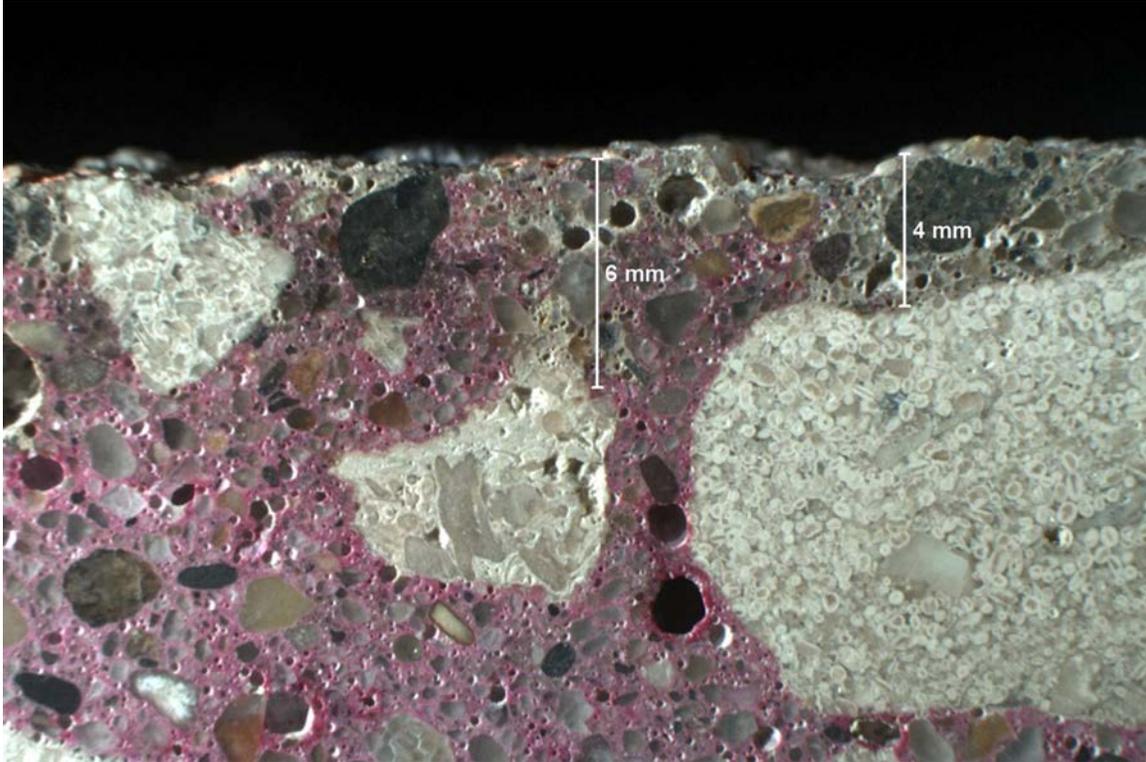
PHOTO: 7



SAMPLE ID: #1 DESCRIPTION: Incipient spalling in the top surface of the core sample(mapped in red dashed line), directly adjacent to the joint.
MAG: 5x

PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 8



SAMPLE ID: #1 DESCRIPTION: Carbonation (unstained paste) proceeds up to 6mm depth from the mortar eroded top surface of the core sample.
MAG: 5x

PHOTO: 9



SAMPLE ID: #1 DESCRIPTION: Microcracking, proceeding through coarse aggregates at depth in the core, is mapped in red ink.
MAG: 5x

PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 10



SAMPLE ID: #1 DESCRIPTION: Overall hardened air void content proximate to the top surface.

MAG: 15x

PHOTO: 11

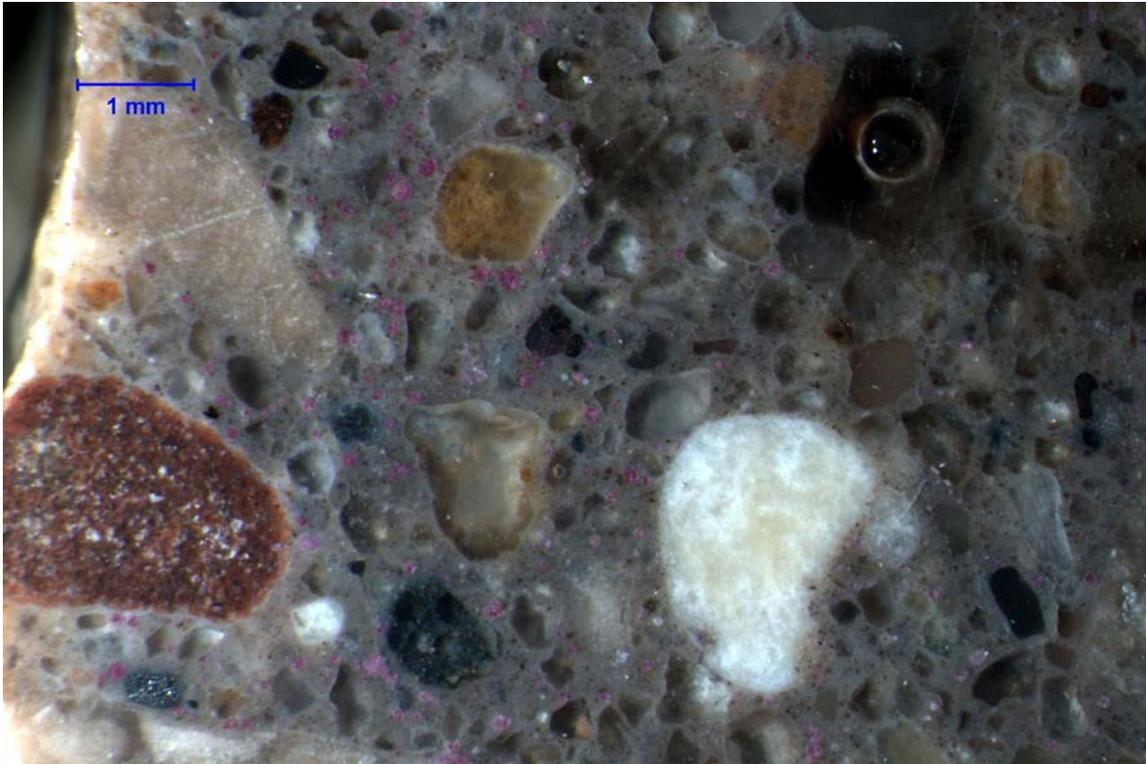


SAMPLE ID: #1 DESCRIPTION: Much of the air voids proximate to the joint and at 140mm depth from the top surface are filled with secondary ettringite.

MAG: 15x

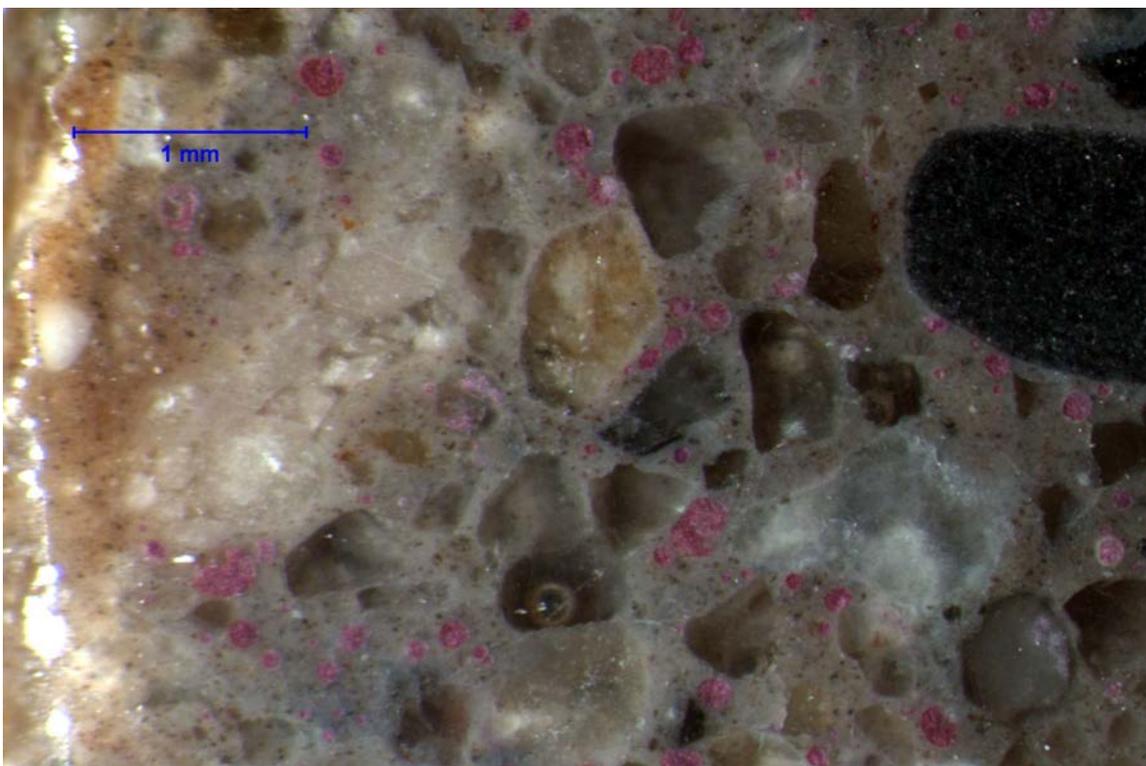
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 12



SAMPLE ID: #1 DESCRIPTION: Much of the air voids proximate to the distressed joint plane are filled with secondary ettringite which has been stained a magenta coloration.
MAG: 15x

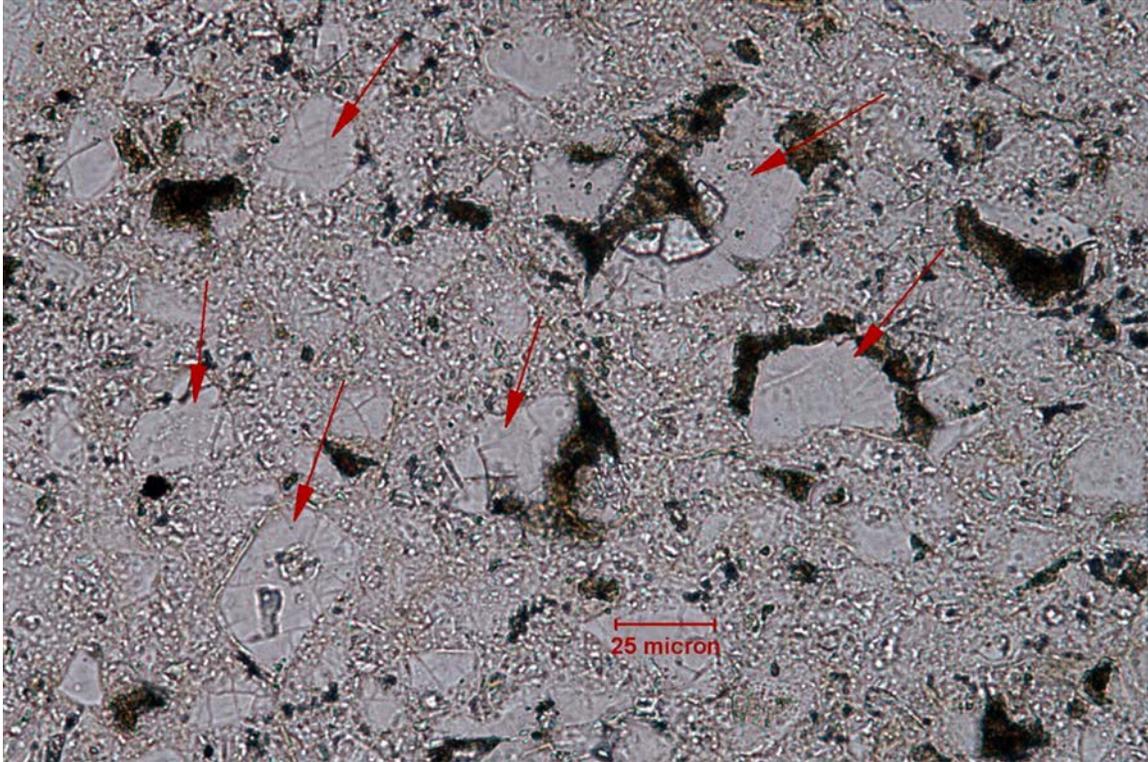
PHOTO: 13



SAMPLE ID: #1 DESCRIPTION: Much of the air voids proximate to the distressed joint plane are filled with secondary ettringite which has been stained a magenta coloration.
MAG: 30x

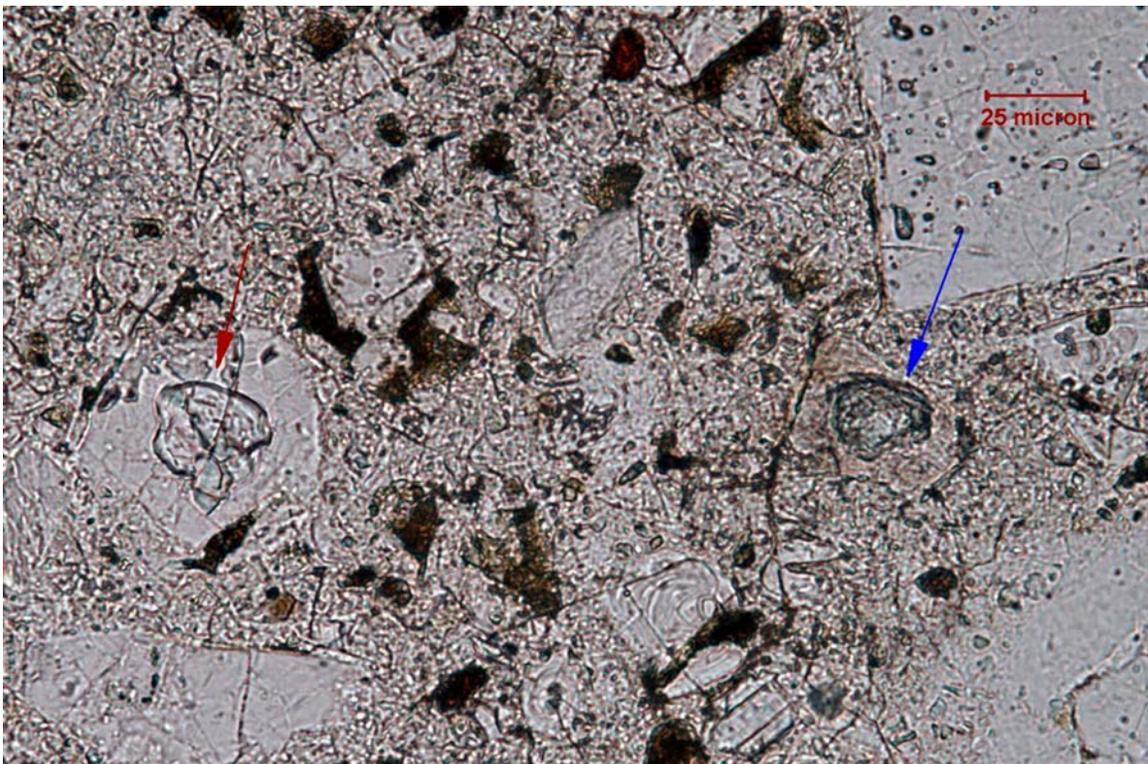
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 14



SAMPLE ID: #1 DESCRIPTION: Well to fully hydrated alite portland cement clinker particles in thin section of concrete paste under plane polarized light.
MAG: 400x

PHOTO: 15



SAMPLE ID: #2 DESCRIPTION: Well hydrated alite (red arrow) and well hydrated belite (blue) portland cement clinker particle in thin section of concrete paste under plane polarized light.
MAG: 400x

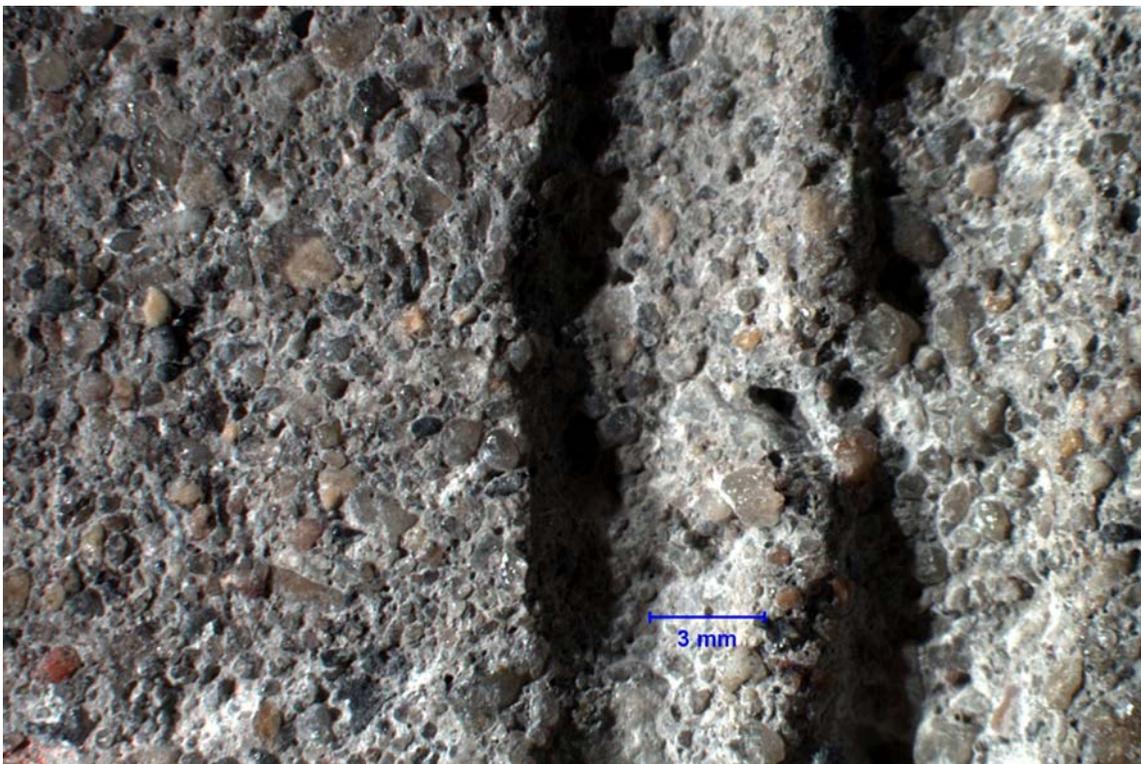
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 16



SAMPLE ID: #2 DESCRIPTION: Sawcut and lapped cross section of core taken through a distressed joint. Microcracking is mapped in red ink. Note some concentration within coarse aggregate particles.

PHOTO: 17



SAMPLE ID: #2 DESCRIPTION: The top surface of the core has undergone moderate mortar erosion exposing many fine aggregates.

MAG: 5x

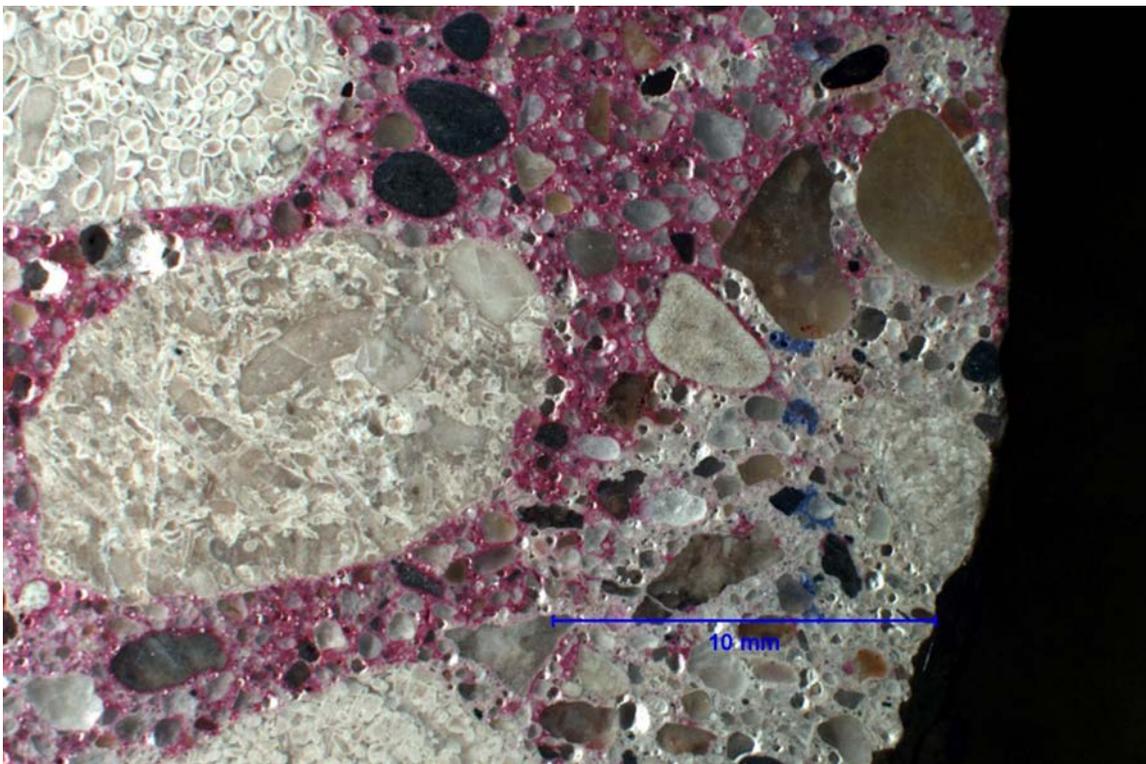
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 18



SAMPLE ID: #2 DESCRIPTION: Carbonation (unstained paste) ranges from negligible to 3mm depth from the top surface of the core. In freshly sawcut and lapped cross section of core exposed to phenolphthalein pH indicator.
MAG: 10x

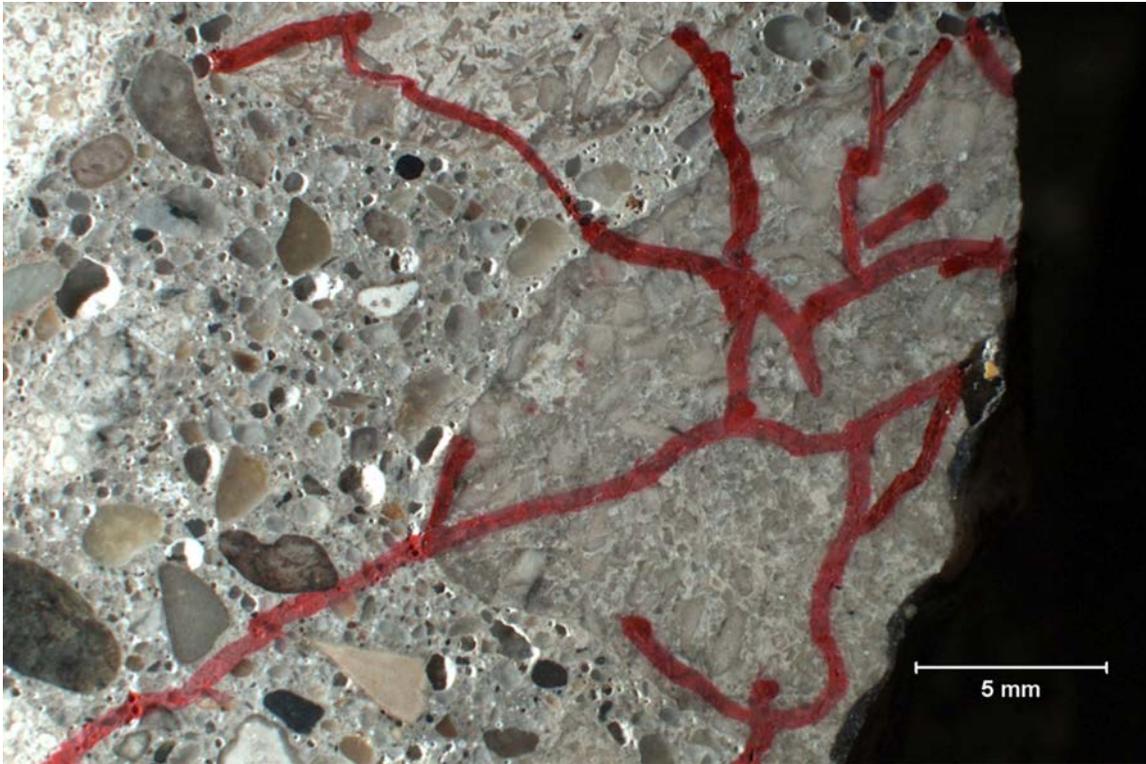
PHOTO: 19



SAMPLE ID: #2 DESCRIPTION: Carbonation (unstained paste) ranges from negligible to 10mm depth from the sawcut and distressed joint surface of the core (R).
MAG: 5x

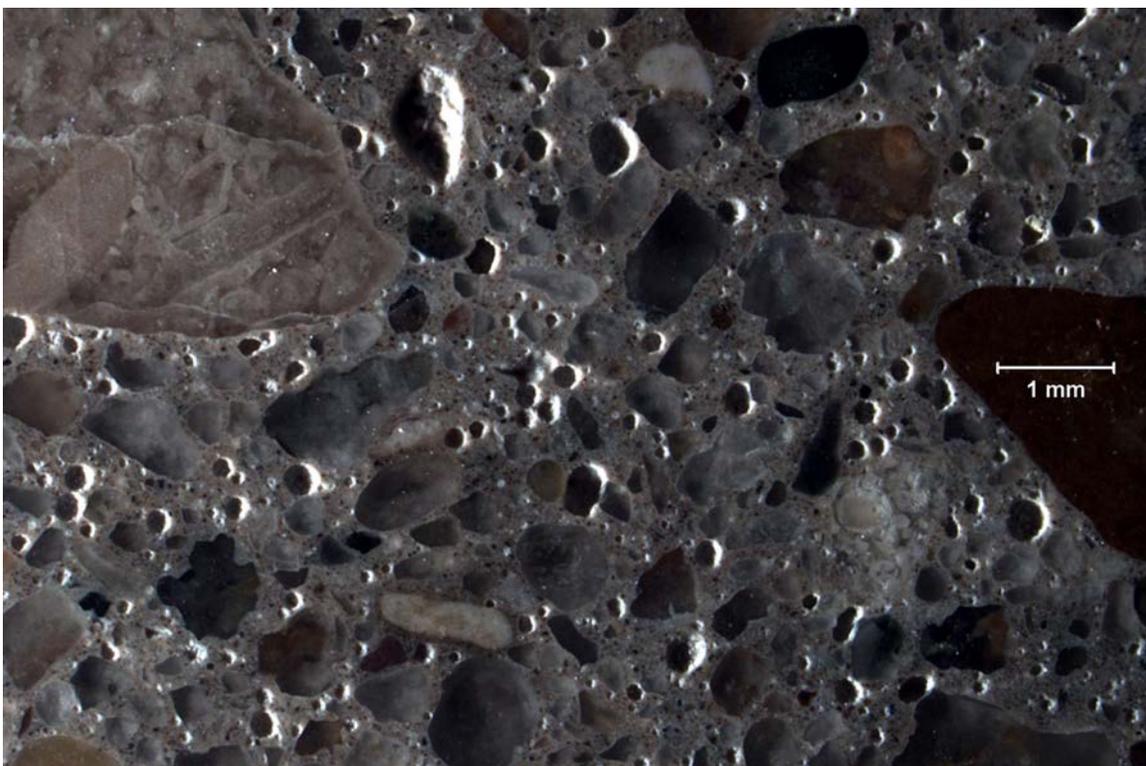
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 20



SAMPLE ID: #2 DESCRIPTION: Microcracking, mapped in red ink, appears to concentrate within a coarse aggregate particle at the distressed joint plane.
MAG: 5x

PHOTO: 21



SAMPLE ID: #2 DESCRIPTION: Overall hardened air void content proximate to the top surface.
MAG: 15x

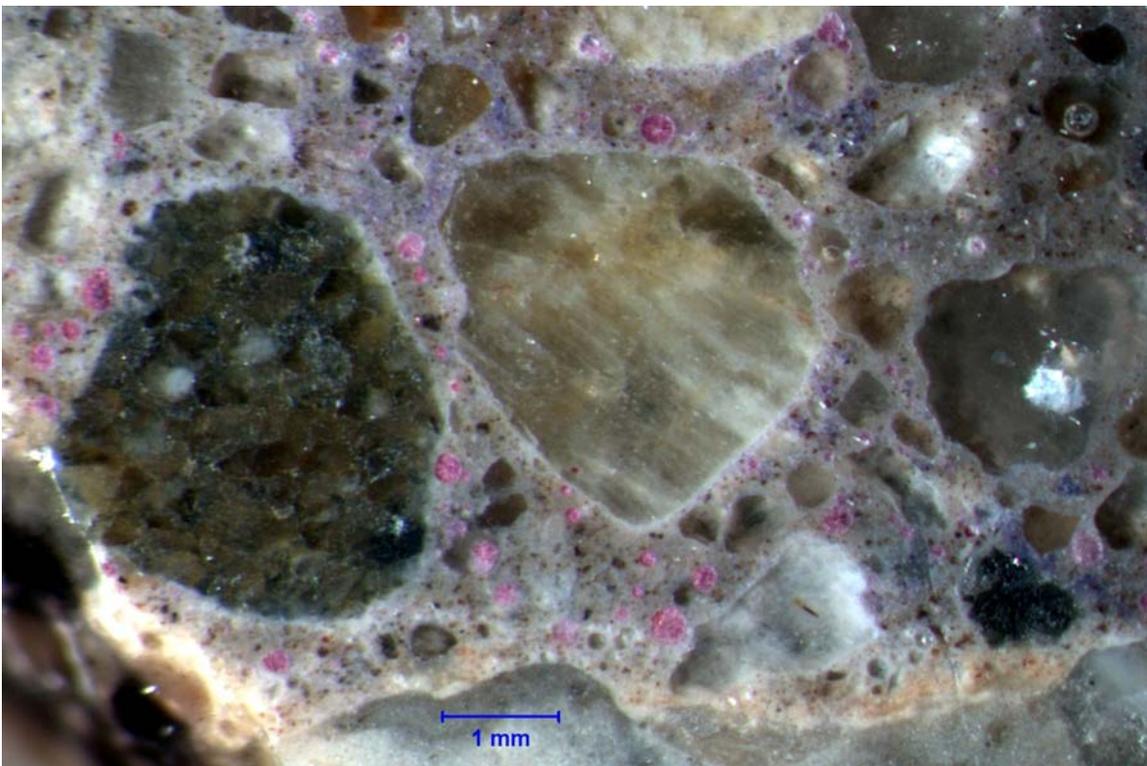
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 22



SAMPLE ID: #2 DESCRIPTION: Much of the finer air voidspaces in the concrete paste, proximate to the joint distress and at 55mm depth in the core, are filled with secondary ettringite
MAG: 5x

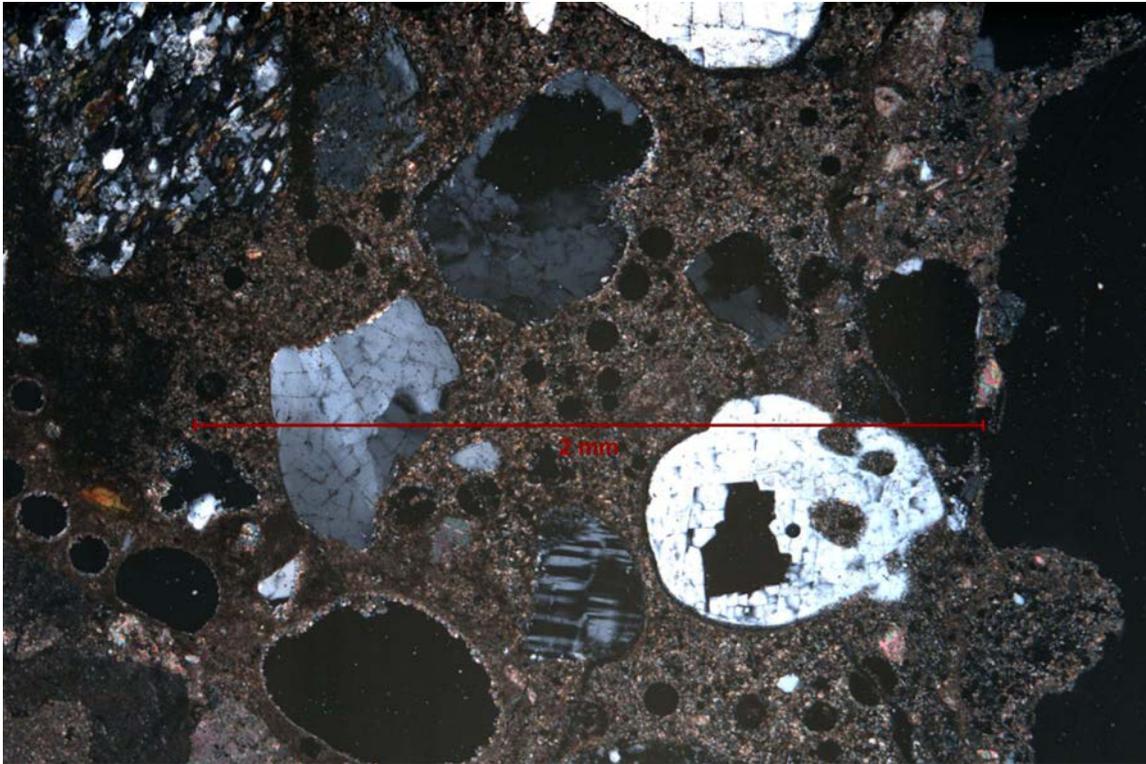
PHOTO: 23



SAMPLE ID: #2 DESCRIPTION: Much of the air voids proximate to the joint are filled with secondary ettringite; stained a magenta coloration.
MAG: 30x

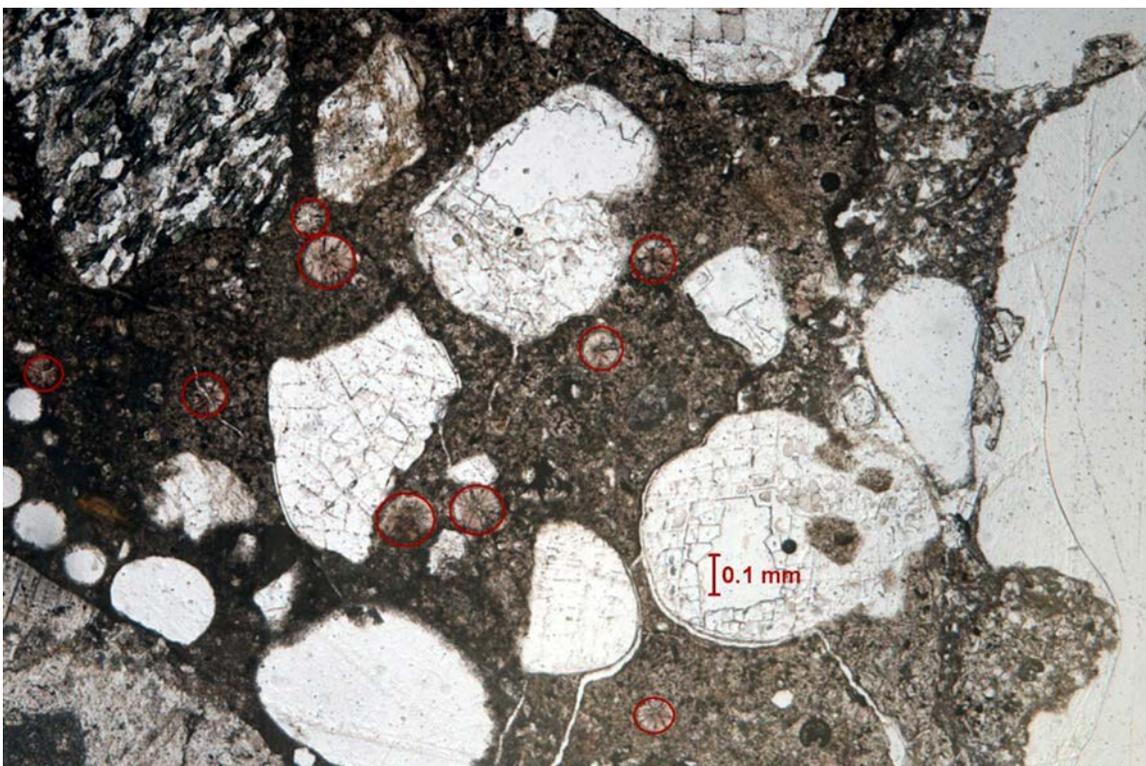
PROJECT: Evaluation of Joint Distress
Delaware Avenue @ 36th Street, Ankeny, Iowa

PHOTO: 24



SAMPLE ID: #2 DESCRIPTION: Brightly colored, carbonated concrete paste to 2mm depth from the joint distress plane (right); in thin section of concrete under cross polarized light.
MAG: 40x

PHOTO: 25



SAMPLE ID: #2 DESCRIPTION: Much of the air voids proximate to the joint are filled with secondary ettringite; outlined in red in thin section under plane polarized light.
MAG: 40x

APPENDIX D.

INVESTIGATION OF LOCALIZED JOINT DETERIORATION IN MINNESOTA

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INTRODUCTION

The aim of the work described in this report is to continue collecting information about potential causes of joint deterioration by looking at appropriate field examples.

Reports have been received from projects in several Midwest states that concrete, at joints, is deteriorating prematurely in various types of pavement from 5 to 30 years old.

Following is a list of some of the mechanisms that may be contributing to the distress:

- New air-entraining admixtures changing the minimum requirements (stability and minimum air content or spacing factor)
- Early entry saws causing bruising
- Lack of curing on joint faces
- Over vibration at joints
- Increasing use of SCMs
- Increasing application rates of deicing salts
- Use of more aggressive deicing salts
- Backer rods trapping water
- Cementitious chemistry
- Non-drainable bases
- Aggregate faces exposed to weather

It is likely that several or all of these are of these mechanisms are contributing to the distress at the same time and possible that distress at different locations are the result of different combinations of these mechanisms.

The work in this report covers an investigation of localized damage occurring in on highways in Minnesota.

BACKGROUND

The Minnesota DOT (MnDOT) changed their specification in the 1990s to require that mixtures have a w/cm less than 0.40. In 2011, MnDOT extracted cores from highways around the state representing both low and high w/cm mixtures. Four cores were selected for examination under this project to assess why variations in joint performance were observed.

ROUTE 12 MEEKER COUNTY (4705-30)

Two cores were taken from Route 12 west of Minneapolis. One, labeled 4 (Figure 1), was selected as representing a distressed joint, while the other, labeled 7, appeared to be in better condition (Figure 2).



Figure 1. 4705-30 Core 4

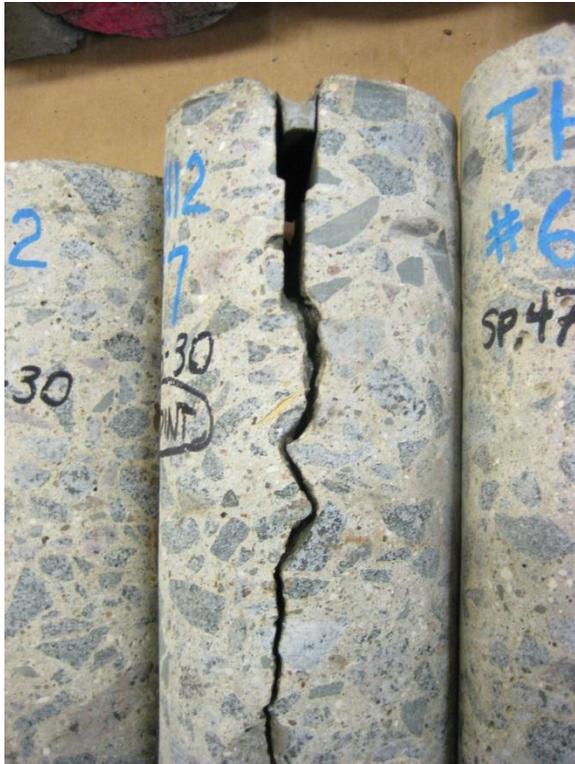


Figure 2. 4705-30 Core 7

Petrographic Data

The full petrographic report is included at the end of this appendix. The findings may be summarized as follows:

- The silicone sealant in both joints was de-bonded from the concrete
- Both joints were cracked out
- Damage in Core 7 was extensive but some damage was observed in Core 4
- Cracking is typical of freeze-thaw distress
- Both cores exhibited air voids filled with ettringite and the depth of ettringite-filled voids is greater in Core 4, indicating greater permeability in this core
- Carbonation is slightly deeper in Core 4 than Core 7, also indicating greater permeability
- The air void parameters are shown in Table 1
- Both samples contained 15-25% fly ash
- Top surface of both cores was in good condition

Table 1. Petrographic data 4705-30

	Non-Distressed Core 7	Distressed Core 4
Original air content %	6.7	9.6
Effective air content, %	4.6	8.3
Original spacing factor, in.	0.007	0.004
Effective spacing factor, in.	0.013	0.007
Estimated w/cm	0.40-0.45	0.43-0.48

Discussion

It is notable that distress is more closely correlated with w/cm and permeability than the air void system.

ROUTE 94 STEARNS COUNTY (7380-199)

Two cores were taken from Route 94 near Brainerd. One, labeled 7009 (Figure 3), was selected as representing a distressed joint including a so-called tunnel at the bottom of the joint, while the other, labeled 7012, appeared to be in better condition (Figure 4).



Figure 3. 7380 Core 7009



Figure 4. 7380 Core 7012

Petrographic Data

The full petrographic report is included at the end of this appendix. The findings may be summarized as follows:

- The silicone sealant was de-bonded from the concrete in core 7009 but bonded in core 7012
- Both joints were cracked out
- Damage typical of freeze-thaw distress was extensive in Core 7009 and no damage was observed in Core 7012
- Both cores exhibit air voids filled with ettringite but the extent is greater in Core 7009
- Carbonation is slightly deeper in Core 7012 than Core 7009
- The air void parameters are shown in Table 1
- Both samples contained 15-25% fly ash
- Top surface of both cores was in good condition

Table 2. Petrographic data 7380-199

	Non-Distressed (7012)	Distressed (7009)
Original air content %	11.0	7.0
Effective air content, %	-	4.9
Original spacing factor, in.	0.004	0.006
Effective spacing factor, in.	-	0.010
Estimated w/cm	0.35-0.40	0.35-0.40

Discussion

In this case, the better performance appears to be tied to the very high air content, while both samples had similar, low w/cm.

PETROGRAPHIC REPORT

The site report follows in this appendix.

REPORT OF CONCRETE ANALYSIS

PROJECT:

Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and
I-94 Stearns County, MN

REPORTED TO:

MI Tech Transportation Institute
MI Technological University
1400 Townsend Dr.
Houghton, MI 49931

ATTN: Larry Sutter, PhD

AET PROJECT NO: 24-00425

DATE: June 28, 2012

INTRODUCTION

This report presents the results of laboratory work performed by our firm on four concrete core samples submitted by Maria Masten of the Minnesota Department of Transportation (MNDOT) on September 21, 2011. We understand two cores were obtained from concrete pavement joints from MNDOT Project 4705-30 on US-12 in Meeker County, MN and two cores were obtained from concrete pavement joints from MNDOT project 7380-1199 on I-94 in Stearns County, MN. This section of US-12 was reportedly placed in 1996. The section of I-94 was placed in 1998 or 1999. The scope of our work was limited to performing petrographic analysis on the four core samples to document the general overall quality, composition, and condition of the concrete cores.

CONCLUSIONS

Based on our observations and testing, we believe:

1. From the top surface appearance of all four of the cores, the concrete joints exhibited good condition. However, core "4" from US-12 and core "7009" from I-94 exhibit significant distress and mass lost at depth in the joints from cyclic freeze-thaw action while saturated. Further, core "4" is cracked sub-horizontally several times by unknown forces. Core "7" exhibits the initiation of paste distress while core "7012" is relatively pristine. All four concretes were well consolidated and were purposefully air entrained. All four cores originally contained air void systems with parameters considered freeze-thaw resistant under severe exposure conditions. In the distressed cores, copious amounts of secondary ettringite fill most of the finer air voidspaces with several millimeters of the distressed joint plane; rendering the air void system ineffective at resisting further cyclic freeze-thaw action while saturated.

2. The infilling by ettringite is occurring during the saturation of the concrete paste by solutions of deicers and does not require the concrete to be "distressed" before the infilling occurs. Surrounding soils and traditionally mined sodium chloride mineral sources may contain sulfate available for the production of the ettringite. However, it is possible enough sulfate was available in the concrete making materials to fuel all of the ettringite produced. The concrete paste containing the now "compromised" air void systems were made poorly resistant to cyclic freeze-thaw action by the infilling and are subjected to distress as would any originally poor quality air void system. The distress is progressive at the joints. Poor joint drainage allows constant supply of deicer laden solutions, saturation, and severe freeze-thaw cycling.
3. Core "4" was centered and taken directly through a silicone sealed (with backer rod), sawcut control joint. The top surface of the core exhibited minor mortar erosion. The silicone sealant was mostly de-bonded on both sides of the joint and the sawcuts were in relatively pristine condition; apart from "rounding" and wear of the top surface edges. Apart from the very thin top few millimeters (meniscus) of the silicone, the joint sealant mostly "cleanly" de-bonded from the sawcut and the vertical surfaces of the sealant in contact with the concrete are darkly stained. The distress in core "4" was characterized by mass lost along the entire depth of the resulting joint crack; with the greatest loss of 10mm to 20mm between approx. 95mm and 182mm depth in the core. Some incipient distress (sub-vertical microcracking) was observed between 115mm and 135mm depth in the joint. The concrete was purposefully air entrained and originally contained a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Overall original air void parameters include a 6.9% entrained-sized void volume and a 0.004" spacing factor. Secondary ettringite, with some portlandite, fills most of the smaller entrained sized voidspaces within approx. 10mm of the joint plane/crack surface; rendering this layer of concrete non-durable. Void fillings decrease with depth from this zone. Sub-horizontal fractures and microcracking of unknown origin was present below 83mm depth in the core. The fracture plane at approx. 130mm depth was stained and aged and not a result of coring.
4. Core "7" was centered and taken directly through a silicone sealed (with backer rod), sawcut control joint. The top surface of the core exhibited minor mortar erosion. The silicone sealant was mostly de-bonded on both sides of the joint and the sawcuts were in relatively pristine condition; apart from "rounding" and wear of the top surface edges. In general, apart from the very thin top few millimeters (meniscus) of the silicone, the joint sealant mostly "cleanly" de-bonded from the sawcut and the vertical surfaces of the sealant in contact with the concrete are darkly stained. The distress in core "7" was characterized by mass lost along the entire depth of the resulting joint crack; with the greatest loss of 10mm to 20mm between approx. 95mm and 182mm depth in the core. Some incipient distress (sub-vertical microcracking) was observed between 115mm and 135mm depth in the joint. The concrete was purposefully air entrained and originally contained a well-distributed air void system considered freeze-thaw resistant under severe

exposure conditions. Original measured air void parameters include a 4.3% entrained-sized void volume and a 0.007" spacing factor. Secondary ettringite, with some portlandite, fills most of the smaller entrained sized voidspaces within approx. 20mm of the joint plane/surface. Void fillings decrease with depth from the joint plane. Actual measured air void parameters, which excludes the ettringite void fillings, in a band between approx. 0mm and at least 20mm (0-0.75") depth from the joint surface (below 57mm depth in the core), are 2.5% entrained volume and a 0.013" spacing factor.

5. In general, the coarse aggregate in all four samples was hard, sound, and durable and is not participating in any level of distress of the concrete joints. No evidence of alkali-silica reactivity (ASR) associated with the coarse aggregate was observed. Cores "4" and "7" from project 4705-30 contained abundant reacted shale and chert fine aggregate particles producing no obvious distress in the concrete.
6. Core "7009" was centered and taken directly through a silicone sealed (with backer rod), sawcut control joint. The top surface of the core exhibited minor mortar erosion. The silicone sealant was completely de-bonded from one side of the joint and the sawcuts were in relatively pristine condition; apart from "rounding" and wear of the top surface edges. In general, apart from the very thin top few millimeters (meniscus) of the silicone, the joint sealant was "cleanly" de-bonded from the one side of the sawcut and the vertical surface of the sealant in contact with the concrete are darkly stained. The distress in core "7009" was characterized chiefly by "tunneling"; an oval shaped loss of paste to 22mm in width between approx. the base of the reservoir sawcut and approx. 90mm depth in the core. Significant incipient distress (sub-vertical microcracking) was observed on both sides of the joint crack to 20mm depth laterally and between 120mm depth and the bottom surface of the core. Measured "existing" air void parameters in the 0 to 25mm of the paste directly adjacent to the joint crack and in the lower half of the core are poor and include a loss of 1.5% entrained sized air void volume and a spacing factor which rose from 0.006" to 0.010".
7. Core "7012" was centered and taken directly through a silicone sealed (with backer rod), sawcut control joint. The top surface of the core exhibited minor mortar erosion. The silicone sealant was well bonded to both sides of the joint and the sawcuts were in relatively pristine condition; apart from "rounding" and wear of the top surface edges. The silicone sealant exhibits good bond and contact along its entire thickness. No distress was observed along the entire depth of the joint. the concrete was purposefully air entrained and exhibits high quality parameters for freeze-thaw resistance under severe exposure conditions. Secondary ettringite does fill some of the smaller entrained sized voidspaces within 3mm of the joint crack plane and within several millimeters of the base of the pilot sawcut.

SAMPLE IDENTIFICATION

Sample ID:	4 4705-30	7 4705-30	7009 7380-199	7012 7380-199
Sample Type:	100mm (4") Diameter Hardened Concrete Cores			
Sample Lengths:	245mm (9 5/8")	240mm (9 1/2")	247mm (9 3/4")	255mm (10")

TEST RESULTS AND SUMMARY OF GENERAL CONCRETE PROPERTIES

Our complete petrographic analysis documentation appears on the attached sheets entitled 00 LAB 001 "Petrographic Examination of Hardened Concrete, ASTM:C856." A brief summary of these results is as follows:

1. The coarse aggregate in cores 4 and 7 was comprised of 19mm (3/4") nominal sized crushed granite and basalt that appeared generally well graded and exhibited good overall distribution. The coarse aggregate in cores 7009 and 7012 was comprised of 38mm (1 1/2") nominal sized crushed granite and basalt that appeared generally well graded and exhibited good overall distribution. Both coarse aggregates are similar and consistent with crushed granitic and basaltic material mined near St. Cloud, MN, by Martin Marietta. The fine aggregate was a natural glacial sand composed of quartz, feldspar and lithic fragments.
2. The paste color in core 4 was mottled light gray to tan and in core 7 mottled medium light gray to tan. The paste color in cores 7009 and 7012 was a similar medium gray. The paste hardness in all four cores was judged to be "moderate" to "moderately hard" with the paste/ coarse aggregate bond in all four cores generally considered to be fair.
3. The original top surface condition of the four cores was generally roughly screeded and tined or deeply broomed. Minor mortar erosion and /or traffic wear has exposed many fine aggregates. Overall, the depth of carbonation ranged from negligible up to an 8mm maximum depth, intermittently, from the top surface of cores. Carbonation, in all cores, "spikes" significantly deep along fine sub-vertical drying shrinkage microcracking common in the cores.
4. The w/cm of cores 4 and 7 was somewhat similar and was estimated to be between 0.40 and 0.48 with approximately 4 to 8% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 – 15% replacement of portland cement. Portland cement hydration was very advanced. The w/cm of cores 7009 and 7012 was similar and was estimated to be between 0.35 and 0.40 with approximately 8 to 10%

residual portland cement clinker particles and an amount of flyash visually consistent with a 15 – 25% replacement of portland cement.

Air Content Testing

Sample ID	4 4705-30 "original air"	4 4705-30 "effective air 0-22mm from joint"	7 4705-30 "original air"	7 4705-30 "effective air 0-20mm from joint"
Total Air Content (%)	9.6	8.3	6.7	4.6
“Entrained” Air (%) voids < 1mm (0.040”)	6.9	4.8	4.3	2.5
“Entrapped” Air (%) voids > 1mm (0.040”)	2.7	3.5	2.4	2.1
Spacing Factor, mm (in.)	0.102 (0.004)	0.178 (0.007)	0.178 (0.007)	0.330 (0.013)

Sample ID	7009 7380-199 "original air"	7009 7380-199 "effective air 0- 25mm from joint"	7012 7380-199 "original air"
Total Air Content (%)	7.0	4.9	11.0
“Entrained” Air (%) voids < 1mm (0.040”)	4.9	3.4	8.2
“Entrapped” Air (%) voids > 1mm (0.040”)	2.1	1.5	2.8
Spacing Factor, mm (in.)	0.152 (0.006)	0.254 (0.010)	0.102 (0.004)

TEST PROCEDURES

Laboratory testing was performed in November, 2011 and subsequent dates. Our procedures were as follows:

Petrographic Analysis

A petrographic analysis was performed in accordance with Standard Operating Procedure 00 LAB 001, “Petrographic Examination of Hardened Concrete,” ASTM:C856-latest revision. The petrographic analysis consisted of reviewing the cement paste and aggregate qualities on a whole basis on sawcut and lapped, and fractured sections. Reflected light microscopy was performed under an Olympus SZX-12 binocular stereozoom microscope at magnifications up to 160x. The

depth of carbonation was documented using a phenolphthalein pH indicator solution applied on freshly sawcut and lapped surfaces of the concrete sample. The paste-coarse aggregate bond quality was determined by fracturing a sound section of the concrete in the laboratory with a rock hammer.

The water/cementitious of the concrete was estimated by viewing a thin section of each concrete core under an Olympus BX-51 polarizing light microscope at magnifications of up to 1000x. Thin section analysis was performed in accordance with Standard Operating Procedure 00 LAB 013, "Determining the Water/Cement of Portland Cement Concrete, APS Method." An additional, smaller, sawcut subdivision of the concrete sample is epoxy impregnated, highly polished, and then attached to a glass slide using an optically clear epoxy. Excess sample is sawcut from the glass and the thin slice remaining on the slide is lapped and polished until the concrete reaches 25 microns or less in thickness. Thin section analysis allows for the observation of portland cement morphology, including: phase identification, an estimate of the amount of residual material, and spatial relationships. Also, the presence and relative amounts of supplementary cementitious materials and pozzolans may be identified and estimated.

Air Content Testing

Air content testing was performed using Standard Operating Procedure 00 LAB 003, "Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete, ASTM:C457-latest revision." The linear traverse method was used. The concrete core was sawcut perpendicular with respect to the horizontal plane of the concrete as placed and then lapped prior to testing.

REMARKS

The test samples will be retained for a period of at least sixty days from the date of this report. Unless further instructions are received by that time, the samples may be discarded. Test results relate only to the items tested. No warranty, express or implied, is made.

Report Prepared By:

Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: 4, SP4705-30

Date: January 31, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** The core was taken directly through a sealed, sawcut and cracked pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut "normal" to a sawcut and cracked joint measuring 245mm (9 ⁵/₈" x 100mm (4") x 33mm (1 ¹/₄") thick, a 240mm (9 ¹/₂") x 95mm (3 ³/₄") x up to 32mm (1 ¹/₄") thick section (in two pieces), and two 76mm (3") x 52mm (2") wide thin sections that were sawcut and prepared from the original 100mm (4") diameter x 245mm (9 ⁵/₈") long core. The thin sections were located between 5mm and 80mm depth and 150mm and 230mm depth in from the top surface of the core; in cross section and along the sawcut and cracked and distressed portions of the joint.
2. **Surface Conditions:**
Top: Rough screeded surface with minor mortar erosion exposing fine aggregate surfaces.
Bottom: Rough, irregular, formed surface; placed on recycled concrete base, some of which is incorporated into the bottom surface of the concrete.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core was taken through a sealed pavement joint. The light gray silicone joint sealant was mostly de-bonded from both sides of the sawcut joint. The joint was characterized by an intact approx. 3mm wide sawcut proceeding 64mm (2 ¹/₂") depth from the top surface and an approx. 10mm wide reservoir cut to 37mm (1 ¹/₂") depth; with the resulting joint crack proceeding the depth of the core. A foam backer rod was present. The core was fractured in sub-horizontal orientations at approx. 132mm and 230mm on one side of the joint and 113mm, 167mm, and 217mm on the other. A few fine sub-vertical microcracks (incipient scaling/spalling), proceeding through the paste-only, were observed in thin section only, between 150mm and 230mm depth from the top surface and within a few mm of the distressed joint surface. A loss of paste incorporates between negligible and 12mm of total concrete paste between the two sides of the joint crack. The cracked joint plane is characterized by numerous relatively "clean" and un-distressed granitic gneiss coarse aggregates protruding from the concrete joint. In general, the widest loss of concrete (at least 10mm) occurs between 95mm and 182mm depth. A wider degree of distress, in the form of a conical void, occurs below 210mm depth from the top surface. The core exhibits significant residual interlock between the two halves of core. The coarse granitic gneiss aggregate appeared sound. No evidence of ASR associated with the coarse aggregate was observed. Numerous alkali-silica "reacted" shale and chert fine aggregate were present in the core. Sub-horizontal microcracking, mostly in the paste and proceeding through of the reacted shale and chert fine aggregates, occur at approx. 95mm, 92mm, 122mm, and 137mm; with several microcracks concentrated below 215mm depth in the cross section of core.

The rough screeded top surface of the core exhibits moderate mortar erosion/traffic wear; exposing many fine aggregate surfaces. The concrete was fairly well consolidated, with only a few entrapped voidspace observed up to 12mm in diameter in the mid-section of the core. The concrete was purposefully air entrained and originally contained a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air void parameters include a 6.9% entrained-sized void volume and a 0.004" spacing factor. Secondary ettringite, with some portlandite, fills most of the smaller entrained sized voidspaces within approx. 10mm of the joint plane/crack surface. Void fillings decrease with depth from this zone. Actual measured air void parameters, which excludes the ettringite void fillings, in a band between approx. 0mm and at least 22mm (0-1.0") depth from the joint surface (below 70mm depth in the core), are a 4.8% entrained volume and a 0.007" spacing factor.

II. Aggregate

1. **Coarse:** 19mm (¾") nominal sized crushed granitic gneiss. The coarse aggregate appeared well graded and exhibited good overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 6.9% original entrained air content. 4.8% “actual” un-filled entrained air between 0mm and at least 25mm depth from the distressed joint (below 70mm depth from the top surface).
2. Depth of carbonation: Ranged from 1mm up to 8mm depth from the top surface of the core; along sub-vertical drying shrinkage microcracking. Ranged from negligible up to 2mm depth from the sawcut joint surface and from 2mm up to approx. 10mm depth from the distressed joint surface.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Mottled Light Gray (Munsell® N7) to tan.
6. Paste hardness: Moderate (<Moh’s 3)
7. Microcracking: Several fine sub-vertical microcracks (incipient spalling) were observed in thin section (in the paste-only) along the joint (cracked) surface between 150mm and 230mm depth from the top surface of the core. A few fine, sub-vertical drying shrinkage microcracks proceed up to 7mm depth from the top surface. Sub-horizontal microcracking, mostly in the paste and proceeding through a few reactive shale and chert fine aggregates, occur at approx. 95mm, 92mm, 122mm, 137mm, and several concentrated below 215mm depth in the cross section of core.
8. Secondary deposits: White ettringite, along with some scattered clear platelets of portlandite, fills most of the entrained sized air voids between the distressed joint surface (and below 30mm depth from the top surface along the sawcut) and approx. 5 to 10mm depth into the core. Void fillings become less abundant with distance from this zone.
9. w/cm: Estimated at between 0.43 and 0.48 with approximately 4 to 6% residual portland cement clinker particles and an amount of flyash visually consistent with a 15 to 25% replacement of portland cement.
10. Cement hydration: Alites: Mostly fully.
Belites: Well.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: 7, SP4705-30

Date: January 31, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** The core was taken directly through a sealed, sawcut and cracked pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut “normal” to a sawcut and cracked joint measuring 237mm (9 ³/₈”) x 100mm (4”) x 25mm (1”) thick, a 240mm (9 ¹/₂”) x 100mm (4”) x up to 45mm (1 ³/₄”) thick section (in two pieces), and two 76mm (3”) x 52mm (2”) wide thin sections that were sawcut and prepared from the original 100mm (4”) diameter x 240mm (9 ¹/₂”) long core. The thin sections were located between 23mm and 100mm depth from the top surface and 145mm and 225mm depth in the core; in cross section and along the sawcut and cracked portions of the joint.
2. **Surface Conditions:**
Top: Rough screeded surface with minor mortar erosion exposing fine aggregate surfaces.
Bottom: Rough, irregular, formed surface; placed on recycled concrete base, some of which is incorporated into the bottom surface of the concrete.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core was taken through a sealed pavement joint. The light gray silicone joint sealant was mostly de-bonded from both sides of the sawcut joint. The joint was characterized by an approx. 3mm wide sawcut proceeding 65mm (2 ¹/₂”) depth from the top surface and an approx. 10mm wide reservoir cut to 32mm (1 ¹/₄”) depth; with foam backer rod. Several sub-vertical microcracks (incipient scaling/spalling), observed in the paste-only, were observed between 75mm and 215mm depth in the cracked joint surface and incorporates between a few mm and 8mm of total concrete paste between the two sides of the joint crack. The joint plane is characterized by numerous relatively “clean” and un-distressed granitic gneiss coarse aggregates protruding from the concrete joint. The widest loss of concrete (4mm to 7mm) occurs between 65mm and 75mm depth in the concrete from the top surface. The core exhibits relatively tight, residual interlock between the two halves of core; with a few coarse aggregate bisected by the joint at depth in the core. The coarse granitic gneiss aggregate appeared sound. No evidence of ASR associated with the coarse aggregate was observed. Numerous alkali-silica “reacted” shale fine aggregate were present in the core.

The rough screeded top surface of the core exhibits moderate mortar erosion/traffic wear; exposing many fine aggregate surfaces. The concrete was fairly well consolidated, with only a few entrapped voidspace observed up to 12mm in diameter in the mid-section of the core. The concrete was purposefully air entrained and originally contained a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air void parameters include a 4.3% entrained-sized void volume and a 0.007” spacing factor. Secondary ettringite, with some portlandite, fills most of the smaller entrained sized voidspaces within approx. 20mm of the joint plane/surface. Void fillings decrease with depth from the joint plane. Actual measured air void parameters, which excludes the ettringite void fillings, in a band between approx. 0mm and at least 20mm (0-0.75”) depth from the joint surface (below 57mm depth in the core), are 2.5% entrained volume and a 0.013” spacing factor.

II. Aggregate

1. **Coarse:** 19mm (¾”) nominal sized crushed granitic gneiss. The coarse aggregate appeared well graded and exhibited good overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. **Air Content:** 4.3% original entrained air content. 2.5% “actual” un-filled entrained air between 0mm and at least 20mm depth from the distressed joint (below 57mm depth).
2. **Depth of carbonation:** Up to 6mm depth from the top surface of the core. Mostly negligible along the sawcut joint. Ranged from mostly negligible up to 4mm depth from the distressed joint surface.

3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Mottled Medium Light Gray (Munsell® N6) to tan.
6. Paste hardness: Moderately hard (Moh's 3)
7. Microcracking: Several sub-vertical microcracks (incipient spalling) were observed along the joint (cracked) surface between 75mm and 215mm depth from the top surface of the core. A few fine, sub-vertical drying shrinkage microcracks proceed up to 5mm depth from the top surface.
8. Secondary deposits: White, generally acicular grown ettringite along with some clear platelets of portlandite fills most of the finer entrained sized air voids between the joint surface and approx. 20mm depth into the core. Void fillings become less abundant with distance from this zone.
9. w/cm: Estimated at between 0.40 and 0.45 with approximately 6 to 8% residual portland cement clinker particles and an amount of flyash visually consistent with a 15 to 25% replacement of portland cement.
10. Cement hydration: Alites: Well to fully.
Belites: Well.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: 7009, SP7380-199

Date: February 29, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** The core was taken directly through a sealed, sawcut and cracked pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut "normal" to a sawcut and cracked joint measuring 247mm (9 3/4") x 95mm (3 3/4") x 33mm (1 1/4") thick, a 247mm (9 3/4") x 86mm (3 3/8") x up to 26mm (1") thick section (in two pieces), and two 76mm (3") x 52mm (2") wide thin sections that were sawcut and prepared from the original 95mm (3 3/4") diameter x 247mm (9 3/4") long core. The thin sections were located between 80mm and 155mm depth and 157mm and 235mm depth in from the top surface of the core; in cross section and along the sawcut and cracked and distressed portions of the joint.
2. **Surface Conditions:**
Top: Rough screeded and tined surface with minor mortar erosion exposing fine aggregate surfaces.
Bottom: Rough, irregular, formed surface of unknown composition.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core was taken through a sealed pavement joint. The light gray silicone joint sealant was completely de-bonded from one side of the sawcut joint. The joint was characterized by a partially intact approx. 3-4mm wide sawcut proceeding 77mm (3") depth from the top surface and an approx. 10mm wide reservoir cut to 28mm (1 1/8") depth; with the resulting joint crack proceeding the depth of the core. A foam backer rod was present. A loss of concrete paste in a "vertical oval shape" and up to 22mm in width "centers" around the lower approx. 40mm of the pilot sawcut. A loss of paste occurs from between the base of the reservoir cut and up to approx. 90mm depth along the joint. Below this point, the crack is relatively tight and intimate and proceeds through several coarse aggregate, as opposed to around them. The distressed joint plane is characterized by several relatively "clean" and undistressed or sawcut granitic gneiss coarse aggregates protruding from the distressed concrete paste. Some, fine, concentrated sub-vertical microcracking (incipient scaling/spalling), proceeding through the paste-only, were observed proximate to the distressed zone. Incipient sub-vertical spalling (micro and macrocracking), proceeding through the paste only, occurs on both sides of the joint and within 20mm of the joint plane; between 120mm depth and the bottom surface of the core.

The coarse granitic gneiss aggregate was hard, sound, and durable. No evidence of ASR associated with the coarse aggregate was observed.

The rough screeded and tined top surface of the core exhibits moderate mortar erosion/traffic wear; exposing many fine aggregate surfaces. The concrete was fairly well consolidated, with only a few entrapped voidspace observed up to 12mm in diameter in the mid-section of the core. The concrete was purposefully air entrained and originally contained a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air void parameters include a 4.9% entrained-sized void volume and a 0.006" spacing factor. Secondary ettringite, with some portlandite, fills most of the smaller entrained sized voidspaces within approx. 10mm of the joint plane/crack surface. Void fillings decrease with depth from this zone. Actual measured air void parameters, which excludes the ettringite void fillings, in a band between approx. 0mm and at most 25mm (0-1.0") depth from the joint surface (starting below 35mm depth in the core), are a 3.4% actual, unfilled entrained volume and a 0.010" spacing factor. At between approx. 25mm and 37mm depth from the joint, the air void parameters improve to a 4.4% entrained volume and a 0.008" spacing factor.

II. Aggregate

1. **Coarse:** 38mm (1 1/2") nominal sized crushed granitic gneiss. The coarse aggregate appeared well graded and exhibited good overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 4.9% original entrained air content. 3.9% “actual” un-filled entrained air between 0mm and at most 25mm depth from the distressed joint (below 35mm depth from the top surface). 4.4% “actual” unfilled air void content between approx. 25mm and 37mm depth from the distressed joint.
2. Depth of carbonation: Ranged from negligible up to 5mm depth from the top surface of the core; along fine sub-vertical drying shrinkage microcracking and consolidation voidspaces. Ranged from negligible up to 3mm depth from the sawcut joint surface and from negligible up to approx. 6mm depth from the distressed joint surface. Negligible below 175mm depth in the joint.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Similar to Medium Gray (Munsell® N5).
6. Paste hardness: Moderately-hard (>Moh’s 3)
7. Microcracking: Sub-vertical macro/microcracks (incipient spalling) were observed (in the paste-only) oriented sub-parallel to the joint (cracked) surface and within 20mm of the joint; below 120mm depth from the top surface of the core. Numerous other microcracks were observed sub-parallel and proximate (within a few mm) of the distressed region of the joint between approx. 35mm and 90mm depth from the top surface.
8. Secondary deposits: White ettringite, along with some scattered occurrences of clear platelets of portlandite, fills most of the entrained sized air voids between the sawcut and distressed joint surface (and generally below 30mm depth from the top surface along the sawcut) and approx. 10mm depth into the core. Void fillings become less abundant with distance from this zone.
9. w/cm: Estimated at between 0.35 and 0.40 with approximately 8 to 10% residual portland cement clinker particles and an amount of flyash visually consistent with a 15 to 25% replacement of portland cement.
10. Cement hydration: Alites: Well.
Belites: Moderate.

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No. 24-00425
Sample ID: 7012, SP7380-199

Date: February 29, 2012
Performed by: G. Moulzolf

I. General Observations

1. **Sample Dimensions:** The core was taken directly through a sealed, sawcut and cracked pavement joint. Our analysis was performed on both lapped sides of a cross section (two pieces) of core sawcut "normal" to a sawcut and cracked joint measuring 255mm (10") x 95mm (3 3/4") x 3mm (1 1/4") thick, a 255mm (10") x 86mm (3 3/8") x up to 28mm (1 1/8") thick section (in two pieces), and three 76mm (3") x 52mm (2") wide thin sections that were sawcut and prepared from the original 95mm (3 3/4") diameter x 255mm (10") long core. The thin sections were located between 5mm and 85mm depth, 100mm depth and 175mm, and 180mm and 250mm depth in from the top surface of the core; in cross section and along the sawcut and cracked and distressed portions of the joint.
2. **Surface Conditions:**
Top: Rough screeded and tined surface with minor mortar erosion exposing fine aggregate surfaces.
Bottom: Rough, irregular, formed surface, placed upon apparent asphalt-stabilized base.
3. **Reinforcement:** None observed.
4. **General Physical Conditions:** The core was taken through a sealed pavement joint. The light gray silicone joint sealant was well bonded to both sides of the sawcut joint and was forcibly torn during handling of the core. The joint was characterized by an approx. 3mm wide sawcut proceeding 82mm (3 1/4") depth from the top surface and an approx. 10mm wide reservoir cut to 32mm (1 1/4") depth; with the resulting joint crack proceeding the depth of the core. A foam backer rod was present. The crack is relatively tight and intimate and proceeds through several coarse aggregate, as opposed to around them. The coarse granitic gneiss aggregate was hard, sound, and durable. No evidence of ASR associated with the coarse aggregate was observed.

The rough screeded and tined top surface of the core exhibits moderate mortar erosion/traffic wear; exposing many fine aggregate surfaces. The concrete was fairly well consolidated, but contains at least 2 entrapped voidspaces observed to 12mm in diameter in the mid-section of the core. The concrete was purposefully air entrained and contained a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. The original air void parameters include a 9.2% entrained-sized void volume and a 0.004" spacing factor. In general, secondary ettringite fills some of the smaller entrained sized voidspaces within approx. 3mm of the joint plane/crack surface; with a concentration of void fillings in the surrounding several millimeters of paste at the base of the sawcut.

II. Aggregate

1. **Coarse:** 36mm (1 1/2") nominal sized crushed granitic gneiss. The coarse aggregate appeared well graded and exhibited good overall distribution.
2. **Fine:** Natural quartz, feldspar, and lithic sand. The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. **Air Content:** 9.2% original entrained air content. 8.2% "actual" un-filled entrained air between 0mm and at least 25mm depth from the distressed joint (below 98mm depth from the top surface).
2. **Depth of carbonation:** Ranged from negligible up to 3mm depth from the top surface of the core; along fine sub-vertical drying shrinkage microcracking and consolidation voidspaces. Ranged from negligible up to 5mm depth from the sawcut joint surface and from negligible up to approx. 3mm depth from the joint surface. Negligible below 140mm depth in the joint.

3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Similar to Medium Gray (Munsell® N5).
6. Paste hardness: Moderately-hard (>Moh's 3)
7. Microcracking: A single, fine microcrack was observed at a low angle and oriented sub-parallel to the joint crack at the base of the sawcut. A few, very fine sub-vertical drying shrinkage microcracks proceed to 2mm depth from the top surface.
8. Secondary deposits: Small, white, acicular clumps of ettringite grows on the lining of most air voids at depth in the concrete. Ettringite fills a small amount of the finest entrained sized air voids scattered throughout the depth of the core; with some concentration within a few mm of the joint crack and at the base of the pilot sawcut.
9. w/cm: Estimated at between 0.35 and 0.40 with approximately 8 to 10% residual portland cement clinker particles and an amount of flyash visually consistent with a 15 to 25% replacement of portland cement.
10. Cement hydration: Alites: Well.
Belites: Moderate.

AIR VOID ANALYSIS

PROJECT:

REPORTED TO:

AET PROJECT NO:

ATTN:

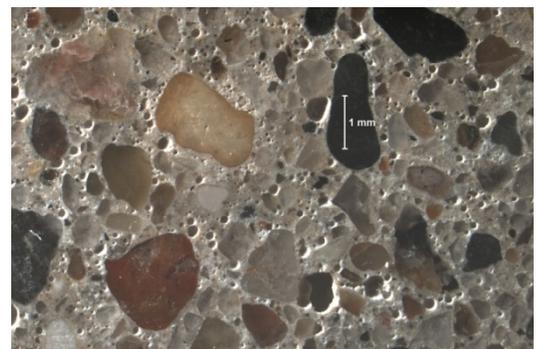
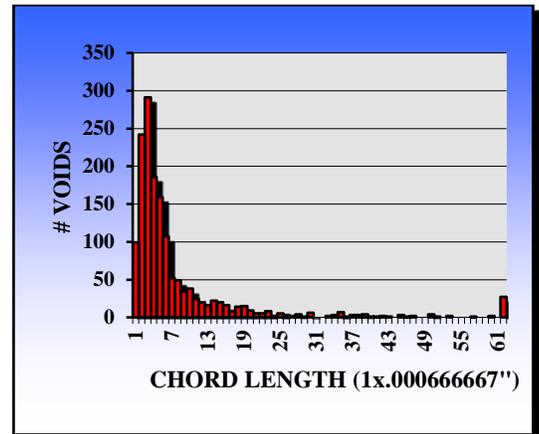
DATE:

Sample Number: #4, SP4705-30
Conformance: Overall, the sample contained an air void system which was originally consistent with current technology for freeze-thaw resistance. Ettringite-filled voids were counted.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 95mm (3 3/4") diameter by 245mm (9 5/8") long

Test Data: By ASTM C:457

Air Void Content %	9.6
Entrained, % < 0.040"(1mm)	6.9
Entrapped, % > 0.040"(1mm)	2.7
Air Voids/inch	15.3
Specific Surface, in ² /in ³	640
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	100
Test Date	1/31/2012



Magnification: 15x
Description: Hardened air void system 20mm from the top surface.

AIR VOID ANALYSIS

PROJECT:

REPORTED TO:

AET PROJECT NO:

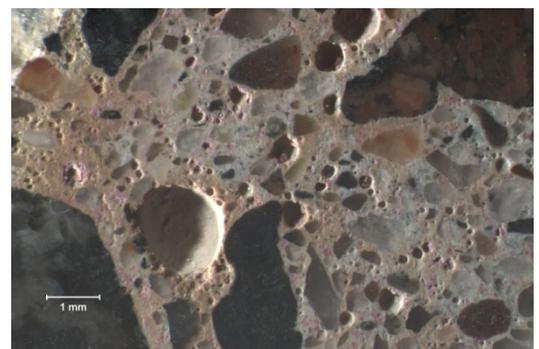
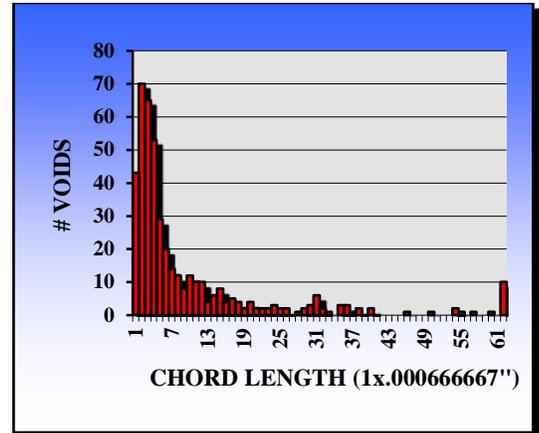
ATTN:

DATE:

Sample Number: #4, SP4705-30
Conformance: The concrete between 0mm and 22mm from the joint contained an air void system which is consistent with current technology for freeze-thaw resistance. Ettringite-filled voids were not counted.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 95mm (3 3/4") diameter by 245mm (9 5/8") long

Test Data: By ASTM C:457
Air Void Content % 8.3
Entrained, % < 0.040"(1mm) 4.8
Entrapped, % > 0.040"(1mm) 3.5
Air Voids/inch 8.8
Specific Surface, in²/in³ 420
Spacing Factor, inches 0.007
Paste Content, % estimated 26
Magnification 75x
Traverse Length, inches 50
Test Date 1/31/2012



Magnification: 15x
Description: Hardened air void system 150mm from the top surface and at the joint crack.

AIR VOID ANALYSIS

PROJECT:

REPORTED TO:

AET PROJECT NO:

ATTN:

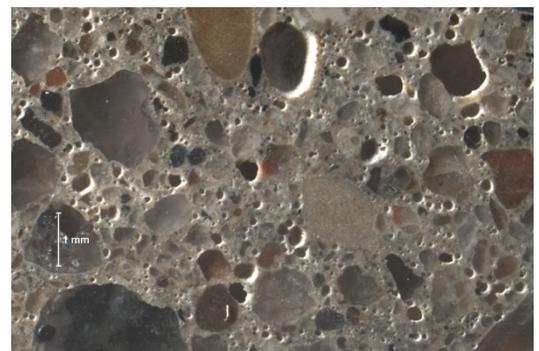
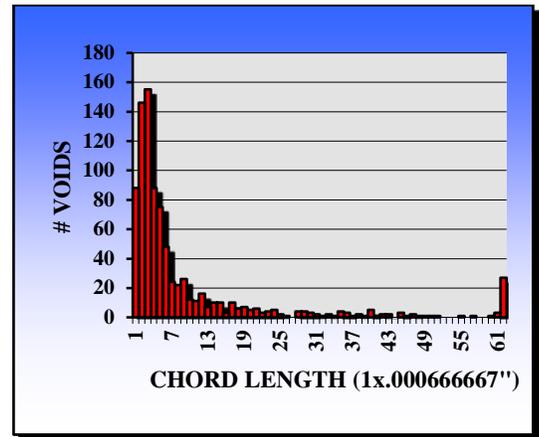
DATE:

Sample Number: #7, SP4705-30
Conformance: Overall, the sample contained an air void system which was originally consistent with current technology for freeze-thaw resistance. Any ettringite-filled voids were counted.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 95mm (3 3/4") diameter by 240mm (9 1/2") long

Test Data: By ASTM C:457

Air Void Content %	6.7
Entrained, % < 0.040"(1mm)	4.3
Entrapped, % > 0.040"(1mm)	2.4
Air Voids/inch	8.7
Specific Surface, in ² /in ³	520
Spacing Factor, inches	0.007
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	100
Test Date	1/31/2012



Magnification: 15x
Description: Hardened air void system 10mm from the top surface.

PROJECT:

REPORTED TO:

AET PROJECT NO:

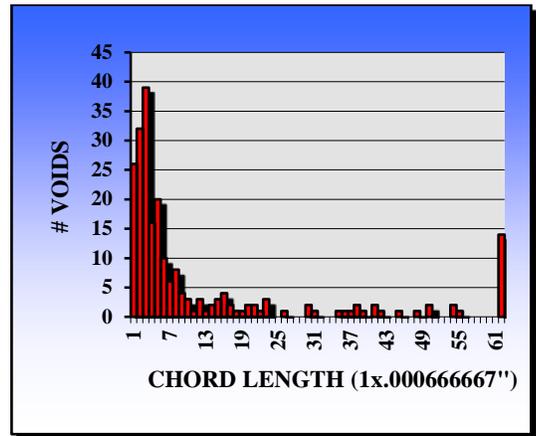
ATTN:

DATE:

Sample Number: #7, SP4705-30
Conformance: The concrete between 0mm and 20mm from the joint contained an air void system which is not consistent with current technology for freeze-thaw resistance. Ettringite-filled voids were not counted.

Sample Data By ASTM C457
 Description: Hardened Concrete Core
 Dimensions: 95mm (3 3/4") diameter by 240mm (9 1/2") long

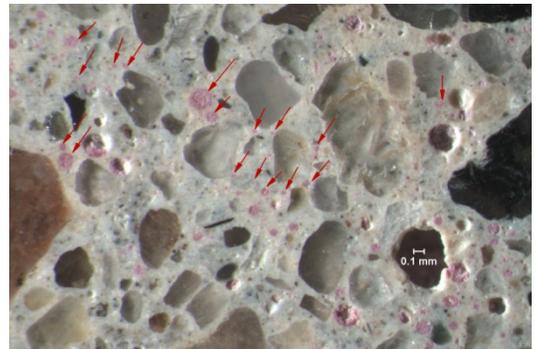
Test Data: By ASTM C:457
 Air Void Content % 4.6
 Entrained, % < 0.040"(1mm) 2.5
 Entrapped, % > 0.040"(1mm) 2.1
 Air Voids/inch 4.5
 Specific Surface, in²/in³ 390
 Spacing Factor, inches 0.013
 Paste Content, % estimated 26
 Magnification 75x
 Traverse Length, inches 50
 Test Date 1/31/2012



Report Prepared By:



Gerard Moulzoh, PG
 Vice President/Principal Petrographer
 FL License #PG2496, MN License #30023



Magnification: 30x
 Description: Filled air void system 120mm from the top surface and 8mm from the joint crack.

AIR VOID ANALYSIS

PROJECT:

REPORTED TO:

AET PROJECT NO:

ATTN:

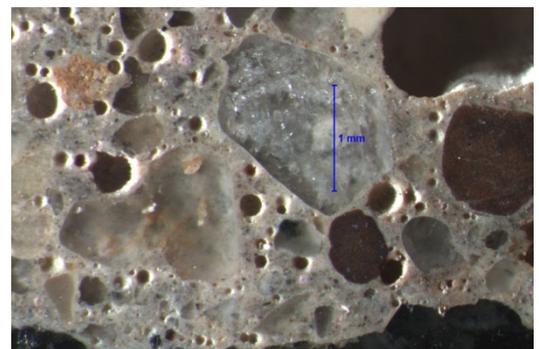
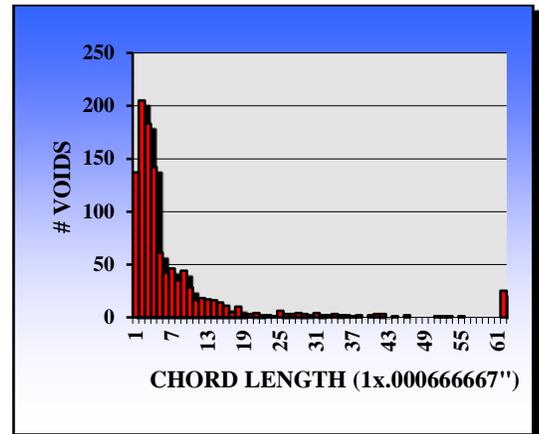
DATE:

Sample Number: 7009, SP7380-199
Conformance: Overall, the sample contained an air void system which was originally consistent with current technology for freeze-thaw resistance. Ettringite-filled voids were counted.

Sample Data By ASTM C457
Description: Hardened Concrete Core
Dimensions: 95mm (3 3/4") diameter by 247mm (9 3/4") long

Test Data: By ASTM C:457

Air Void Content %	7.0
Entrained, % < 0.040"(1mm)	4.9
Entrapped, % > 0.040"(1mm)	2.1
Air Voids/inch	11.5
Specific Surface, in ² /in ³	660
Spacing Factor, inches	0.006
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	98
Test Date	2/29/12



Magnification: 30x
Description: Hardened air void system 70mm from top; 45mm from joint.

AIR VOID ANALYSIS

PROJECT:

REPORTED TO:

AET PROJECT NO:

ATTN:

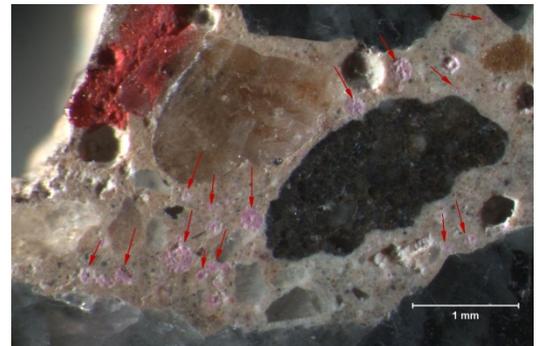
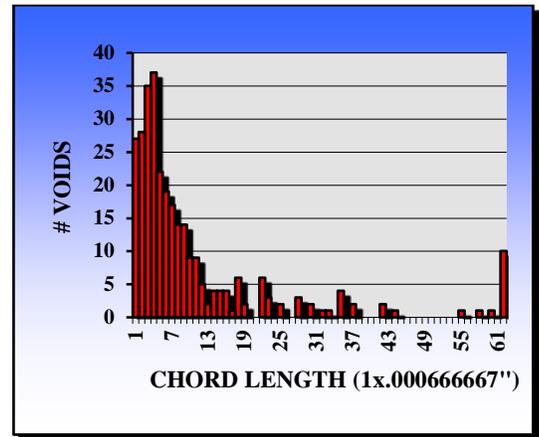
DATE:

Sample Number: 7009, SP7380-199
Conformance: The concrete, between 0 and 25mm from the joint, exhibits air void parameters which are not consistent with current technology for freeze-thaw resistance.

Sample Data
Description: Hardened Concrete Core
Dimensions: 95mm (3 3/4") diameter by 247mm (9 3/4") long

Test Data: By ASTM C:457

Air Void Content %	4.9
Entrained, % < 0.040"(1mm)	3.4
Entrapped, % > 0.040"(1mm)	1.5
Air Voids/inch	6.10
Specific Surface, in ² /in ³	500
Spacing Factor, inches	0.010
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	49
Test Date	2/29/12



Magnification: 30x
Description: Hardened air void system 70mm from top; 0mm from joint.

AIR VOID ANALYSIS

PROJECT:

REPORTED TO:

AET PROJECT NO:

ATTN:

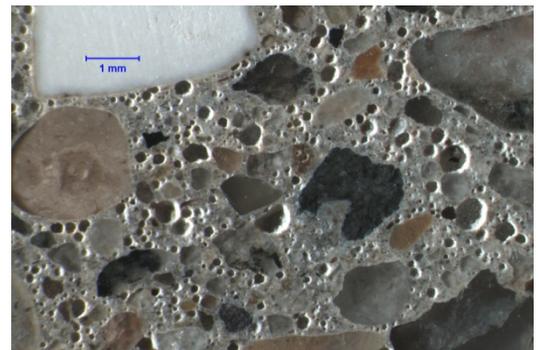
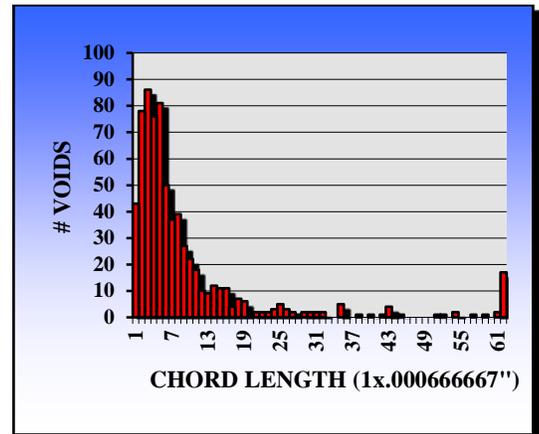
DATE:

Sample Number: 7012, SP7380-199
Conformance: The concrete sample contained an air void system which was consistent with current technology for freeze-thaw resistance.

Sample Data
By ASTM C457
Description: Hardened Concrete Core
Dimensions: 95mm (3 3/4") diameter by 255mm (10") long

Test Data: By ASTM C:457

Air Void Content %	11.0
Entrained, % < 0.040"(1mm)	8.2
Entrapped, % > 0.040"(1mm)	2.8
Air Voids/inch	15.4
Specific Surface, in ² /in ³	570
Spacing Factor, inches	0.004
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	45
Test Date	2/29/12



Magnification: 15x

Description: Overall view of hardened air void system.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 1



SAMPLE ID: 4, 4705-30 DESCRIPTION: Core sample taken directly through a pavement joint, as received. Top surface is left. Existing fractures are mapped in red ink.

PHOTO: 2



SAMPLE ID: 4, 4705-30 DESCRIPTION: Top surface of the core as received. Note core was taken through a sawcut and silicone sealed control joint.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 3



SAMPLE ID: 7, 4705-30 DESCRIPTION: Core sample taken directly through a pavement joint, as received. Top surface is left.

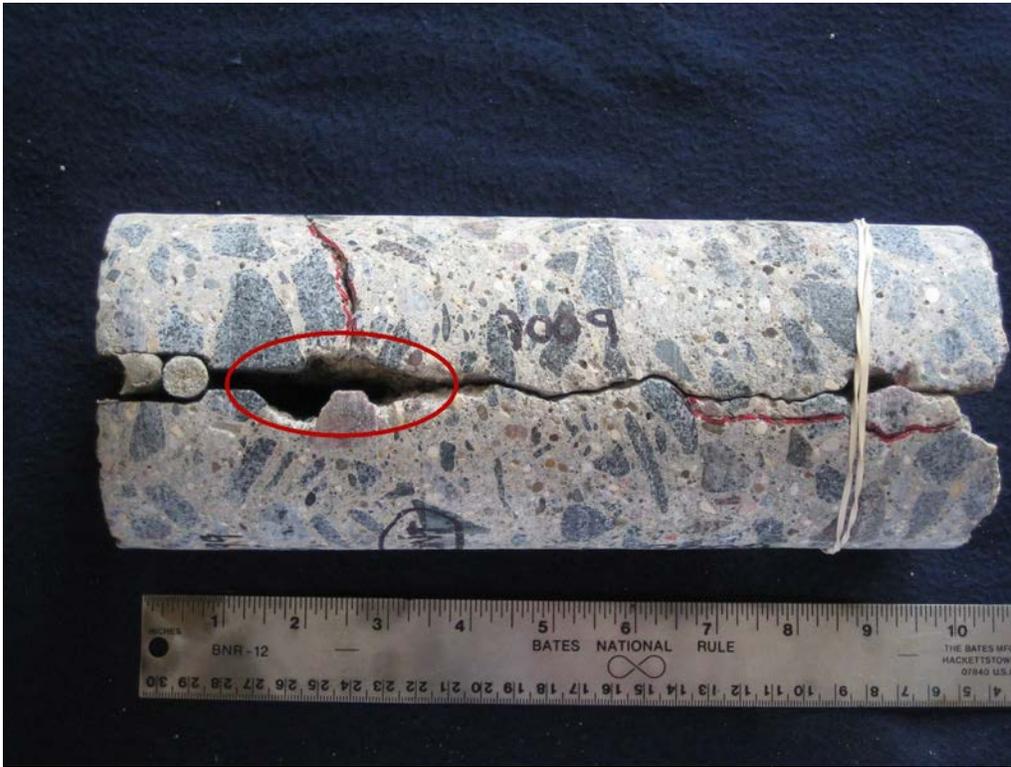
PHOTO: 4



SAMPLE ID: 7, 4705-30 DESCRIPTION: Top surface of the core as received. Note core was taken through a sawcut and silicone sealed control joint.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 5



SAMPLE ID: 7009, 7380-199

DESCRIPTION: Core sample taken directly through a pavement joint, as received. Top surface is left. Note "tunneling" below the sawcut (circled).

PHOTO: 6



SAMPLE ID: 7009, 7380-199

DESCRIPTION: Top surface of the core as received. Note core was taken through a sawcut and silicone sealed control joint.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 7



SAMPLE ID: 7012, 7380-199

DESCRIPTION: Core sample taken directly through a pavement joint, as received. Top surface is left. Note joint crack bisects a large coarse aggregate particle (outlined in black).

PHOTO: 8



SAMPLE ID: 7012, 7380-199

DESCRIPTION: Mortar-eroded top surface of the core as received. Note core was taken through a sawcut and silicone sealed control joint.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN



PHOTO: 9

SAMPLE ID: 4, 4705-30 DESCRIPTION: Sawcut and lapped cross section of core. Mostly sub-horizontally oriented fractures and microcracking are mapped in red ink.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

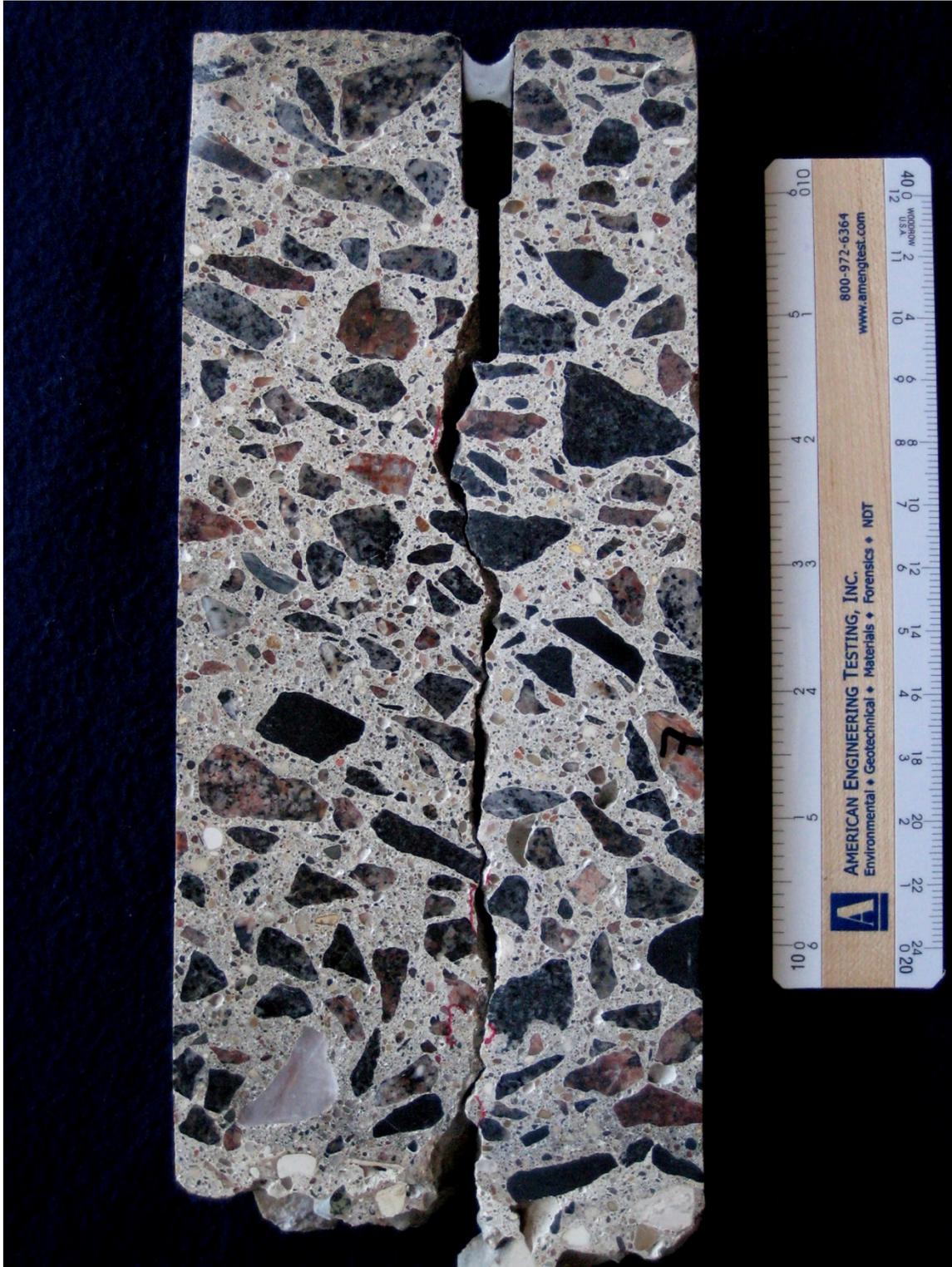


PHOTO: 10

SAMPLE ID: 7, 4705-30 **DESCRIPTION:** Sawcut and lapped cross section of core. Some fine sub-vertically oriented microcracks along the joint crack are mapped in red ink.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

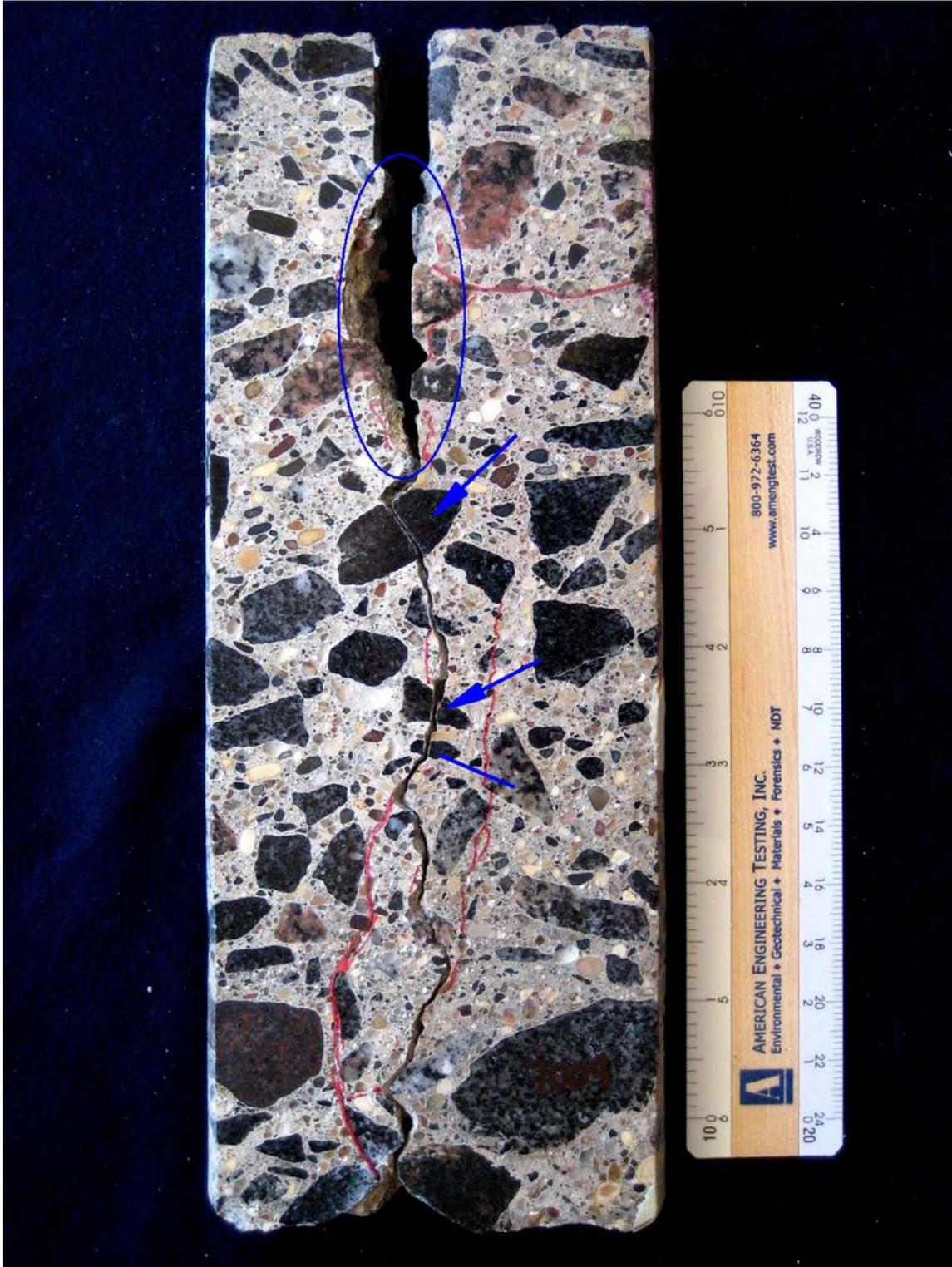


PHOTO: 11

SAMPLE ID: 7009, 7380-199

DESCRIPTION: Sawcut and lapped cross section of core. Note "tunneling" below the sawcut (circled), bisected coarse aggregates (arrows), and sub-vertical microcracking along the joint crack, mapped in red ink.

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 12

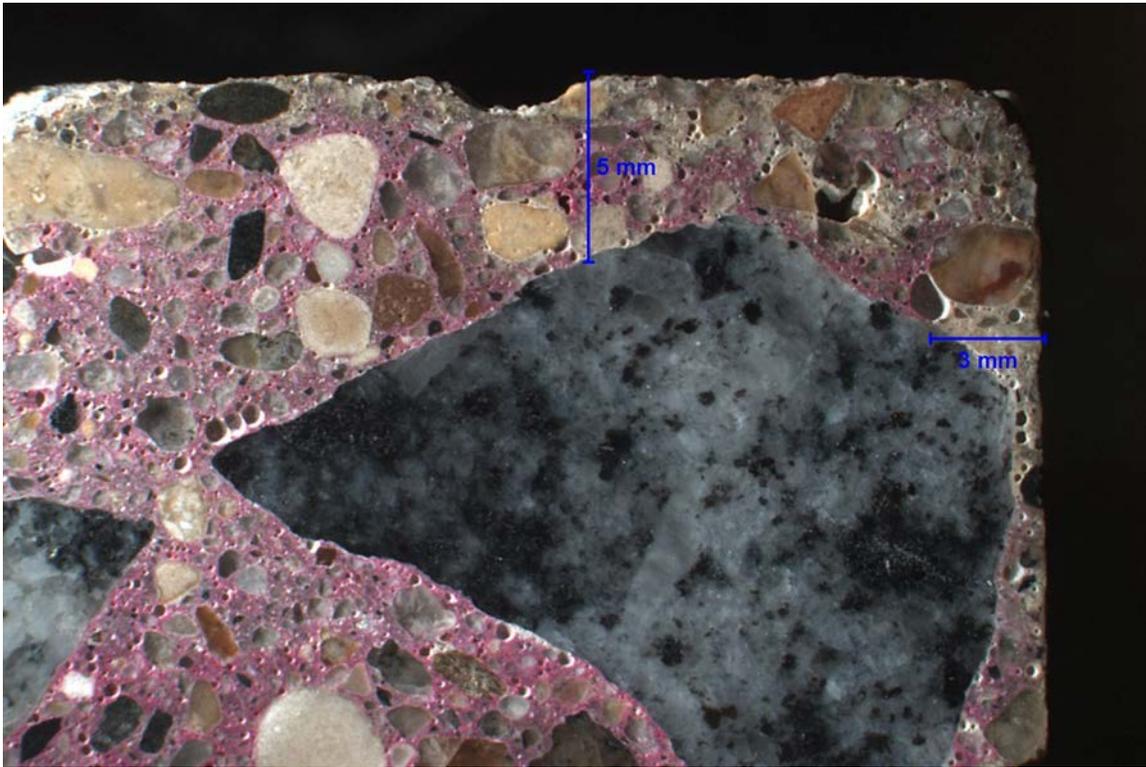


SAMPLE ID: 7012, 7380-199

DESCRIPTION: Sawcut and lapped cross section of core taken through a joint. Note resulting crack bisects a coarse aggregate (arrow).

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

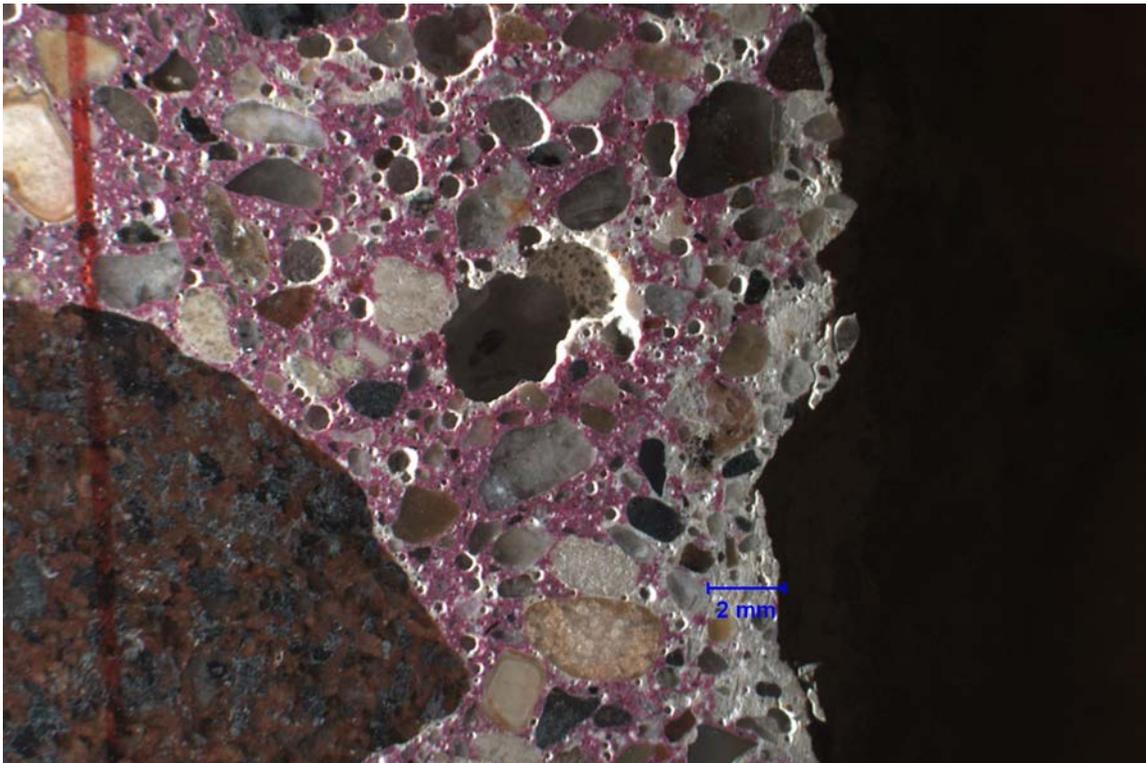
PHOTO: 13



SAMPLE ID: 4, 4705-30 DESCRIPTION: Carbonation (unstained) proceeds up to 5mm depth from the top surface and up to 3mm depth from the sawcut joint surface; in this view of sawcut and lapped cross section of core exposed to phenolphthalein pH indicator.

MAG: 5x

PHOTO: 14

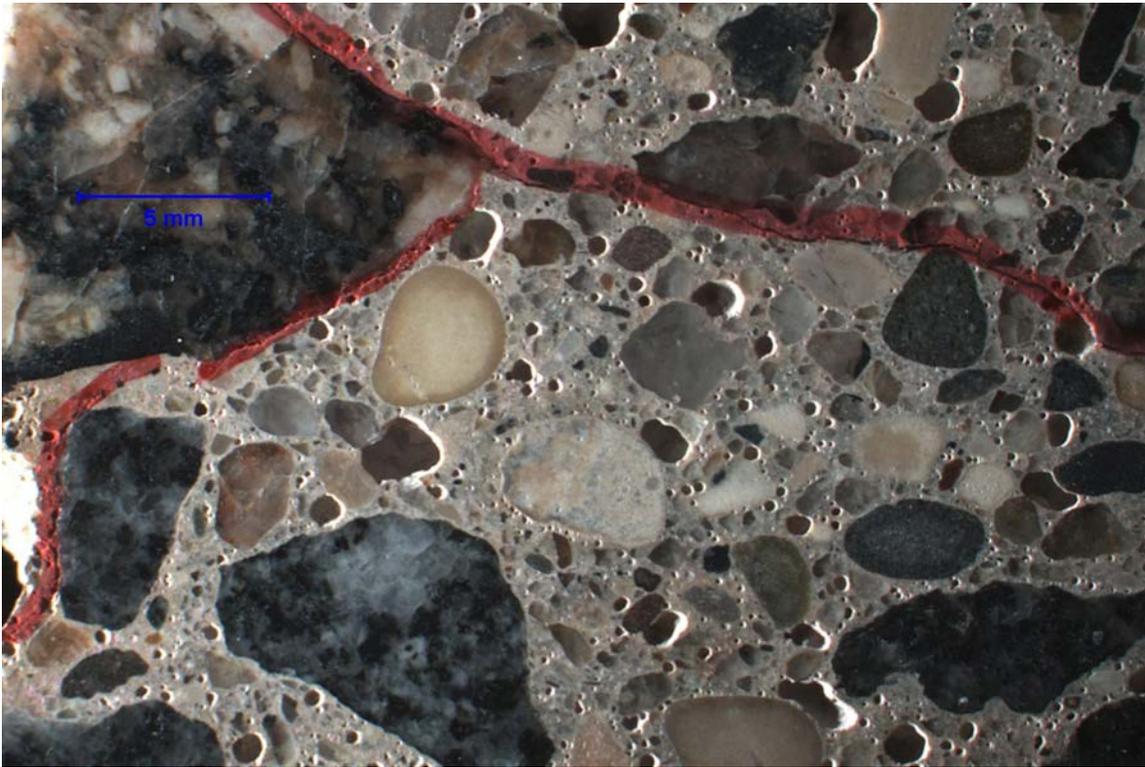


SAMPLE ID: 4, 4705-30 DESCRIPTION: Carbonation (unstained paste) proceeds up to 2mm depth from the distressed joint plane at 100mm depth in the core.

MAG: 5x

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 15

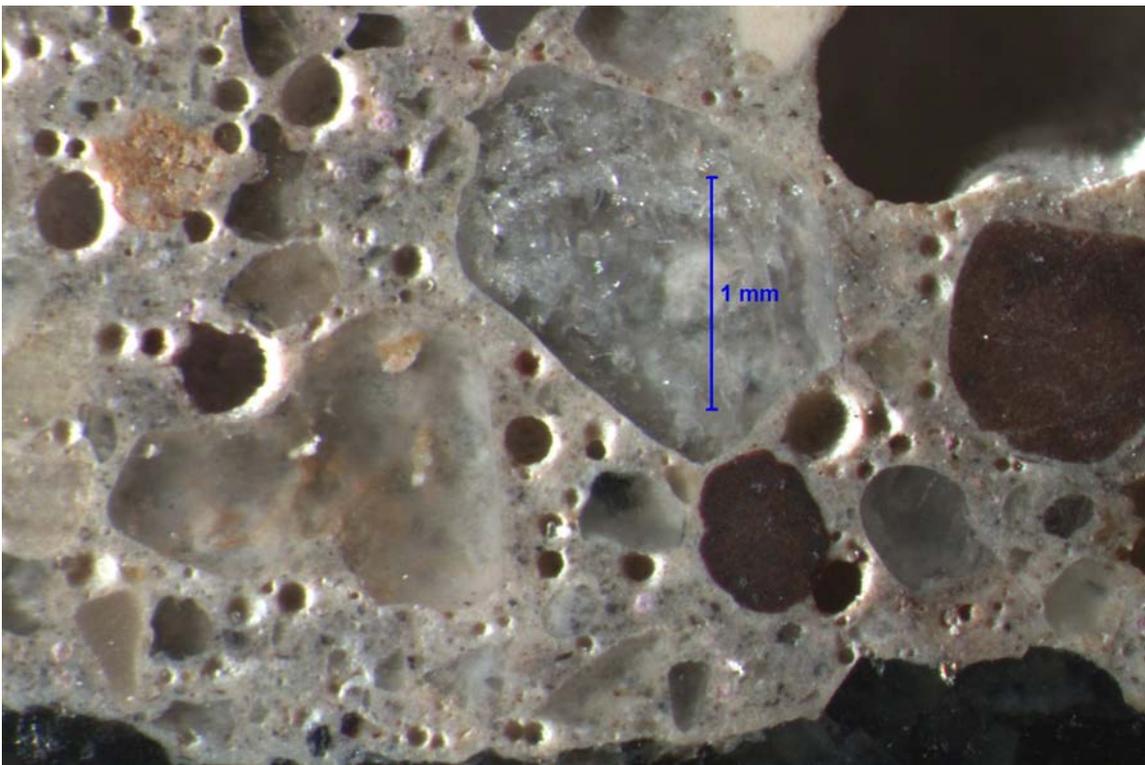


SAMPLE ID: 7009, 7380-199

DESCRIPTION: Overall view of air void system at 60mm depth in the core. Not loss of fine air voidspaces on left 1/3 of image from secondary ettringite fillings.

MAG: 5x

PHOTO: 16



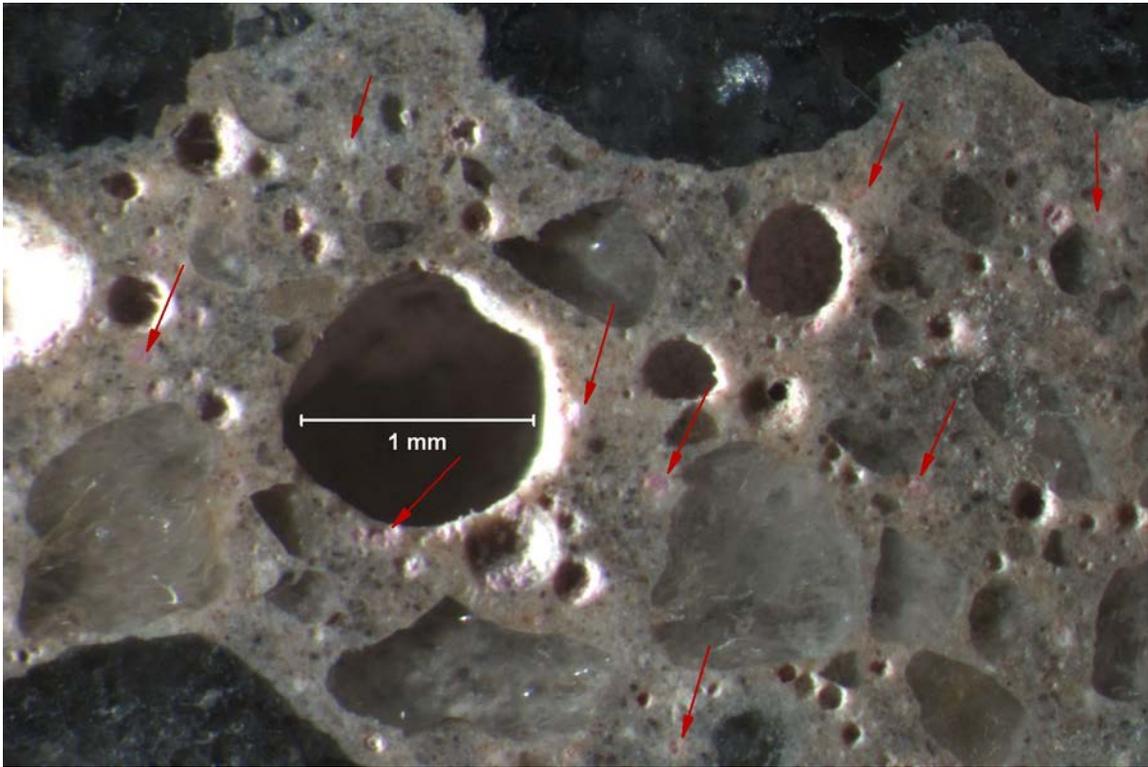
SAMPLE ID: 7009, 7380-199

DESCRIPTION: Air void system at 70mm depth in the core and 45mm depth from the distressed joint plane.

MAG: 30x

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 17

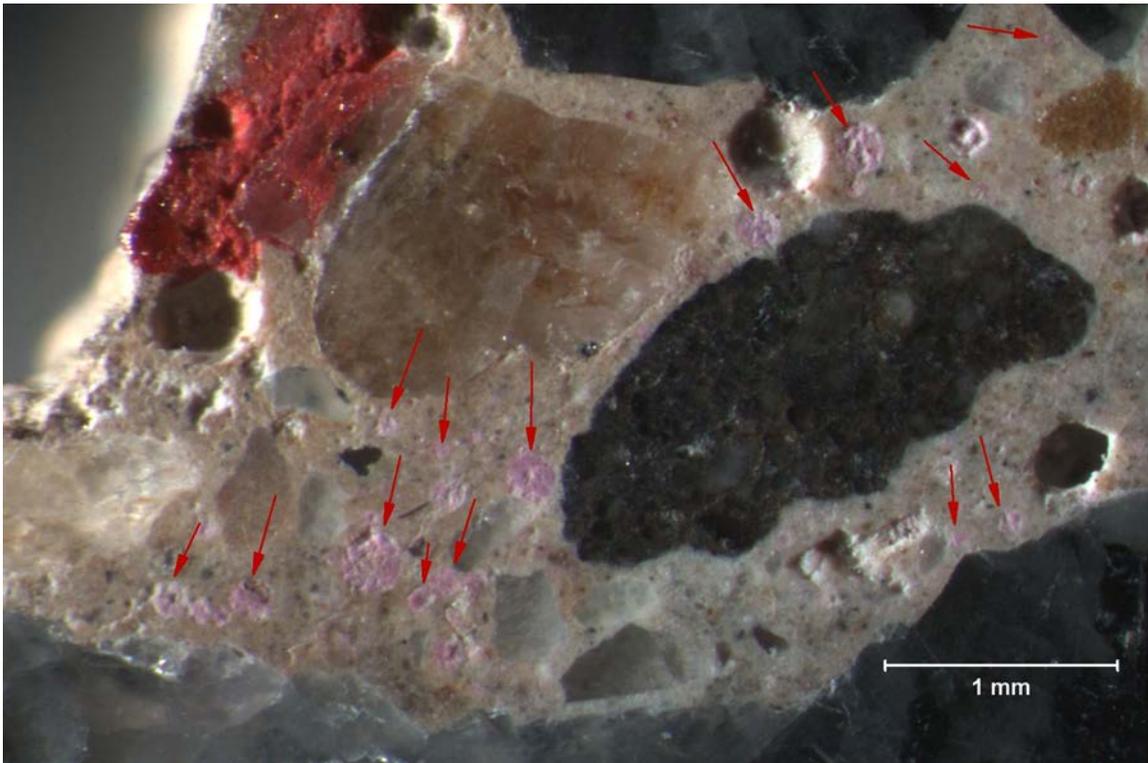


SAMPLE ID: 7009, 7380-199

DESCRIPTION: Overall view of air void system at 70mm depth in the core and 25mm from the distressed joint plane. Note (stained) ettringite-filled air voidspaces (arrows).

MAG: 15x

PHOTO: 18



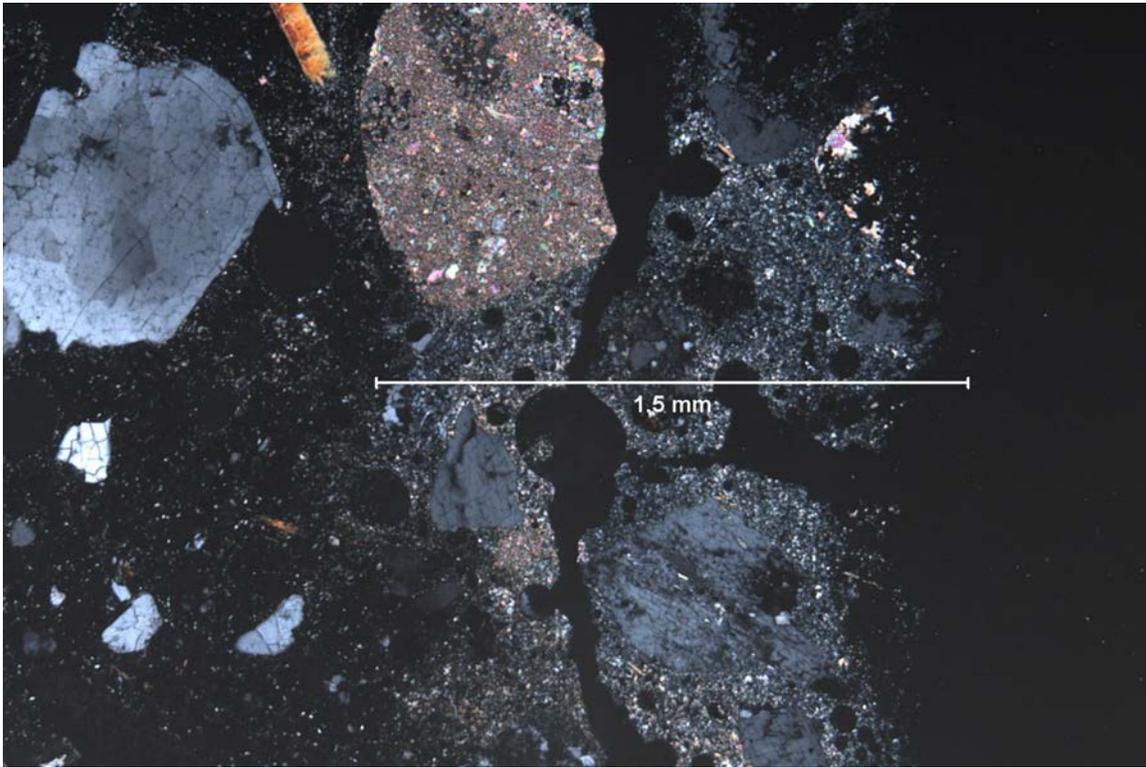
SAMPLE ID: 7009, 7380-199

DESCRIPTION: Air void system at 70mm depth in the core and at the distressed joint plane (L). Note stained ettringite-filled voidspaces marked with arrows.

MAG: 30x

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 19

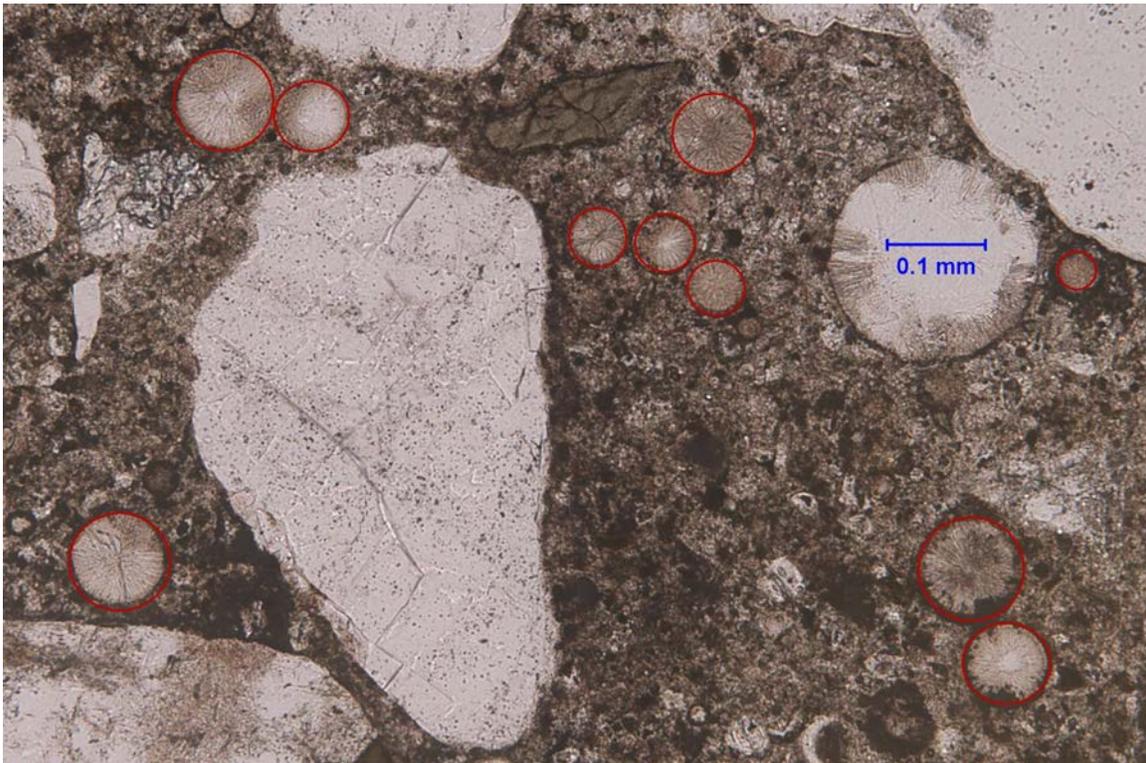


SAMPLE ID: 7009, 7380-199

DESCRIPTION: Overall view of brightly colored carbonated paste to 1.5mm depth from the distressed joint plane; in thin section of concrete under cross polarized light.

MAG: 40x

PHOTO: 20



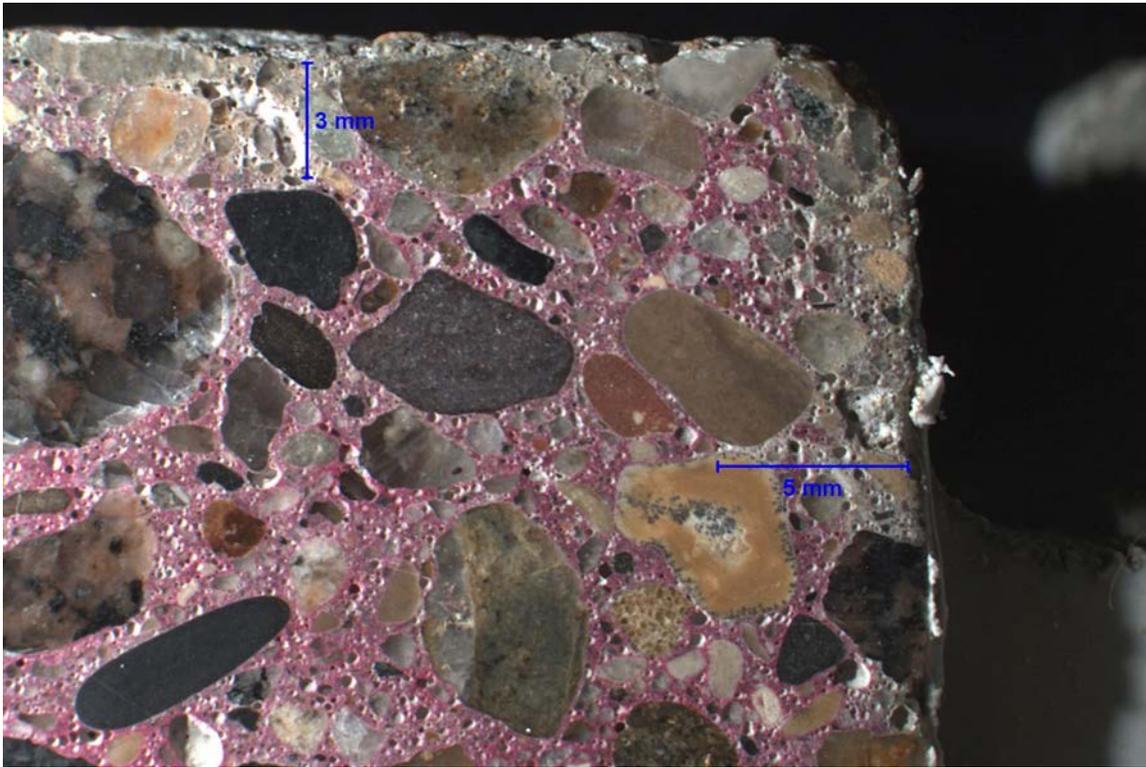
SAMPLE ID: 7009, 7380-199

DESCRIPTION: Ettringite-filled voidspaces, outlined in red, in thin section of concrete paste adjacent to the distressed joint plane, under plane polarized light.

MAG: 100x

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 21

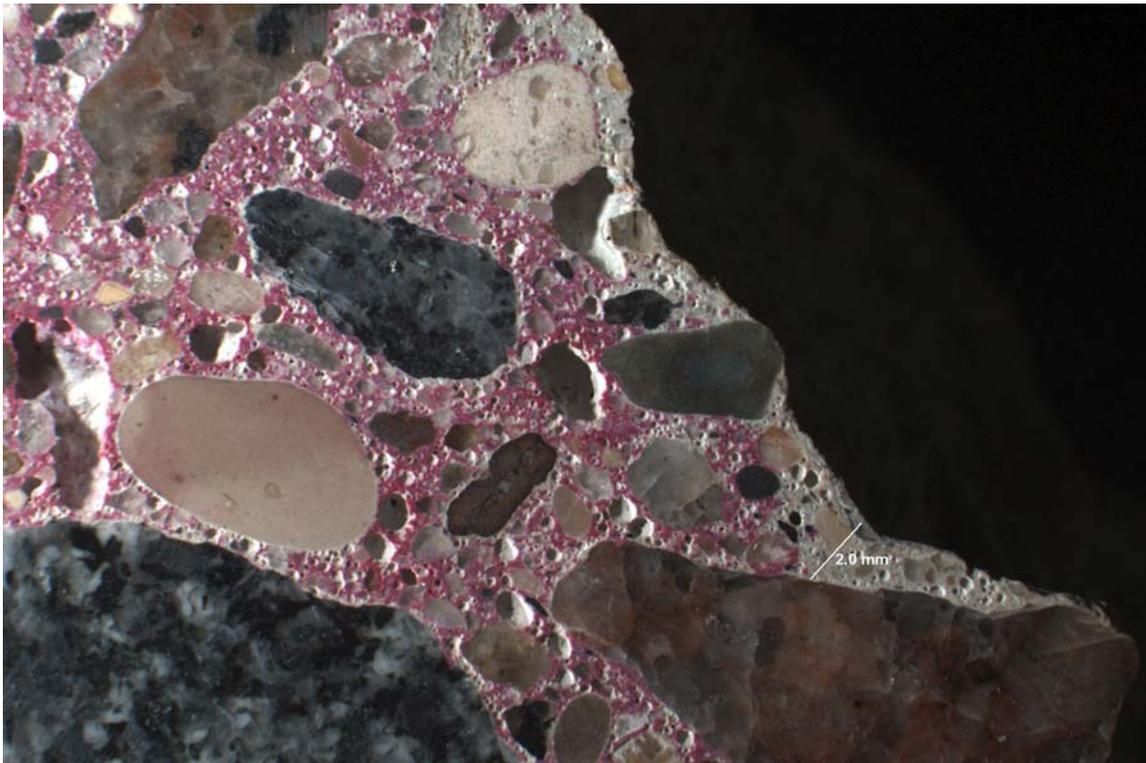


SAMPLE ID: 7012, 7380-199

DESCRIPTION: Carbonation (unstained) ranged from negligible up to 3mm depth from the top surface and ranged from negligible up to 5mm depth from the sawcut joint surface; in this view of sawcut and lapped cross section of core exposed to phenolphthalien pH indicator.

MAG: 5x

PHOTO: 22



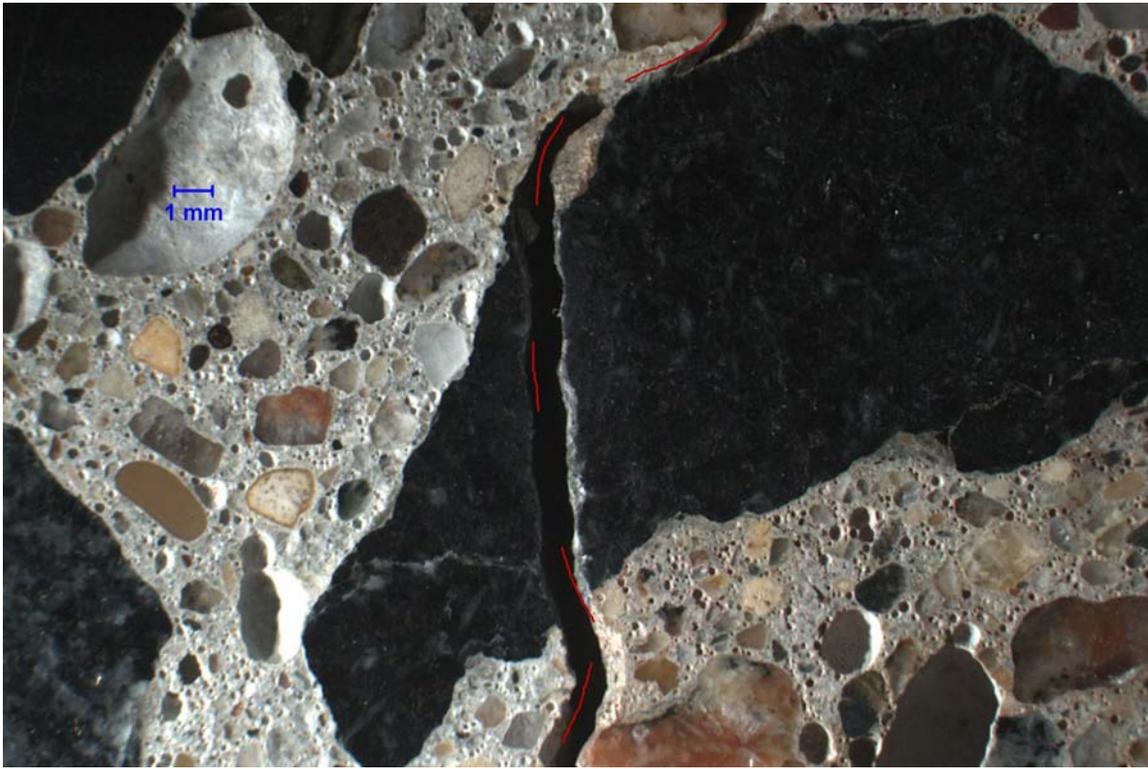
SAMPLE ID: 7012, 7380-199

DESCRIPTION: Carbonation (unstained paste) proceeds up to 2mm depth from the stressed joint plane at 105mm depth in the core.

MAG: 5x

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

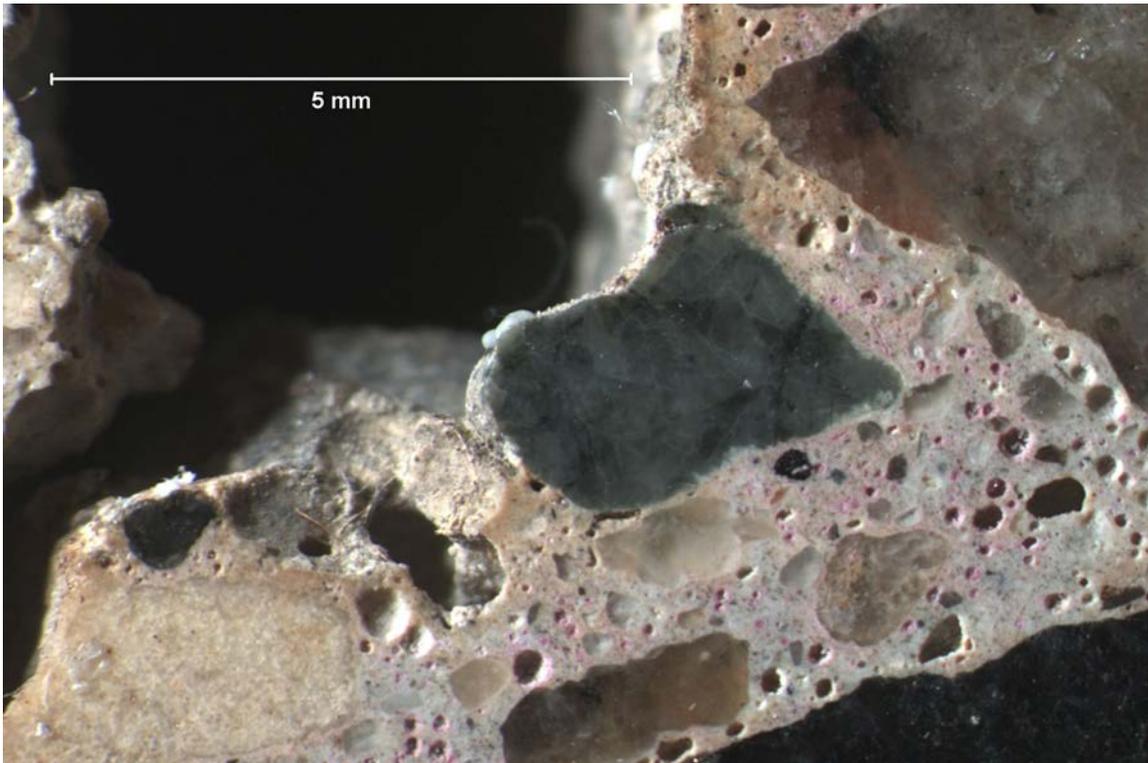
PHOTO: 23



SAMPLE ID: 7012, 7380-199 DESCRIPTION: Cracked coarse aggregate at 165mm depth in the joint crack.

MAG: 5x

PHOTO: 24

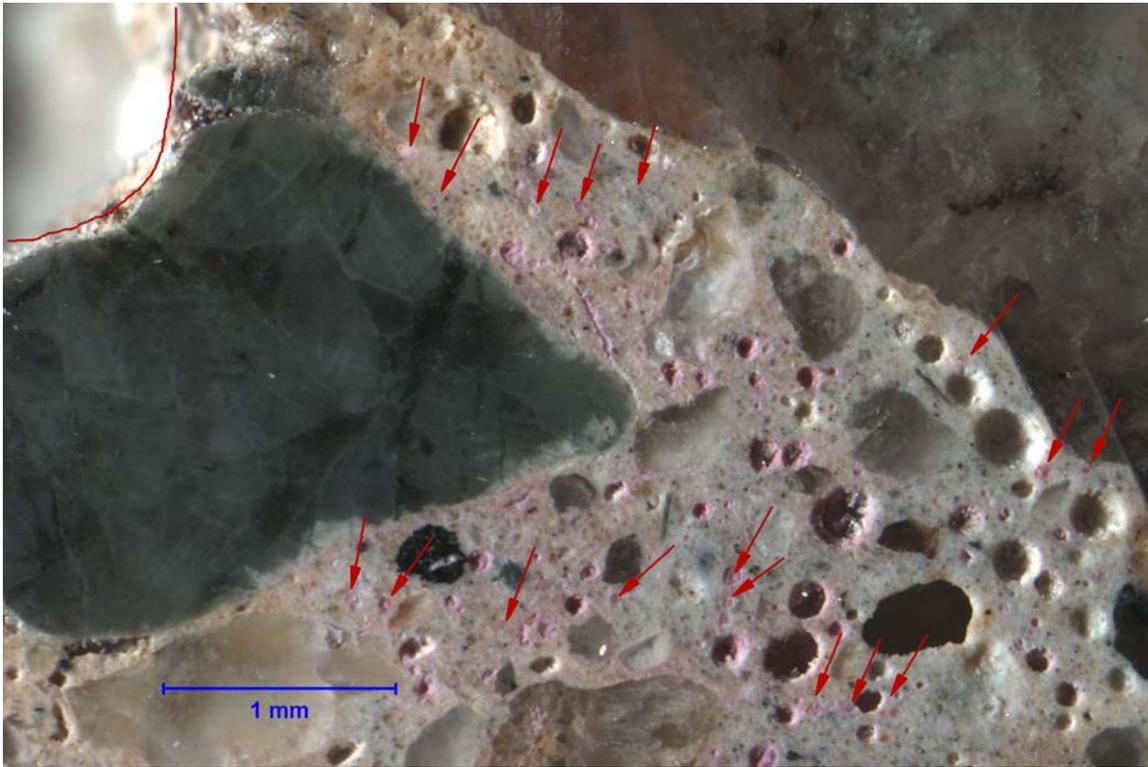


SAMPLE ID: 7012, 7380-199 DESCRIPTION: A concentration of magenta-stained, ettringite-filled voidspaces at the base of the sawcut control joint.

MAG: 5x

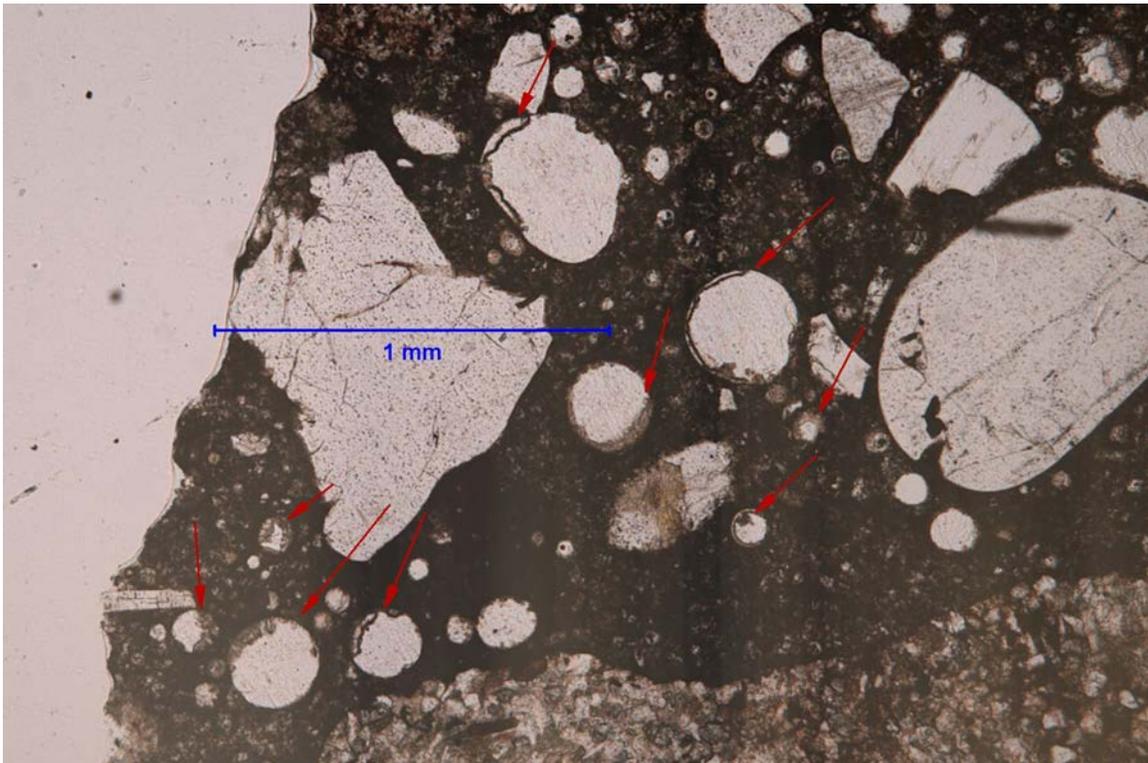
PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 25



SAMPLE ID: 7012, 7380-199 DESCRIPTION: Closer view of fine, ettringite-filled voids at the base of the sawcut.
MAG: 30x

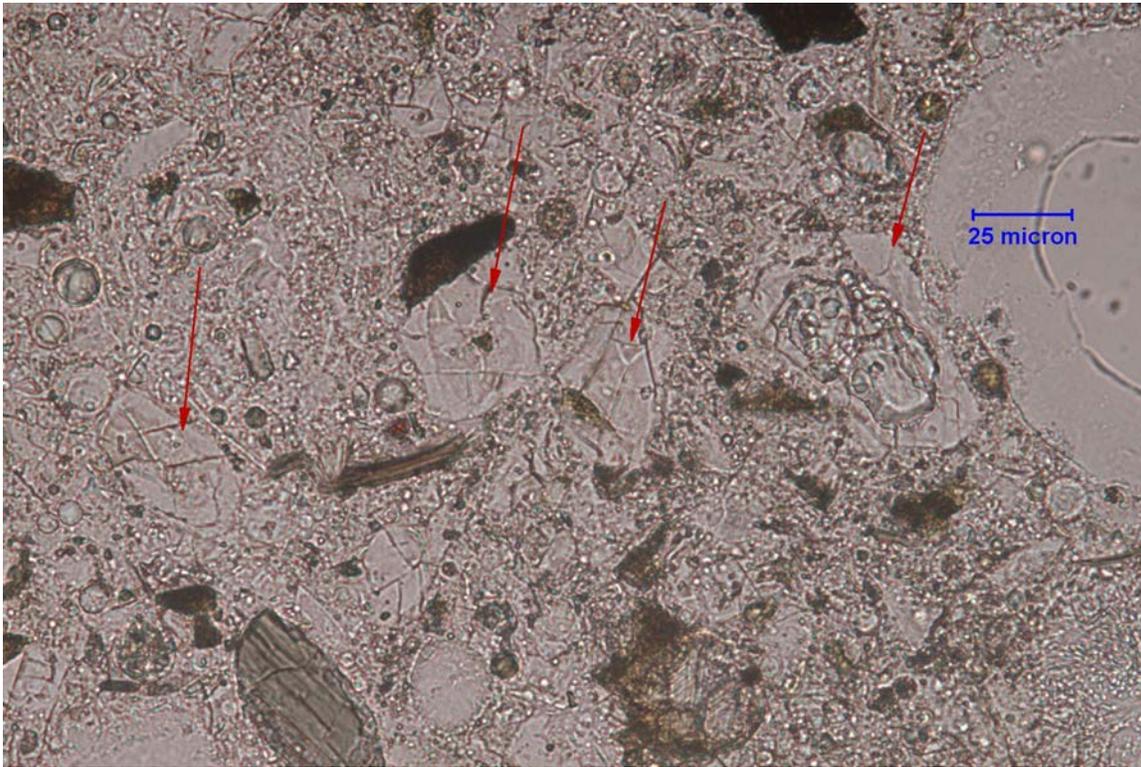
PHOTO: 26



SAMPLE ID: 7012, 7380-199 DESCRIPTION: Occurrences of ettringite on the linings of voidspaces at 140mm depth and directly adjacent to the joint crack (L).
MAG: 40x

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 27

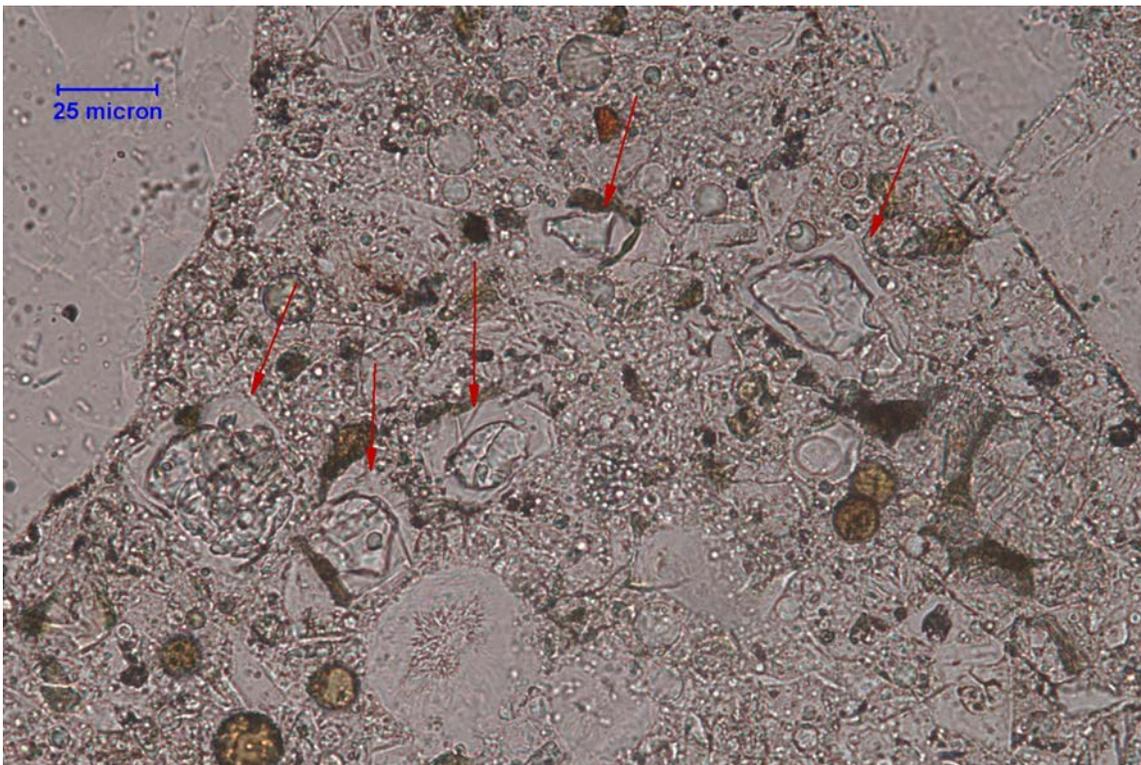


SAMPLE ID: 7012, 7380-199

DESCRIPTION: Well to fully hydrated alite portland cement clinker particles in thin section of concrete paste under plane polarized light. Note abundant spherical flyash pozzolan particles.

MAG: 400x

PHOTO: 28



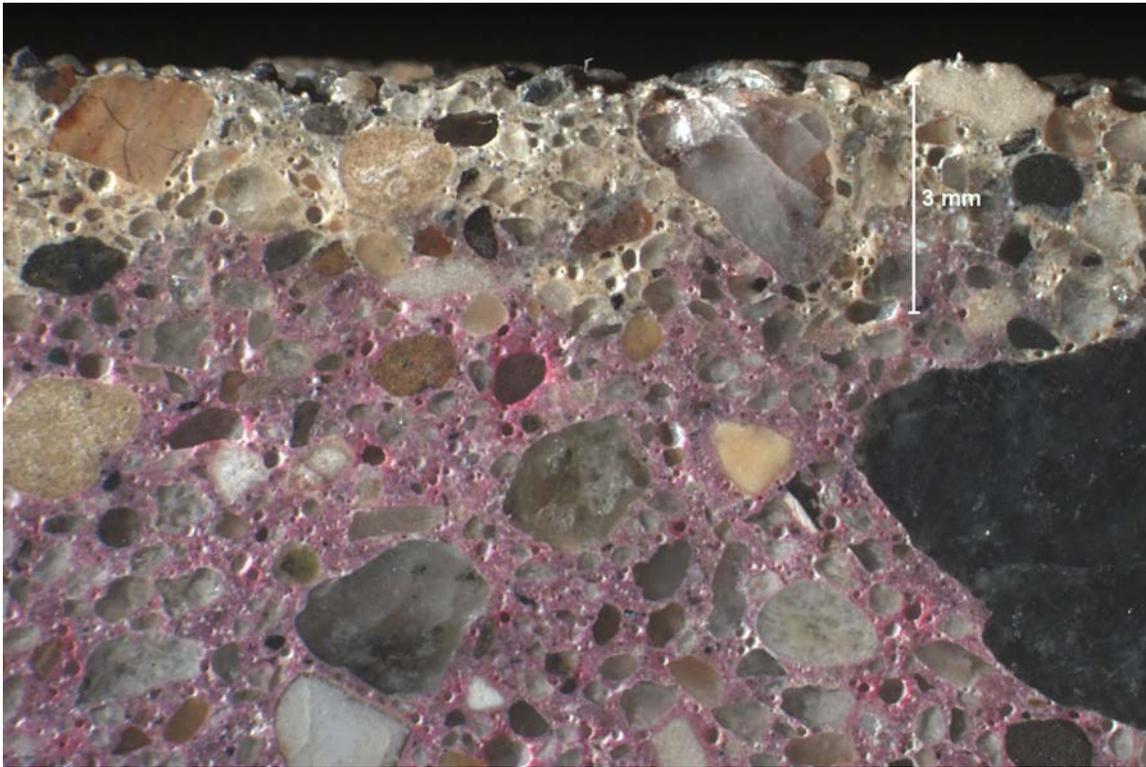
SAMPLE ID: 7009, 7380-199

DESCRIPTION: Well hydrated alite portland cement clinker particles in thin section of concrete paste under plane polarized light. Note abundant spherical flyash pozzolan particles.

MAG: 400x

PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 29



SAMPLE ID: 4, 4705-30 DESCRIPTION: Carbonation (unstained paste) proceeds up to 3mm depth (in this image) from the top surface of the core.
MAG: 10x

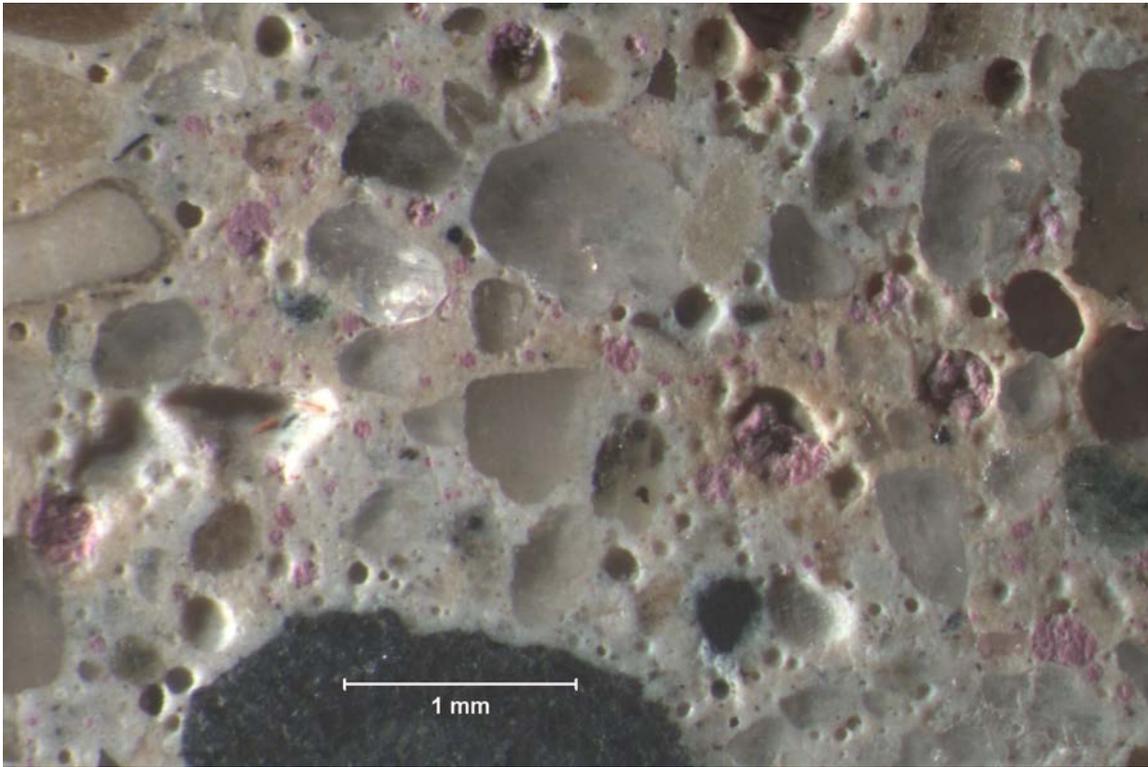
PHOTO: 30



SAMPLE ID: 4, 4705-30 DESCRIPTION: White to clear ASR gel product lines or fills voidspace adjacent to a reactive chert fine aggregate particle. Internal and radiating microcracking is mapped in red dashed lines.
MAG: 400x

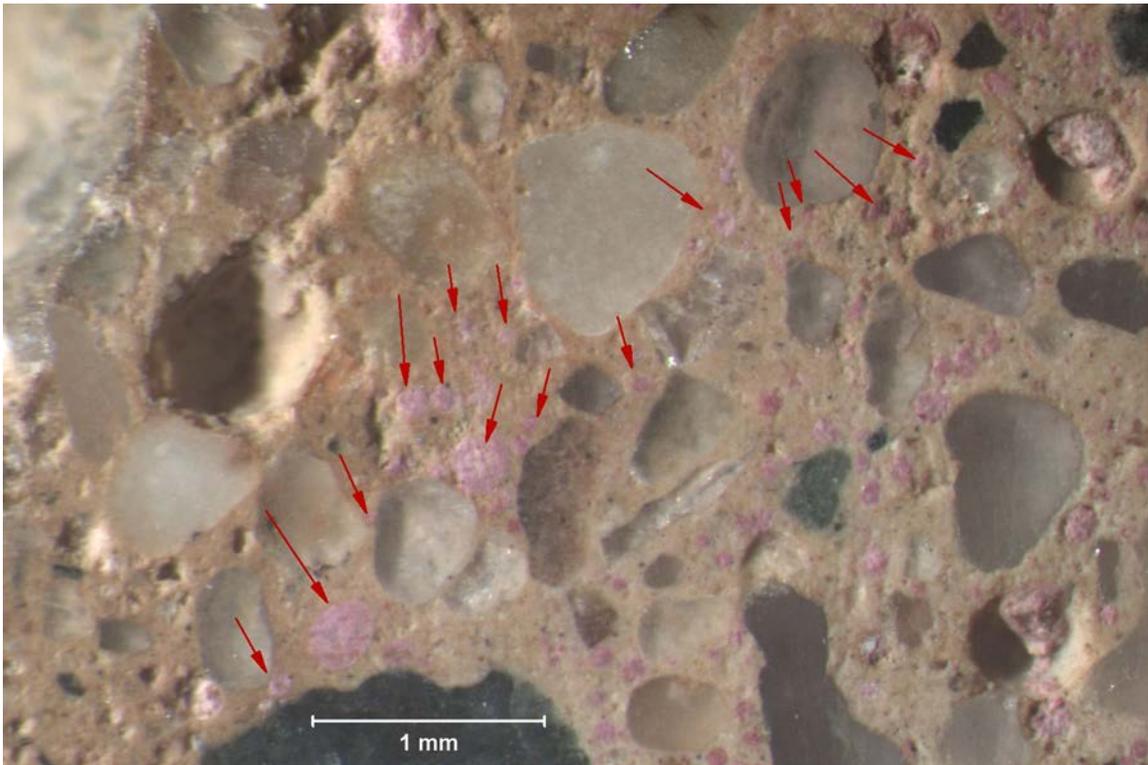
PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 31



SAMPLE ID: 4, 4705-30 DESCRIPTION: Magenta-stained ettringite fills many fine air voidspace in the paste at 20mm from the distressed joint plane at 155mm depth in the core.
MAG: 30x

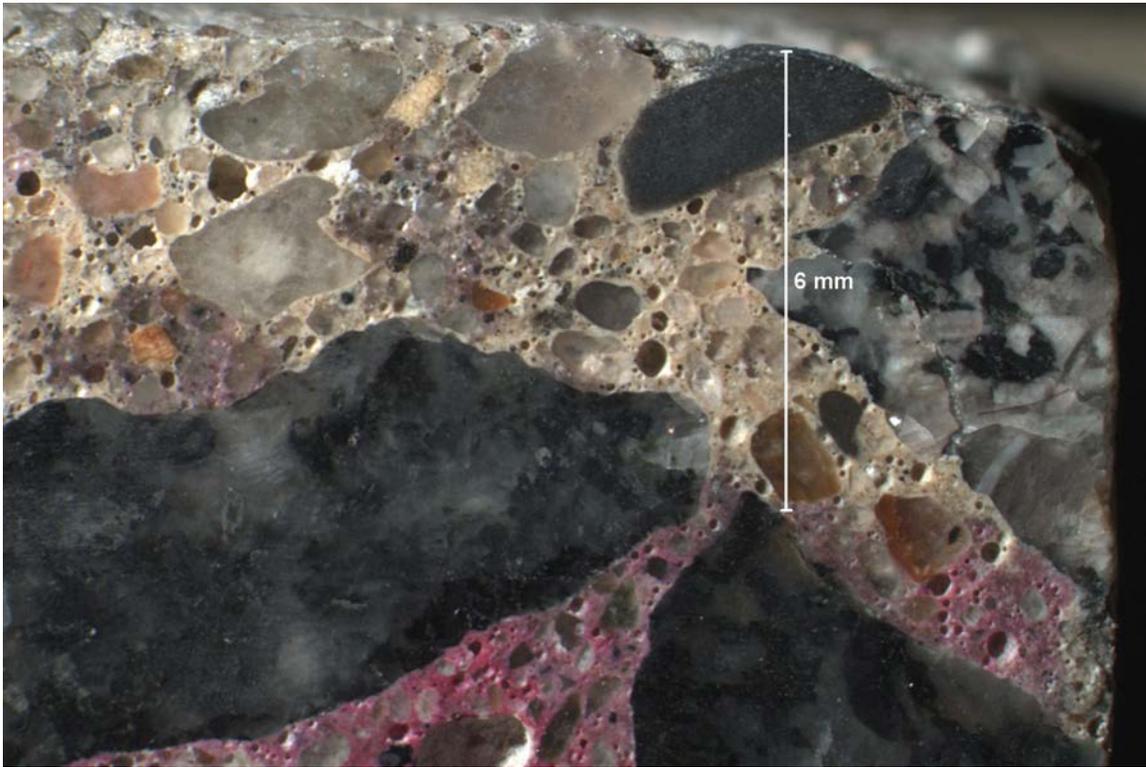
PHOTO: 32



SAMPLE ID: 4, 4705-30 DESCRIPTION: Magenta-stained ettringite fills most fine air voidspace in the paste directly adjacent to the distressed joint plane at 140mm depth in the core.
MAG: 30x

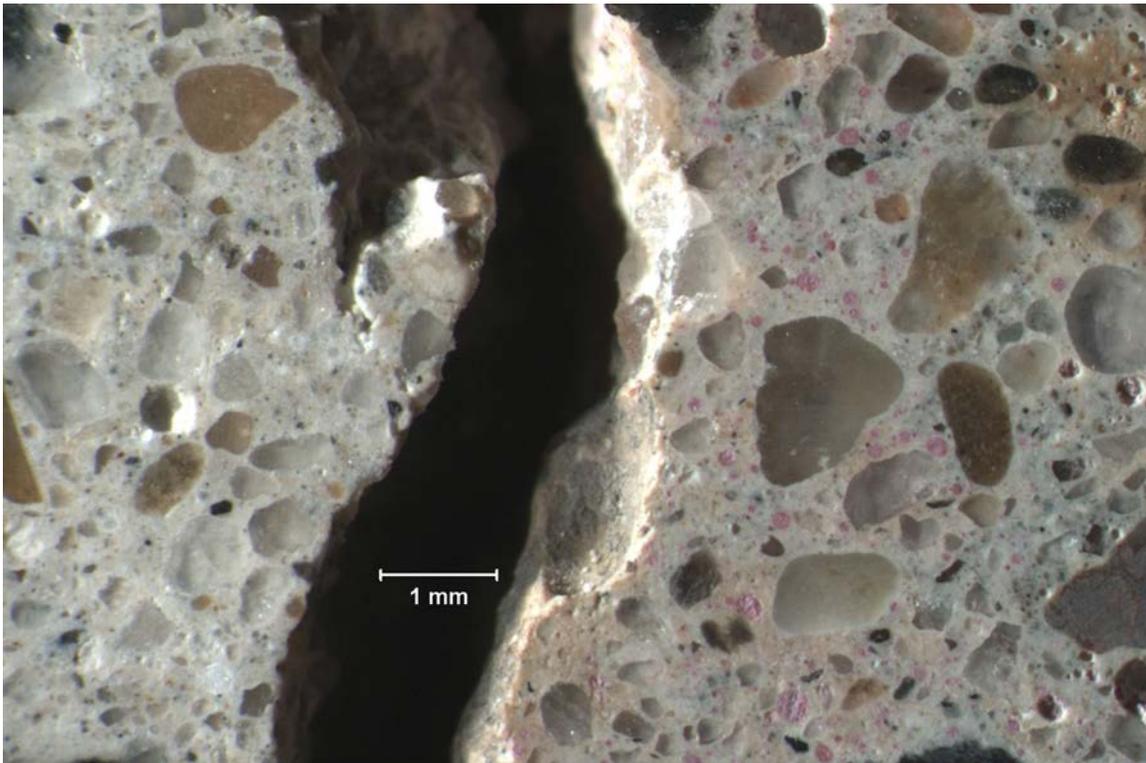
PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 33



SAMPLE ID: 7, 4705-30 DESCRIPTION: Carbonation (unstained paste) proceeds up to 6mm depth from the top surface of the core.
MAG: 5x

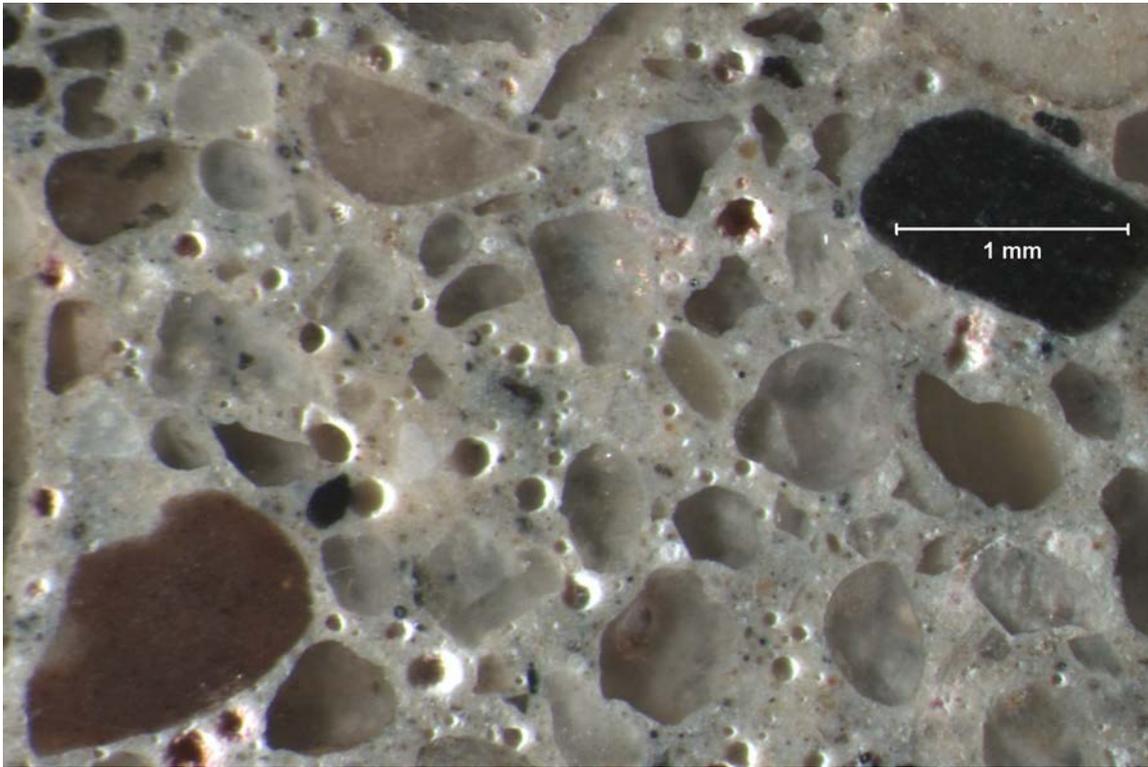
PHOTO: 34



SAMPLE ID: 7, 4705-30 DESCRIPTION: Magenta-stained ettringite (right side) and unstained ettringite (left) fills most fine air void-spaces in the paste directly adjacent to the mildly distressed joint plane at 130+mm depth in the core.
MAG: 15x

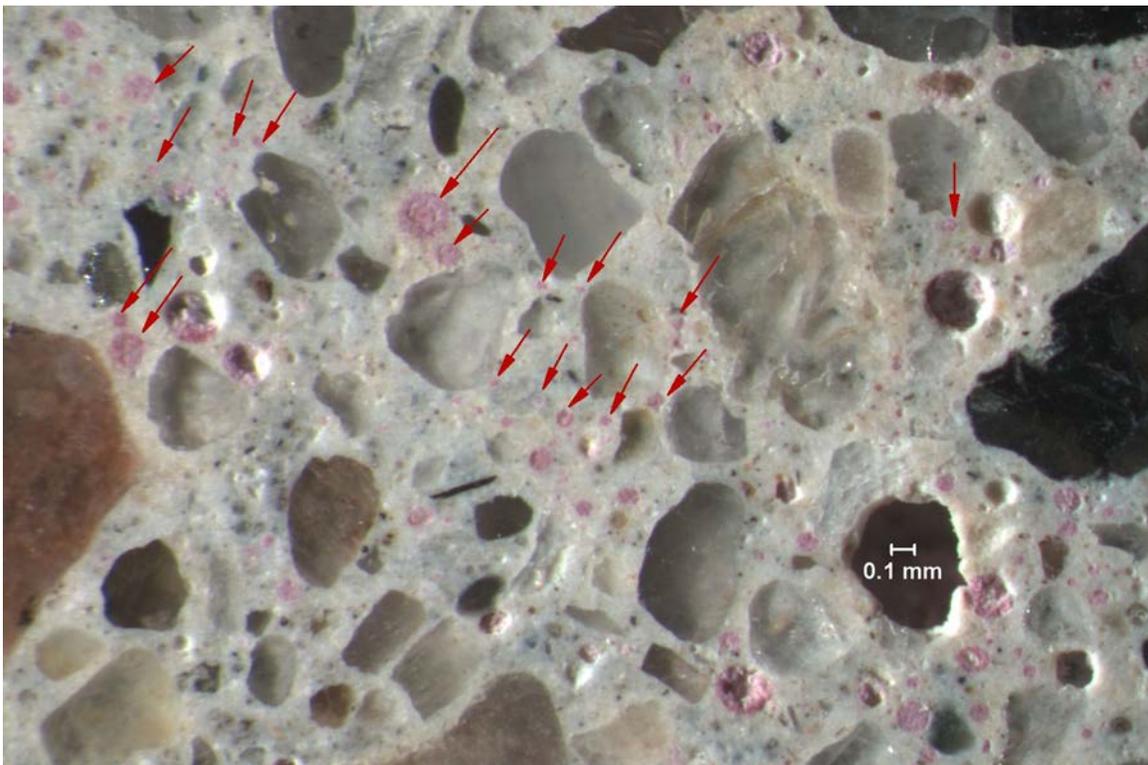
PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 35



SAMPLE ID: 7, 4705-30 DESCRIPTION: Overall view of the air void system at 112mm depth from the top surface of the core and 40mm depth from the joint plane.
MAG: 30x

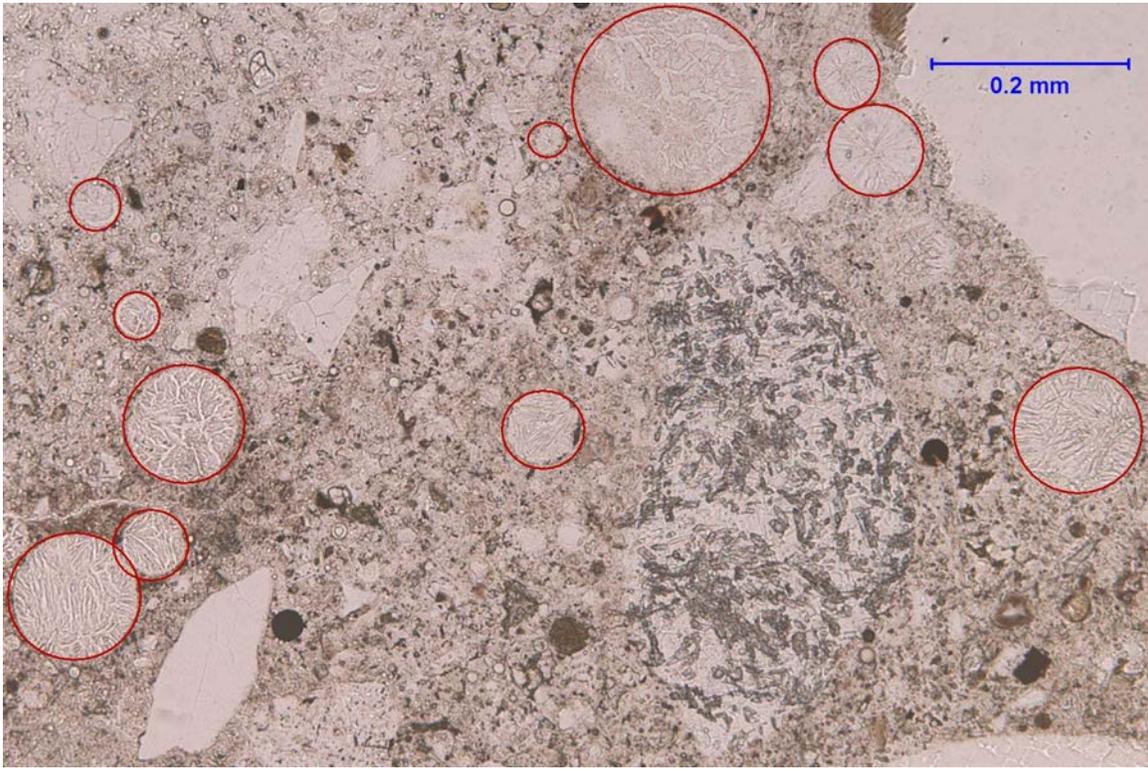
PHOTO: 36



SAMPLE ID: 7, 4705-30 DESCRIPTION: Magenta-stained ettringite fills most fine air voidspaces in the paste at 120mm depth in the core and within 8mm of the mildly distressed joint plane.
MAG: 30x

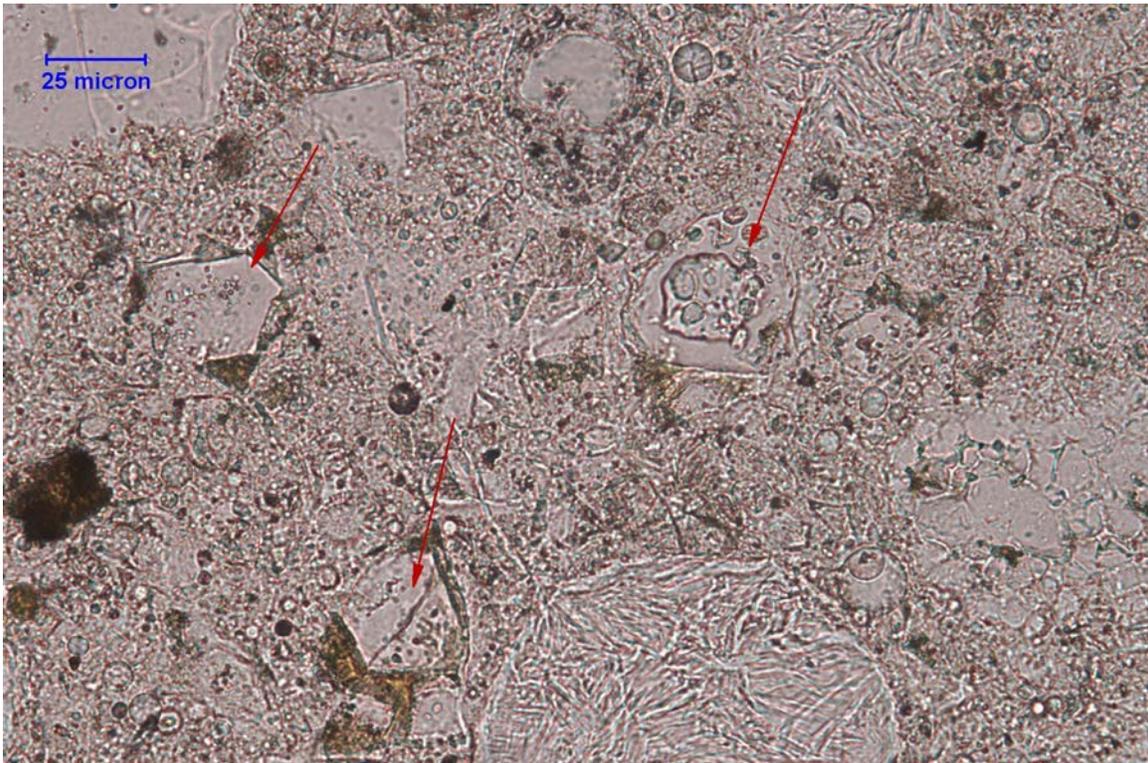
PROJECT: Joint Distress Study
MNDOT 4705-30 & 7380-199
US-12 Meeker County and I-94 Stearns County, MN

PHOTO: 37



SAMPLE ID: 7, 4705-30 DESCRIPTION: Ettringite-filled voidspaces (outlined in red) in the paste proximate to the joint plane in thin section under plane polarized light.
MAG: 100x

PHOTO: 38



SAMPLE ID: 7, 4705-30 DESCRIPTION: Well to fully hydrated alite portland cement clinker particles in thin section of concrete paste under plane polarized light.
MAG: 400x

APPENDIX E.

INVESTIGATION OF EFFECTS OF ADMIXTURE TYPE AND FLY ASH ON FREEZE-THAW DURABILITY OF CONCRETE

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INTRODUCTION

The aim of the work described in this report is to conduct an initial investigation of some of the mechanisms considered to be contributing to the observed premature deterioration of joints in concrete pavements.

Reports have been received from projects in several Midwest states that concrete, at joints, is deteriorating prematurely in various types of pavement from 5 to 30 years old.

It is likely that several mechanisms are contributing to the distress at the same time and possible that different deterioration locations are the result of different combinations of these mechanisms.

This first series was set up to limit the variables to a matrix that can be accommodated in existing equipment.

WORK PLAN

A limited set of concrete mixtures was prepared and samples were exposed to a freezing and thawing environment in accordance with ASTM C 666. The base mixture was an Iowa DOT C-4 WRC mixture as used in some locations where the distress has been observed.

The mechanisms evaluated with this work include the following:

- Effect of air-entraining admixture type
- Effect of fly ash
- Effect of deicing salt
- Effect of saw cutting

While much of this work has already been reported in the literature, this task was intended to lead into and provide a baseline for a larger matrix of innovative testing later.

Variables

The following parameters were varied:

- Type of air entraining admixture: vinsol, tall-oil
- Class C fly ash content: 0% and 15%
- Half of the samples were cured in water for 14 days before drying was started and half were sprayed with curing compound when de-molded and left in the laboratory environment
- Solutions in test cell: water, 3% NaCl

A full matrix of all these variables is 16 tests. Three samples were prepared for each variable in the matrix.

Fixed Parameters

The following parameters were held constant:

- Binder content = 624 pcy
- Target air content: 6.5 to 7.5%
- w/c:= 0.43
- Slump: 2 to 4 in.

Materials and Samples

Mixtures were prepared using the following materials:

- Type I portland cement from a local manufacturer
- Class C fly ash
- 3/4 in. limestone coarse aggregate
- River sand

Mixture proportions and fresh properties are shown in Table 1.

Table 1. Mixture proportions and fresh properties

		0FA Vinsol	0FA Tall-Oil	15FA Vinsol	15FA Tall-Oil
Cement	pcy	624	624	530	530
Fly ash	pcy	0	0	94	94
Coarse aggregate	pcy	1482	1482	1482	1482
Fine Aggregate	pcy	1477	1477	1477	1477
Water	pcy	268	268	268	268
AEA	oz/cwt	0.7	0.35	0.7	0.35
Air content	%	7.5	6.8	7.2	7.0
Slump	inch	4.3	2.5	4.0	3.5
unit weight	pcf	150.4	140.8	148.8	143.6

Samples prepared included 3 x 4 x 12 in. beams and 4 x 8 in. cylinders. A shallow saw cut was cut into the top face of each of the beams to model the sawing conducted in pavements in which distress is sometimes observed. Sawing was conducted 24 hrs after casting. The idea was to

investigate whether exposing the aggregate surface may be contributing to the accelerated distress. A typical saw cut is shown in Figure 1.



Figure 1. Cut being sawn in a beam

Tests

The following tests were conducted:

- ASTM C 666 freeze thaw resistance with half of the samples tested in water and half tested in 3% NaCl solution
- ASTM C39 compressive strength

A visual rating was also determined for the formed, finished (top), and sawn faces of the beams after 300 cycles of freezing and thawing. The rating was based on the approach used in ASTM C 672, where 5 denotes extensive damage and 1 denotes very little to no damage.

Figure 2 illustrates these extremes.



Figure 2. Visual rating 1 (left) and 5 (right)

RESULTS

Compressive strength data are shown in Table 2.

Table 2. Compressive strength data, psi

	0FA Vinsol	0FA Tall-Oil	15FA Vinsol	15FA Tall-Oil
7 day	3865	4095	5430	4520
14 day	4610	5000	5525	5310
28 day	5315	5735	6635	6170

Results of the C 666 tests are shown in Table 3.

Table 3. Results of freeze-thaw tests after 300 cycles

FA	AEA	Cure	Sol'n	RDM, %	Visual Rating, 300 cycles		
					Finished	Formed	Sawn
0	Vinsol	CC	Water	104	0	3	1
0	Vinsol	CC	Salt	100	2	4	1
0	Vinsol	Wet	Water	94	1	3	1
0	Vinsol	Wet	Salt	0	5	5	5
0	Tall-Oil	CC	Water	103	1	3	1
0	Tall-Oil	CC	Salt	101	3	3	1
0	Tall-Oil	Wet	Water	101	1	1	1
0	Tall-Oil	Wet	Salt	96	4	4	3
15	Vinsol	CC	Water	103	1	3	1
15	Vinsol	CC	Salt	100	3	4	3
15	Vinsol	Wet	Water	101	0	1	1
15	Vinsol	Wet	Salt	0	5	5	5
15	Tall-Oil	CC	Water	105	1	3	0
15	Tall-Oil	CC	Salt	100	2	4	1
15	Tall-Oil	Wet	Water	100	1	2	1
15	Tall-Oil	Wet	Salt	0	5	5	5

Samples that may be considered to have failed are highlighted.

DISCUSSION

The greatest distress was observed in the samples that had been wet-cured and tested in salt. While the effect of the salt is not surprising, the poor performance of the wet-cured samples is somewhat surprising. It is likely that, because the wet-cured samples were dried in air for 14 days before testing, they were more likely to absorb salt solution when testing was initiated than the samples coated with curing compound. This finding is supported by the distress only occurring in the salt solution exposure.

Only one set tested in water showed any distress (Vinsol, wet-cured, 0% fly ash) and the amount of distress was small. In general, the salt solution was more aggressive than water.

Little effect can be observed with respect to the effects of using fly ash or the type of admixture in the mixtures.

It is notable that the formed surface seemed to incur more damage than the other surfaces, while the sawn surface performed well.

APPENDIX F.

INVESTIGATION OF EFFECTS OF WATER/CEMENTITIOUS MIXTURE RATIO, AIR CONTENT, AND TIDAL ZONE ON FREEZE-THAW DURABILITY OF CONCRETE

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INTRODUCTION

The aim of the work described in this report is to conduct an investigation of the influence of water/cementitious mixture (w/cm) ratio, air content, and the depth of fluid on the deterioration of concrete during cyclic freezing and thawing.

Reports have been received from projects in several Midwest states that concrete, at joints, is deteriorating prematurely in various types of pavement from 5 to 30 years old.

It is likely that several mechanisms are contributing to the distress at the same time and possible that different deterioration locations are the result of different combinations of these mechanisms.

This work is part of a series to address effects of certain variables.

WORK PLAN

A set of concrete mixtures was prepared and samples were exposed to a freezing and thawing environment in accordance with ASTM C 666 Procedure A, except the beams were under 3% calcium chloride solution instead of fresh water. The depth of solution was limited to half the depth of the beams to evaluate whether samples need to be fully immersed to display distress.

The mechanisms evaluated with this work include the following:

- Effect of w/cm
- Effect of air content
- Effect of exposure to salt solution

Variables

The following parameters were varied:

- w/cm: 0.4 and 0.6
- Target air content: 3% and 6%
- Half the depth of each beam was in salt solution and the other half was in air

Four samples were prepared for each variable in the matrix.

Fixed Parameters

The following parameters were held constant:

- Binder content = 564 pcy
- Coarse aggregate/fine aggregate ratio = 58/42

Materials and Samples

Mixtures were prepared using the following materials:

- Type I portland cement from a local manufacturer
- 3/4 in. limestone coarse aggregate
- River sand

Mixture proportions and fresh properties are shown in Table 1.

Table 1. Mixture proportions and fresh properties

		0.4 w/cm 3.7% Air	0.4 w/cm 5.5% Air	0.55 w/cm 3.5% Air	0.55 w/cm 5.0% Air
Cement	pcy	564	564	564	564
Coarse aggregate	pcy	1883	1806	1710	1633
Fine Aggregate	pcy	1364	1307	1238	1183
Water	pcy	225.6	225.6	338.4	338.4
AEA	oz/cwt	0.3	0.9	0.3	0.6
Air content	%	3.7	5.5	3.5	5.0

Samples prepared included 3 x 4 x 12 in. beams and 4 x 8 in. cylinders. All beams were subjected to 7 days wet curing and 21 days drying before cycling started. Cylinders were cured in water for 28 days before testing.

Tests

The following tests were conducted:

- ASTM C 666 freeze thaw resistance using 3% calcium chloride solution to half the beam height
- ASTM C39 compressive strength

A visual rating was also determined for the wet, dry, and bottom surfaces of the beams after 300 cycles of freezing and thawing. The rating was based on the approach used in ASTM C 672, where a 5 denotes extensive damage and 1 denotes very little to no damage.

After cycling, a sample of the mixture with w/cm of 0.55 and air content of 5.5% was cut out and examined in a scanning electron microscope (SEM).

RESULTS

Compressive strength data are shown in Table 2.

Table 2. 28 day compressive strength data, psi

0.4 w/cm 3.7% Air	0.4 w/cm 5.5% Air	0.55 w/cm 3.5% Air	0.55 w/cm 5.0% Air
6759	5837	3997	4001

Results of the C 666 tests are shown in Table 3 and Figures 1 and 2.

Table 3. Results of freeze-thaw tests after 300 cycles

w/cm	Air content	Length change (in.)	Weight change (lbs)	RDM, (%)	Visual rating, 300 cycles		
					Wet	Dry	Bottom
0.55	5.0	0.0745	0.0426	115.4	1.8	0.1	3.3
0.55	3.5	0.0595	0.0636	104.5	2.1	0.3	2.0
0.40	3.7	0.2928	-0.2395	104.7	2.9	2.0	5.0
0.40	5.5	0.0750	-0.0090	100.8	1.0	0.4	2.0

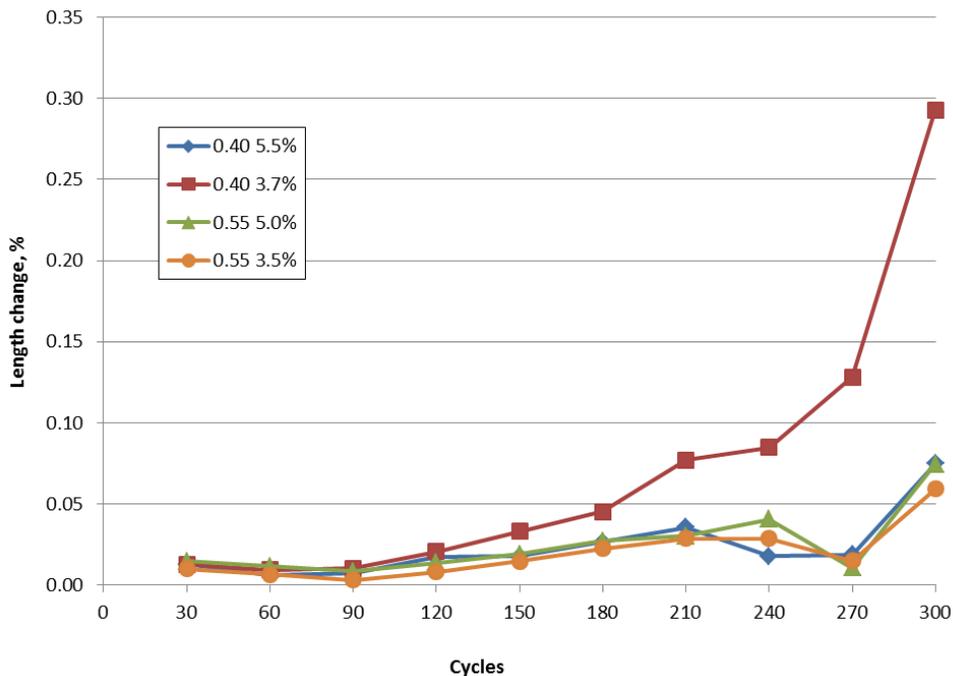


Figure 1. Average of the length change for the four beams over 300 cycles

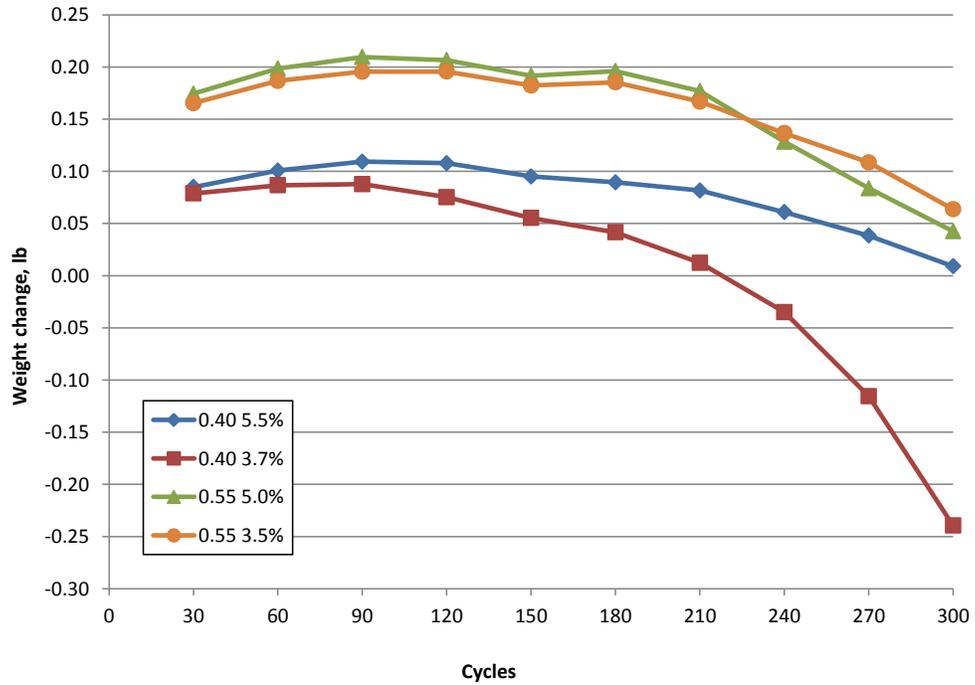


Figure 2. Average of the weight loss for the four beams over 300 cycles

An image from the SEM work is shown in Figure 3.

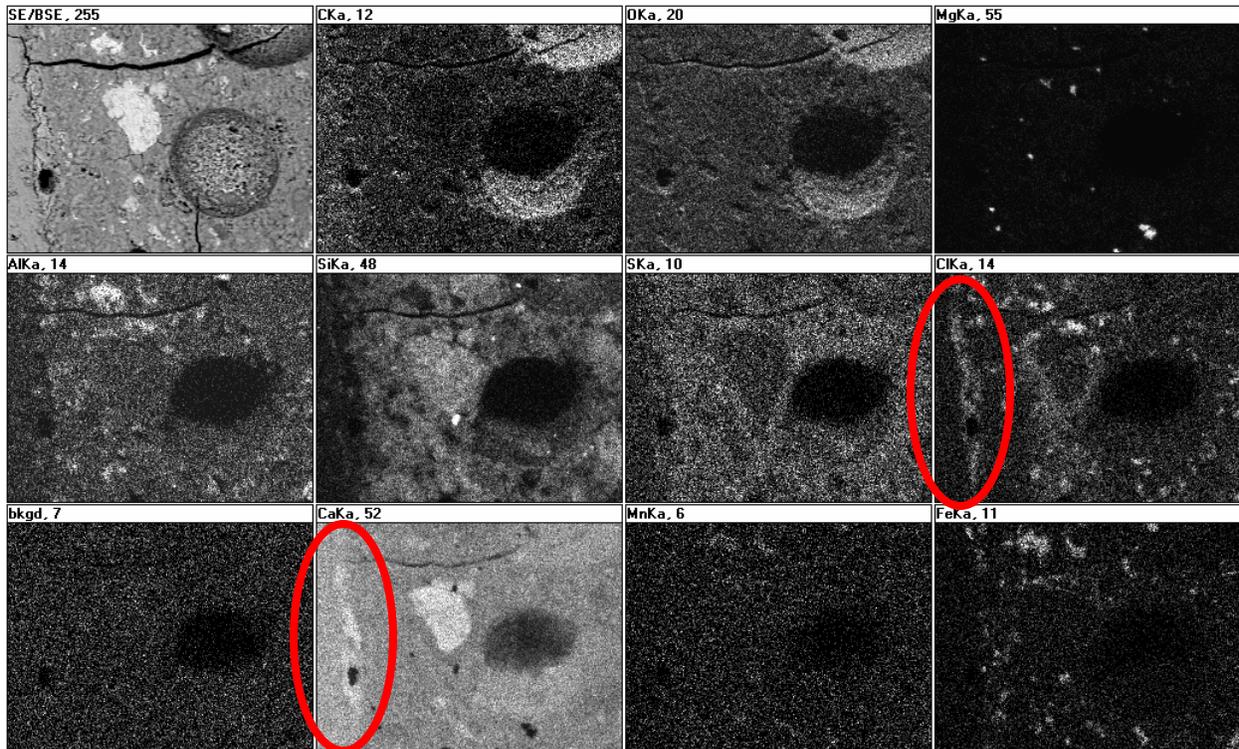


Figure 3. SEM analysis on distressed samples under cyclic freeze thaw in CaCl₂ solution

The original external face of the sample is horizontal and about 3/8 in. above the top of the image. The field of view is about 400 μ m. A coarse aggregate particle is visible to the left of the image.

The aim of the effort was to assess whether solution had penetrated the system through the bulk past or preferentially through the interfacial zone around coarse aggregate particles. This goal was achieved by elemental mapping and looking at chlorides that would have come from sources external to the sample.

Both the chlorine and calcium maps show a lighted area around the aggregate, which indicates that salt solution is concentrated in the interfacial zone.

DISCUSSION

The mass change data show that the higher w/cm mixture gained about the same weight, initially, and this was somewhat higher than the low w/cm mixtures. This finding is as expected.

Subsequently, the greatest distress occurred in the samples containing a low w/cm and low air content. Little difference was observed among the other mixtures at the end of the cycling. The poor performance of the low w/cm and low air content mixture is likely because the laboratory staff later reported difficulty in consolidating those samples.

The visual rating shows, as expected, that the wet portion of the samples have more distress than the dry portion and the bottom side of the samples have the most distress (Figure 4).

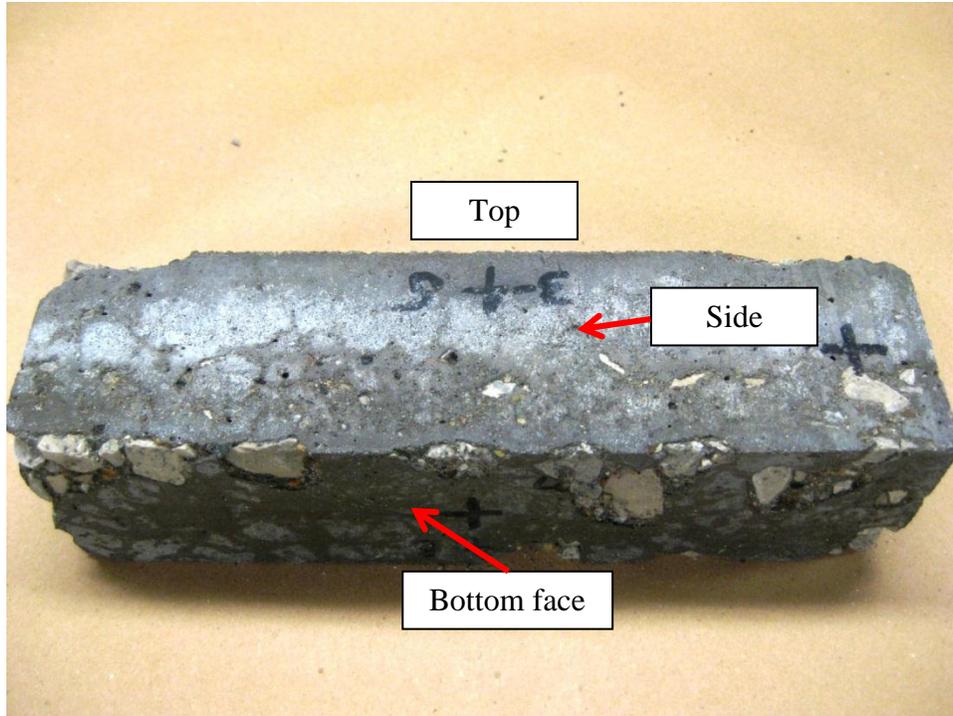


Figure 4. Typical sample after 300 cycles

What is interesting is that this finding indicates that the degree of saturation is not above critical levels more than a fraction of an inch above the water level. This finding is despite the extremely high capillary suction or wicking that may be expected in the size of pores in hydrated cement paste.

It was noted that material loss was primarily in the paste, leaving the coarse aggregate particles clean (Figure 4). This is consistent with field observations.

The bottom face shows the most damage, while the amount of damage does not extend far above the water level (approximately at the + on the top face of the samples, as shown).

APPENDIX G.

INVESTIGATION OF EFFECTS OF INTERFACIAL ZONE ON FREEZE-THAW DURABILITY OF CONCRETE

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INTRODUCTION

The aim of the work described in this report is to conduct an investigation of the influence of interfacial zone to the deterioration of concrete during cyclic freezing and thawing.

Reports have been received from projects in several Midwest states that concrete, at joints, is deteriorating prematurely in various types of pavement from 5 to 30 years old.

It is likely that several mechanisms are contributing to the distress at the same time and possible that different deterioration locations are the result of different combinations of these mechanisms.

One of the mechanisms that is likely to be contributing to the observed behavior is the influence of the interfacial transition zone (ITZ). This is a 10 to 50 μm wide zone of hydrated paste concentrated around coarse aggregate particles that is reported to have less calcium silicate hydrate and more calcium hydroxide (Mehta 1986). The ITZ is reportedly more permeable and of lower strength than the bulk paste (Cwirzen and Penttala 2004).

It is not uncommon to observe a crack about 1 in. from the joint face (Figure 1).



Figure 1. Crack formed about 1 in. from the free surface

In some cases, the concrete in between is in good condition (Figure 2).



Figure 2. Sample removed piece showing that material between the free surface and the new crack is reasonably sound with coarse aggregate particles free of paste

Typically, the crack will form around the coarse aggregate leaving it unusually free of mortar. The material in the wedge between the crack and the free surface is sometimes observed to be in good condition. A possible explanation for this is that a saw cut through a piece of aggregate exposes the interfacial transition zone (ITZ) around the particle. Water or salt solution in the joint may absorb into the ITZ forming a thin layer around the aggregate. Subsequent freezing of water in the ITZ will cause expansion that will tend to separate the aggregate from the paste and drive a vertical crack up to the surface (Figure 3).

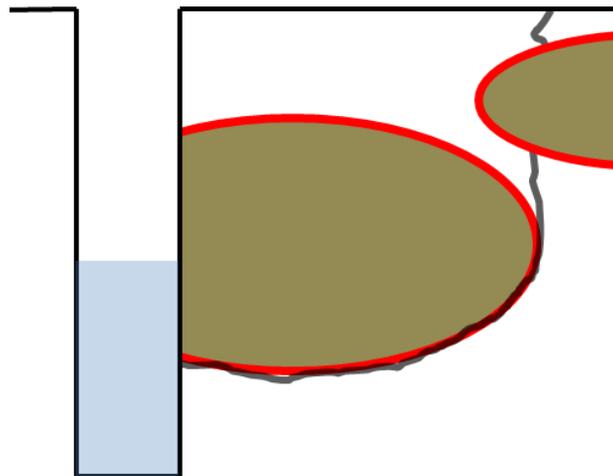


Figure 3. Schematic of how damage is accumulated

Over time, the crack will widen until the wedge is loosened and removed by traffic (Figure 4). The aim of this work was to investigate the feasibility of this hypothesis.



Figure 4. Sample of damage increasing over time (July 2011 to July 2012)

WORK PLAN

The factors that influence the ITZ include (Mehta 1986):

- Type of SCM, silica fume is known to reduce the ITZ
- w/c
- Aggregate type

A set of concrete mixtures was prepared varying these parameters and samples were exposed to a freezing and thawing environment in accordance with ASTM C 666 Procedure A. Two beams were prepared from each mixture. Two extra beams were prepared from the mixtures containing gravel, high water cement ratio and no silica fume, and the mixture with limestone, low water cement ratio and high silica fume content, for testing in 3% sodium chloride solution.

Variables

The following parameters were varied:

- w/cm: 0.4 and 0.5
- Binder: 0, 3 and 5% silica fume
- Coarse aggregate: round gravel and crushed limestone

Two samples were prepared for each variable in the matrix, and two extra beams were prepared from the mixture containing gravel, high w/cm and no silica fume and the mixture with limestone, low w/cm and high silica fume content for testing in 3% sodium chloride solution during the freezing and thawing cycles.

Fixed Parameters

The following parameters were held constant:

- Binder content = 564 pcy
- Target air content = 6 ± 1 %
- Coarse aggregate / fine aggregate ratio = 3/2

Materials and Samples

Mixtures were prepared using the following materials:

- Type I portland cement from a local manufacturer
- Silica fume
- 3/4 in. limestone coarse aggregate and 3/4 in. gravel aggregate
- River sand

Mixture proportions and fresh properties are shown in Table 1.

Table 1. Mixture proportions and fresh properties

		0.4_0SF_G*	0.4_3SF_G	0.4_5SF_G	0.5_0SF_G	0.5_3SF_G	0.5_5SF_G
Cement	pcy	564	547.1	535.8	564	547.1	535.8
Silica fume	pcy	0	16.9	28.2	0	16.9	28.2
Coarse aggregate	pcy	1865	1861	1858	1775	1772	1769
Fine aggregate	pcy	1243	1241	1239	1183	1181	1179
Water	pcy	225.6	225.6	225.6	282	282	282
AEA	oz/cwt	4.8	4.8	4.8	0.48	0.48	0.80
Water reducer	oz/cwt	5.7	6.5	6.5	0	0	0
Air content	%	5.3	6.3	5.5	5.8	5.6	6.5
Slump	In.	0.5	0.8	1.0	8.0	7.0	8.0
Unit weight	pcf	149.0	147.2	147.8	145.0	144.6	144.4

		0.4_0SF_L	0.4_3SF_L	0.4_5SF_L	0.5_0SF_L	0.5_3SF_L	0.5_5SF_L
Cement	pcy	564	547.1	535.8	564	547.1	535.8
Silica fume	pcy	0	16.9	28.2	0	16.9	28.2
Coarse aggregate	pcy	1869	1865	1863	1779	1776	1773
Fine aggregate	pcy	1246	1243	1242	1186	1184	1182
Water	pcy	225.6	225.6	225.6	282	282	282
AEA	oz/cwt	0.48	0.32	1.36	0.56	0.64	0.64
Water reducer	oz/cwt	7.3	6.5	8.1	0	0	0
Air content	%	8.0	6.0	5.5	5.8	6.5	7.3
Slump	In.	5.0	4.5	3.0	8.0	7.8	6.0
Unit weight	pcf	144.2	146.6	148.6	144.0	143.8	142.6

*0.4_0SF_G stands for w/cm=0.4 with 0% silica fume using gravel aggregate

Samples prepared include 3 x 4 x 16 in. beams and 4 x 8 in. cylinders. One vertical face of the beam has been sawn off to expose the interfacial zone. All beams were subjected to 14 days wet curing and 28 days drying before cycling started. The same curing condition was applied to the cylinders before testing for the absorption, air permeability, and split tensile strength of the concrete.

Tests

The following tests were conducted:

- ASTM C 666 Procedure A freeze-thaw resistance with 3% sodium chloride solution applied to the beams with gravel aggregate at high w/cm without silica fume and limestone aggregate at low w/cm with high silica fume content
- Air permeability (University of Cape Town Method) on finished surface and sawn surface
- ASTM C1585 sorption tests on finished surface and saw surface

A visual rating was also determined for the sawn and formed surface of the beams after 600 cycles of freezing and thawing. The rating was based on the approach used in ASTM C 672 where a 5 denotes extensive damage and 1 denotes very little to no damage.

Slices were cut from samples after 600 cycles. These slices were vacuum-saturated in sodium chloride, then 0.1 M silver nitrate was applied. The aim was to observe how solutions would penetrate the different mixtures.

RESULTS

The absorption test results are interpreted as the initial rate of absorption and secondary rate of absorption as shown in Figures 5 and 6.

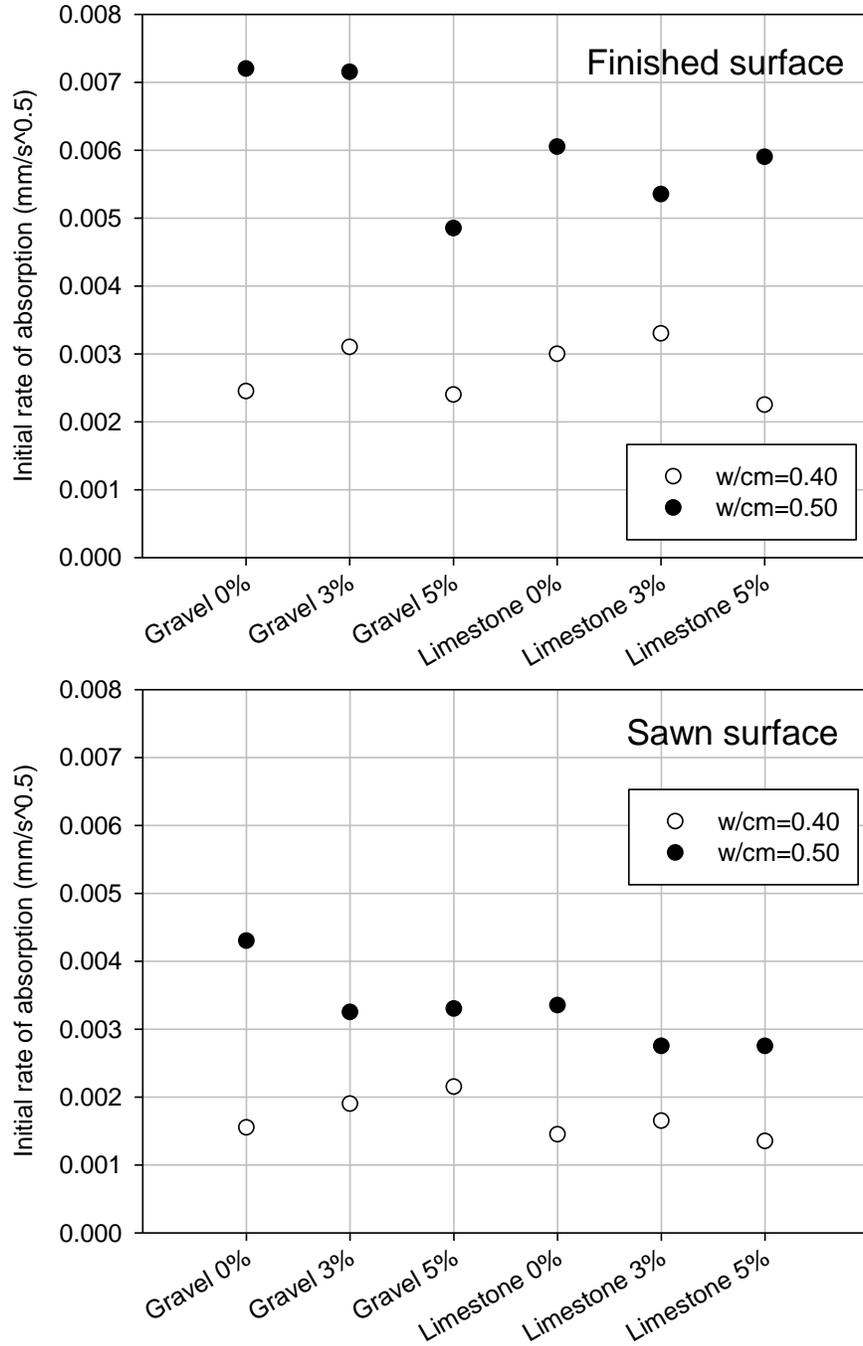


Figure 5. Initial rate of absorption data

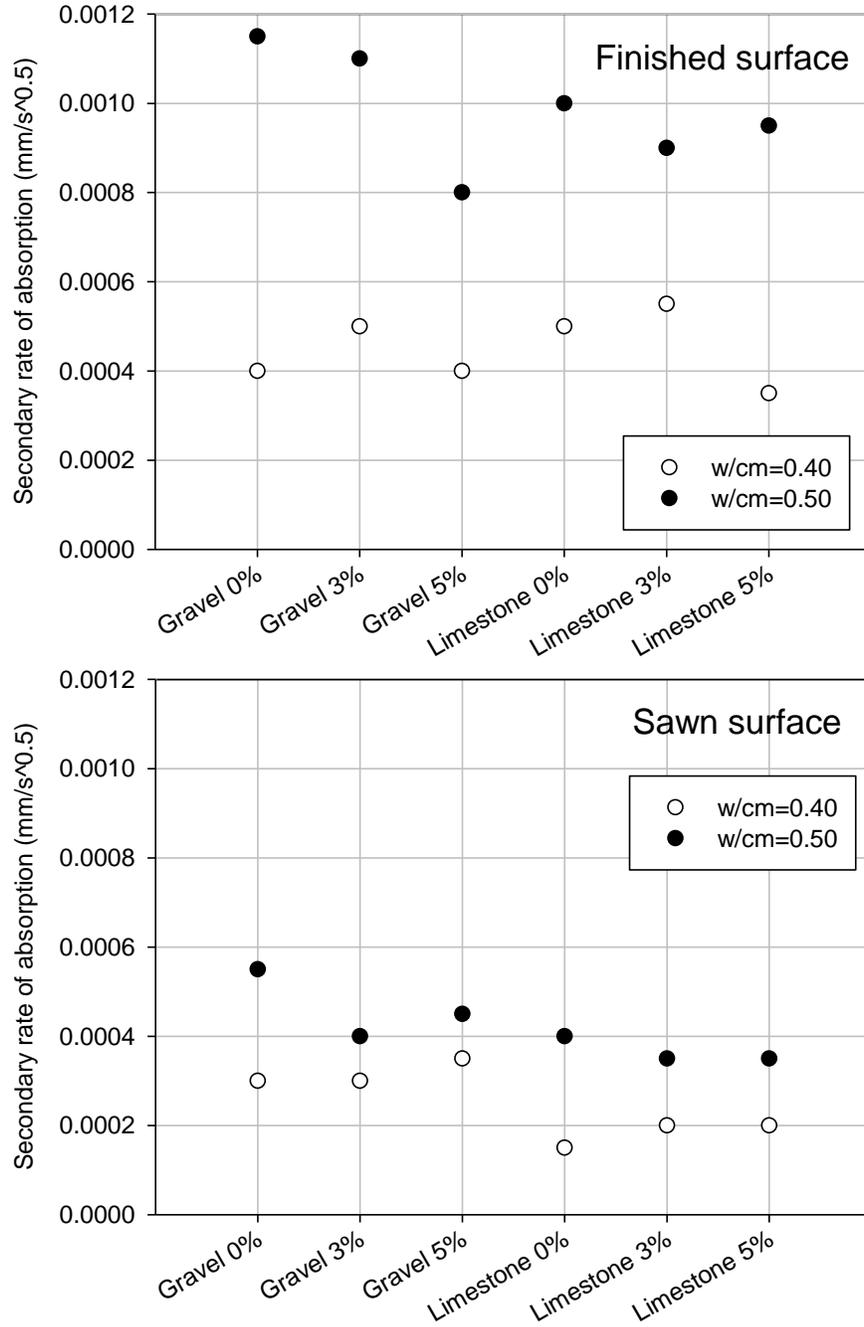


Figure 6. Secondary rate of absorption data

The air permeability data are interpreted as API as shown in Figure 7.

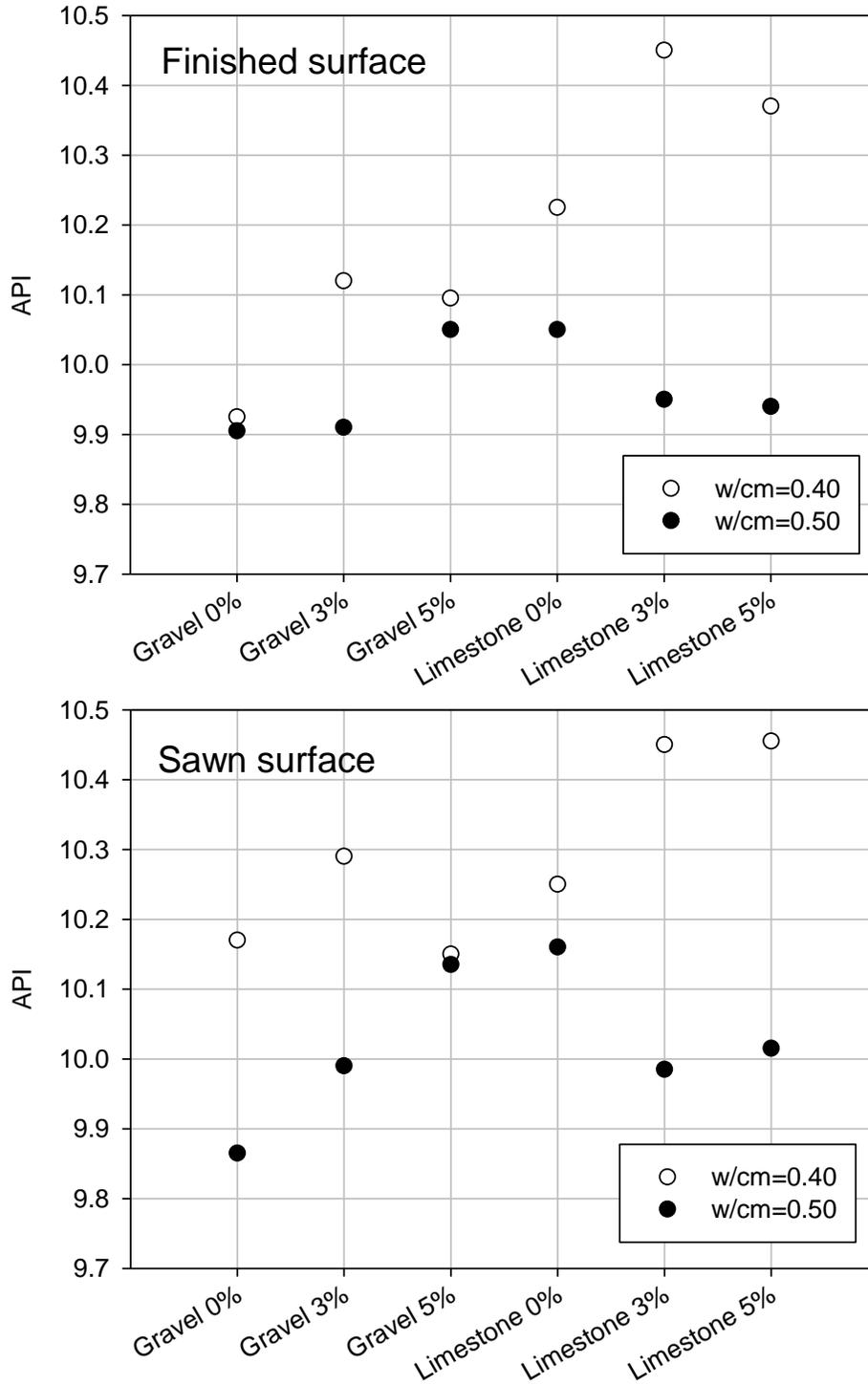


Figure 7. API results

Results of the C 666 tests are shown in Table 2.

Table 2. Results of freeze-thaw tests after 600 cycles

Aggregate type	w/cm	Silica fume content	Solution	Weight change (lbs)	RDM, (%)	Visual rating, 600 cycles	
						Formed face	Saw face
Gravel	0.4	0	Fresh water	-0.2650	52.4	1.5	1.5
		3		0.0348	92.7	2.0	2.0
		5		0.1576	95.8	1.0	1.0
	0.5	0	3% NaCl	0.0960	87.0	1.0	2.0
		0		-1.1462	57.4	4.0	5.0
		3	Fresh water	0.0653	71.4	2.0	3.0
		5		-0.2793	72.0	2.5	1.0
		5		0.1711	99.7	0.5	1.0
Limestone	0.4	3	Fresh water	0.1113	96.5	0.5	1.0
		5		0.1501	48.3	1.0	2.0
		5		3% NaCl	-0.3056	55.5	3.0
		0	Fresh water	0.1664	99.8	1.5	1.5
	3	0.0977		102.2	-	2.5	
	5	0.2008		101.5	2.5	2.0	
	5						

The average measurements of the two beams for each mixture were used for the interpretation as shown in Figures 8 and 9.

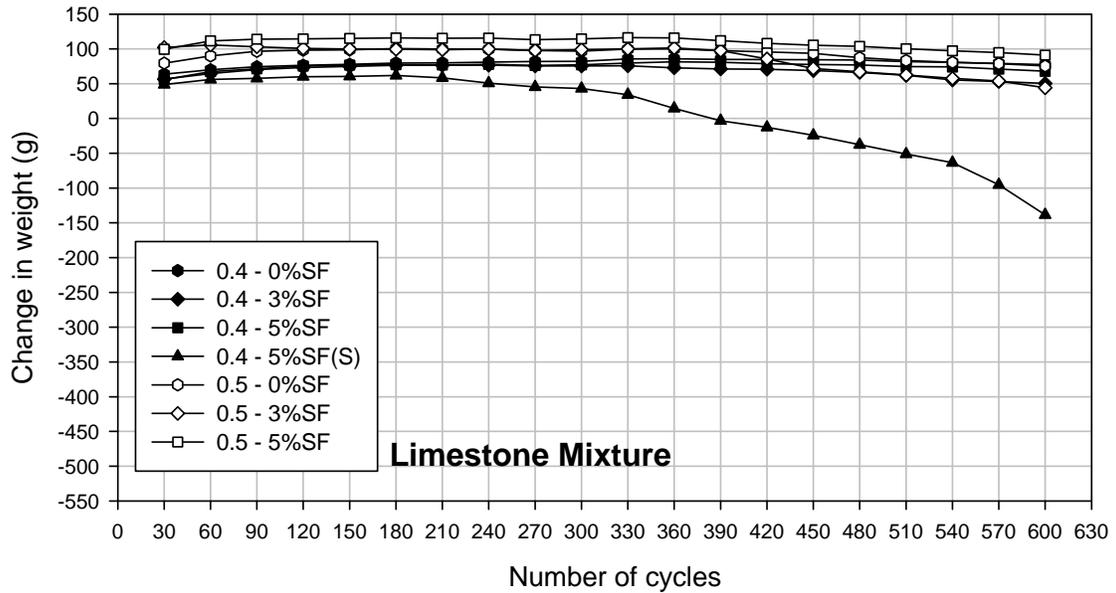
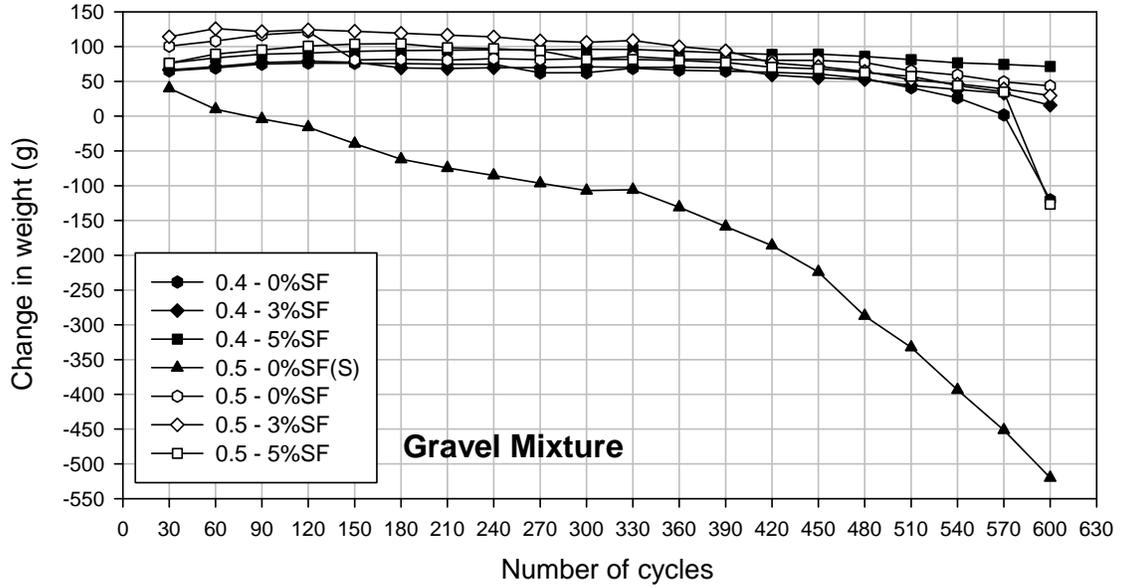


Figure 8. Weight change on the beams for 600 freezing and thawing cycles (S denotes sample tested in salt solution)

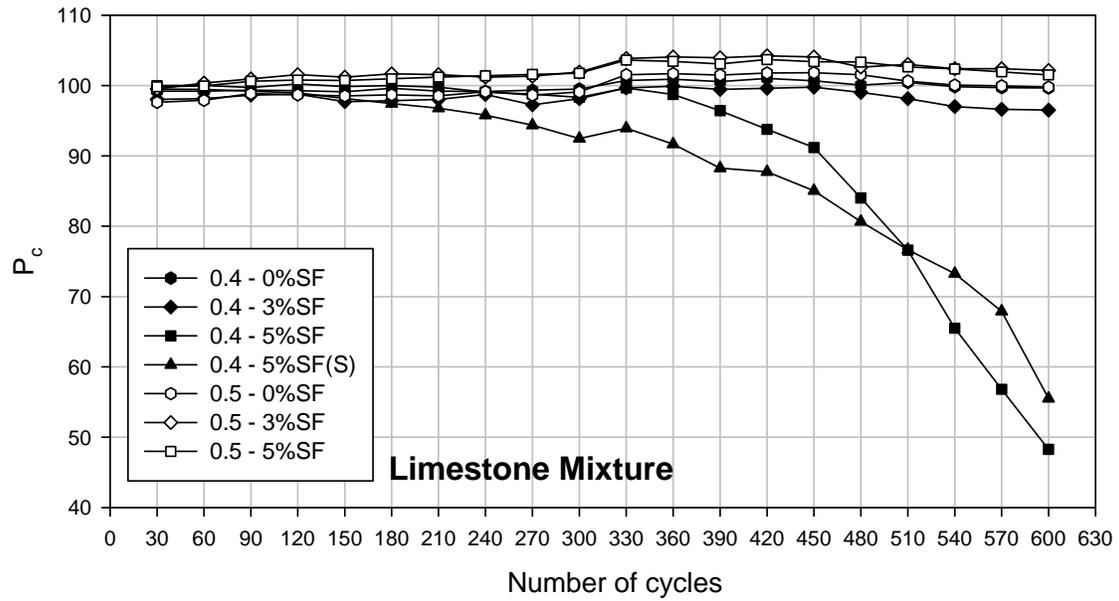
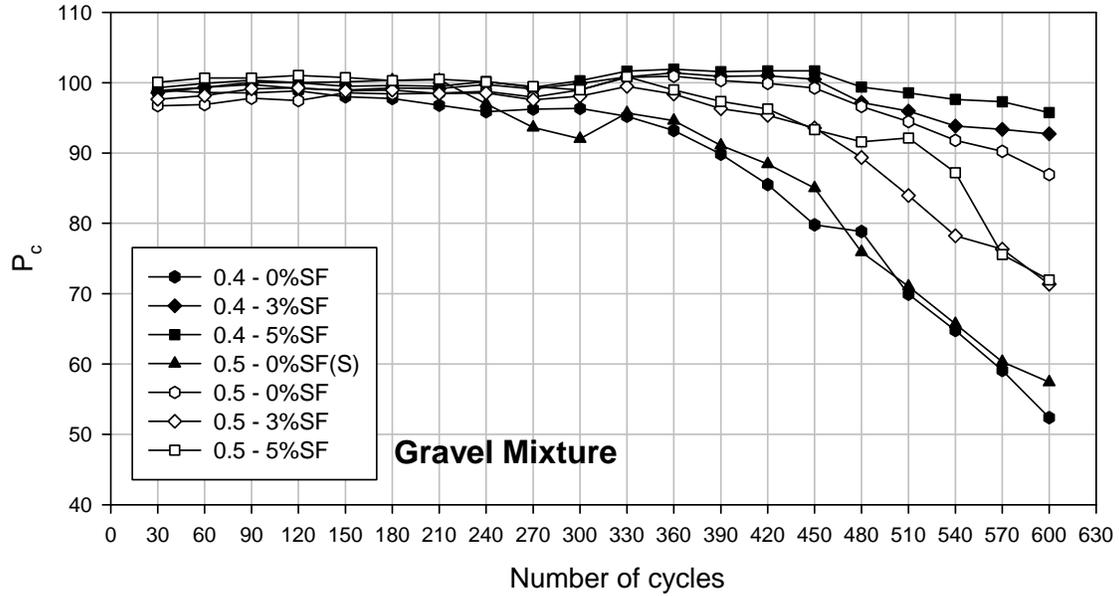


Figure 9. Relative dynamic modulus of elasticity on the beams for 600 freezing and thawing cycles (S denotes sample tested in salt solution)

Images of the samples tested in salt, then cut and treated with silver nitrate are shown in Figure 10.



Figure 10. Samples tested in salt, cut, then treated with silver nitrate to highlight presence of chlorides (a) 0.5 - 0%SF - gravel (b) 0.4 - 5%SF - limestone

DISCUSSION

Concrete mixtures with the higher w/cm ratio exhibited higher absorption and higher air permeability. High w/cm samples also exhibited more salt accumulation around aggregate particles, greater distress, and greater tendency for cracks to go around the aggregate. Surprisingly the higher w/cm mixtures performed slightly better in the freeze-thaw testing. It is possible that this is associated with consolidation difficulties associated with the dry mixtures.

Concrete mixtures with limestone aggregate showed significantly higher durability than the mixtures with gravel aggregate, but this is likely due mainly to a significant effect of pop-outs from lightweight materials in the gravel.

The effects of the silica fume were more significant in the mixtures containing gravel aggregate than those with limestone aggregate. Both absorption and air permeability were improved with increasing silica fume content in mixtures containing high w/cm and gravel. No other trends were observed in effects on absorption and air permeability. No trend could be seen with respect to scaling as a function of the silica fume content.

Based on the visual ratings, the sawn faces of the samples exhibited more distress than the formed face of the samples.

The samples treated with silver nitrate showed a white ring around some of the aggregate particles. This seems to indicate that the salt solution preferentially penetrated into the concrete through the interfacial zone. The limestone aggregates show fewer rings than the sample made with gravel. The sample mixed with gravel also had a higher w/cm without any silica fume.

All are factors likely leading to a more dominant interfacial zone. As an example, some typical distress is shown in Figure 11 with damage to a sample containing gravel, $w/cm = 0.5$, and 5% silica fume (SF).



Figure 11. Laboratory observation of distress incurred during freezing and thawing

The failure surface includes both cracks through and around aggregate particles. Failures around the aggregates are likely associated with the ITZ because it is normally unusual to see aggregate particles without paste adhering to them, unless the mechanism of stress is adjacent to the surface.

REFERENCES

- Cwirzen, A. and Penttala, V. (2004). "Aggregate-Cement Paste Transition Zone Properties Affecting the Salt-Frost Damage of High-Performance Concretes." *Cement and Concrete Research*, 35(4), 671-679
- Mehta, P. K. (1986). *Concrete: Structure, Properties, and Materials*. Englewood Cliffs, NJ: Prentice-Hall,

APPENDIX H.

THE INFLUENCE OF DEICING SALTS ON THE DRYING AND WETTING BEHAVIOR OF CEMENTITIOUS MATERIALS

Numerous concrete pavements in the US have shown premature deterioration at joints. While several causes have been suggested to be responsible for the distress that develops, it is clear that the movement/presence of moisture is a key factor in several of these distress mechanisms including those associated with freeze/thaw and/or physical salt attack. It has been hypothesized (Weiss and Nantung 2005) that deicing salts may increase the degree of saturation at joints over time. To fully understand the influence of fluid properties on the wetting and drying behavior of concrete a series of experiments were performed using aqueous solutions containing deicing salts. Specifically, fundamental wetting and drying properties were obtained for cementitious systems containing aqueous deicing salt solutions. The work compliments work that has shown that sealers may help to reduce the degree of saturation.

The main findings are summarized here:

The main findings are as follows:

1. The presence of deicing salts alters the viscosity, water activity, surface tension and density of the solution. An experimental investigation was conducted to evaluate the change in these properties, analyzing salt solutions with different concentrations and compositions. Compared to the case of pure water, the presence of salt appears to increase surface tension, increase the viscosity, decrease the water activity (or equilibrium relative humidity) and increase the specific gravity.
2. A thermodynamic model was used to relate the equilibrium relative humidity (the humidity at which the system would start to dry) to the properties of the solution evaluated experimentally and to the pore structure. The equilibrium relative humidity resulted to be function of the concentration of the salt solution.
3. The properties of the liquid are known to influence the absorption process in concrete. Sorption tests and water re-absorption were performed using different aqueous solutions. The results showed that as the salt concentration increased, the rate of absorption and the total absorption were reduced proportionally with the square root of the ratio of surface tension and viscosity. The re-absorption tests conducted on samples previously wetted with different salt solution and then oven dried, revealed that pure water would enter in the system differently if salts was deposited in the pores. Therefore, the history of the samples plays a role on the fluid ingress mechanisms.

4. The influence of properties of the solution on drying processes was also studied. Desorption analysis were conducted on mortar samples submerged in calcium chloride, magnesium chloride and sodium chloride solutions with different concentrations. The results confirm a higher degree of saturation of the material in presence of salts. This effect was shown to be function of the salt composition and of the concentration of the solution.

It was also noticed that samples with salt concentrations do not show a reduction in sample mass until the RH decreases below an equilibrium relative humidity, RH_{eq} . In fact, samples may gain mass at high RH due to the hygroscopic nature of the salt. As a result, samples containing deicing salt solutions are likely to have a higher degree of saturation than samples without deicing salt solutions in practice. This is especially true when drying and wetting occur. The initial DOS of the sample was also proved to be important for fluid transport tests. Some sorption tests were conducted using samples conditioned differently (at 50% RH, 65% RH and 80% RH). The results showed that the higher the initial moisture content (or DOS), the lower the water absorbed and the rate of absorption.

5. The non-linear moisture diffusion coefficient was also evaluated from the desorption analysis data. The experimental data were able to be fitted using the model proposed by Xi et al. (1994) and they show a clear trend when adding deicing salt in the system, compared to the case of pure water. The diffusivity versus relative humidity curves tend to shift to lower RH values and to cover a narrower range of humidities starting from the equilibrium relative humidity.

The results of this study show the importance of considering the properties of solutions when describing fluid transport processes. This suggests also that particular care must be taken when performing field tests on concrete exposed to deicing salts. Furthermore, this illustrates the potential benefits of sealers that can keep deicing salts out of the pores in concrete.

These findings were published as technical papers:

- R. Spragg, J. Castro, W. Li, M. Pour-Ghaz, P. T. Huang, and W. J. Weiss. "Wetting and drying of concrete using aqueous solutions containing deicing salts." *Cement and Concrete Composites*, Vol. 33, 2011, pp. 535-542.
- C. Villani, R. Spragg, M. Pour-Ghaz, and W. J. Weiss. The role of deicing salts on the non-linear moisture diffusion coefficient of cementitious materials during drying. 10th International RILEM Symposium on Brittle Matrix Composites, October 15-17, 2012. Warsaw, Poland.